sustainability

Special Issue Reprint

Sustainable Agri-Food Systems

Environment, Economy, Society and Policy—2nd Edition

Edited by
Tarek Ben Hassen, Hamid El Bilali and Carola Strassner

mdpi.com/journal/sustainability

MDPI

Sustainable Agri-Food Systems: Environment, Economy, Society and Policy—2nd Edition

Sustainable Agri-Food Systems: Environment, Economy, Society and Policy—2nd Edition

Guest Editors

Tarek Ben Hassen
Hamid El Bilali
Carola Strassner

MDPI

Basel • Beijing • Wuhan • Barcelona • Belgrade • Novi Sad • Cluj • Manchester

Guest Editors

Tarek Ben Hassen
Department of International Affairs
College of Arts and Sciences,
Qatar University
Doha
Qatar

Hamid El Bilali
Mediterranean Agronomic Institute of Bari, International Centre for Advanced Mediterranean Agronomic Studies (CIHEAM-Bari)
Valenzano
Italy

Carola Strassner
Department of Food, Nutrition & Facilities
FH Münster University of Applied Sciences
Münster
Germany

Editorial Office
MDPI AG
Grosspeteranlage 5
4052 Basel, Switzerland

This is a reprint of the Special Issue, published open access by the journal *Sustainability* (ISSN 2071-1050), freely accessible at: https://www.mdpi.com/journal/sustainability/special_issues/V3ZF823FZ8.

For citation purposes, cite each article independently as indicated on the article page online and as indicated below:

Lastname, A.A.; Lastname, B.B. Article Title. *Journal Name* **Year**, *Volume Number*, Page Range.

ISBN 978-3-7258-3965-0 (Hbk)
ISBN 978-3-7258-3966-7 (PDF)
https://doi.org/10.3390/books978-3-7258-3966-7

Cover image courtesy of Graphic Node

Contents

About the Editors

Tarek Ben Hassen

Tarek Ben Hassen is an Associate Professor of Policy, Planning, and Development at the Department of International Affairs at Qatar University. He holds an M.Sc. in Management of Innovation from the University of Quebec at Chicoutimi (2006) and a Ph.D. in Urban Studies (specializing in Economic Geography) from the University of Quebec in Montreal (2012). His research falls into the subfield of economic geography, focusing on the dynamics of sustainability and innovation within food systems. He has published several works in reputable international journals, including *Sustainability*, *Cities*, *Policy Studies*, *Appetite*, and *Environment, Development and Sustainability*. He was listed among the top 2% of the most cited scientists worldwide in 2023 and 2024, elaborated by Stanford University and Elsevier Publisher.

Hamid El Bilali

Hamid El Bilali is a Senior Researcher and Scientific Administrator at the International Centre for Advanced Mediterranean Agronomic Studies (CIHEAM-Bari), Italy. He graduated in Agronomy from the Hassan II Institute of Agronomy and Veterinary Medicine in Rabat, Morocco. He holds an M.Sc. in Mediterranean Organic Agriculture (CIHEAM-Bari, 2004) and a PhD in Agricultural Sciences (University of Bari, Italy; 2008). Since December 2004, he has been engaged in research, training, and cooperation activities relating to sustainable agri-food systems, food and nutrition security, food losses and waste, sustainable food consumption and production, neglected and underutilized species (NUS), rural livelihood diversification, and rural policy and governance. In the period from February 2017 to January 2019, he served as a Post-doc Fellow on "Sustainability transitions in agri-food systems and food security" at the University of Natural Resources and Life Sciences (BOKU), Vienna. He is the author of more than 200 publications (articles, conference papers, book chapters) and a Member of the editorial boards of numerous journals on agriculture, food, and rural development (e.g., *Frontiers in Sustainable Food Systems*; *North African Journal of Food and Nutrition Research*; *Journal of Agriculture, Food Systems and Community Development*; *Discovery Sustainability*). He has been included over the last four years (2021, 2022, 2023, 2024) in the list of the world's top 2% of scientists elaborated by Stanford University.

Carola Strassner

Carola Strassner is a Life Sciences graduate of the University of Cape Town (Biochemistry, Microbiology), with an M.Sc. in Food Science from the University of Durban/Kwazulu-Natal and an MBA from Henley Management College (today: University of Reading, UK). She obtained her Ph.D. in Nutritional Sciences and Home Economics from the Justus-Liebig University in Germany. Carola gathered industry experience as Head of R&D at a medium-sized German health enterprise and as an entrepreneur in the field of food market consulting. Today, Carola Strassner is a Professor of Sustainable Food Systems and Nutrition Ecology at FH Münster University of Applied Sciences where she specializes in the transformation of food systems, applying this in the out-of-home (HORECA) context and alternative food networks. Dr. Strassner works specifically with institutional catering systems, school meal systems, and organic food systems. She initiated and managed an international network, "Organic Out Of Home", for ten years and is a Board Member of FQH. Carola is Managing Partner of the business company a'verdis—Sustainable FoodService Solutions.

Preface

In recent decades, food systems have been pivotal in discussions regarding sustainable development, especially within the framework of the 2030 Agenda for Sustainable Development and the Sustainable Development Goals (SDGs). These systems are currently facing unparalleled challenges, such as climate change, the loss of biodiversity, resource scarcity, and population growth, while simultaneously playing a significant role in these issues. For example, the COVID-19 pandemic has highlighted the weaknesses of contemporary food systems, worsening problems like food insecurity, malnutrition, rural poverty, and social inequality. This situation has escalated demands for fundamental changes toward sustainability, stressing the importance of strategies such as sustainable agriculture, sustainable diets, short supply chains, and the minimization of food waste. Nevertheless, various approaches reveal differing viewpoints on sustainability, underscoring the necessity for cohesive food policies and governance reforms to facilitate this shift while managing trade-offs between sustainability dimensions.

This reprint of the Special Issue "Sustainable Agri-Food Systems: Environment, Economy, Society and Policy—2nd Edition" consists of an editorial and 14 articles. The 14 articles explore various dimensions of sustainable agri-food systems and can be categorized into three thematic areas: (1) community-based sustainability and socio-economic resilience, (2) environmental sustainability, and (3) consumption patterns and food system dynamics. Together, they offer a comprehensive perspective on the challenges and opportunities in building more sustainable and resilient agri-food systems.

Tarek Ben Hassen, Hamid El Bilali, and Carola Strassner
Guest Editors

sustainability

MDPI

Editorial

Sustainable Agri-Food Systems: Environment, Economy, Society, and Policy—2nd Edition

Tarek Ben Hassen [1,*], Hamid El Bilali [2] and Carola Strassner [3]

1 Department of International Affairs, College of Arts and Sciences, Qatar University, Doha 2713, Qatar
2 International Centre for Advanced Mediterranean Agronomic Studies (CIHEAM-Bari), Valenzano, 70010 Bari, Italy; elbilali@iamb.it
3 Department of Food, Nutrition & Facilities, FH Münster—University of Applied Sciences, 48149 Münster, Germany; strassner@fh-muenster.de
* Correspondence: thassen@qu.edu.qa

Received: 8 February 2025
Accepted: 14 February 2025
Published: 17 February 2025

Citation: Ben Hassen, T.; El Bilali, H.; Strassner, C. Sustainable Agri-Food Systems: Environment, Economy, Society, and Policy—2nd Edition. *Sustainability* **2025**, *17*, 1667. https://doi.org/10.3390/su17041667

Food systems encompass all elements and activities involved in producing, processing, distributing, and consuming food, along with their outputs. A sustainable food system ensures its socio-economic and environmental outcomes do not compromise the resources and bases needed by future generations. Over recent decades, food systems have been central to debates on sustainable development, particularly within the 2030 Agenda for Sustainable Development and the Sustainable Development Goals (SDGs). These systems face unprecedented pressures, including climate change, biodiversity loss, resource scarcity, and population growth, while also contributing significantly to these challenges. For instance, the COVID-19 pandemic has further exposed the vulnerabilities of modern food systems, exacerbating issues like food insecurity, malnutrition, rural poverty, and social inequality. This has intensified calls for systemic transformations toward sustainability, emphasizing strategies such as sustainable agriculture, sustainable diets, short supply chains, and reducing food waste. However, diverse approaches reflect differing perspectives on sustainability, highlighting the need for integrated food policies and governance reforms to achieve this transition.

The 14 papers in this Special Issue explore various dimensions of sustainable agri-food systems and can be categorized into three thematic groups: (1) community-based sustainability and socio-economic resilience, (2) environmental sustainability, and (3) consumption patterns and food system dynamics. These contributions offer a comprehensive perspective on the challenges and opportunities in building more sustainable and resilient agri-food systems.

Firstly, regarding community-based sustainability and socio-economic resilience, in their research, Corubolo and Meroni (Contribution 1) examined how design can support transition strategies in complex food systems by employing Design-Orienting Scenarios (DOSs) and their evolution into Transitioning Design-Orienting Scenarios (T-DOS). Applied to the Milano Food System, T-DOSs combine governance and sustainability strategies to foster multi-actor collaboration and define transformative roles and projects. The methodology is presented as a tool for systemic, outcome-oriented design conversations, leveraging local challenges and resources for practical application in food systems and other complex domains.

Building on the theme of localized strategies for resilience, Acevedo-Ortiz et al. (Contribution 2) focused on rural communities in Oaxaca, Mexico, which face challenges such as food insecurity, economic instability, and loss of traditional agricultural knowledge. Their study explored how crowdfunding-supported home gardens can enhance food security, economic resilience, and community empowerment. Their results showed improved food security for over 70% of households, a 20% reduction in food expenses, and increased income from surplus crops. Traditional practices and community collaboration strengthened women's empowerment and ecological sustainability, demonstrating the potential of blending traditional knowledge with modern funding for sustainable agricultural systems.

A related aspect of community-driven food system sustainability is the role of cultural food movements in shaping local economies and food security. Nazifi et al. (Contribution 3) explored the prerequisites for advancing the Slow Food movement in Iran using a mixed-methods approach, including semi-structured interviews with 15 experts and a structural equation model for quantitative analysis. Six key facets emerged—extension strategies, movement propagation methods, supportive policies, intervening conditions, causal triggers, and outcomes—encompassing 38 sub-components. Significant factors influencing Slow Food promotion included disease prevention, festivals and exhibitions, law revisions, lifestyle changes, food tourism enhancement, and human resource optimization, highlighting actionable pathways for advancing the movement.

Beyond food movements, entrepreneurship plays a crucial role in the economic, social, and environmental sustainability of agri-food systems. Focusing on Perak (Malaysia), Jaafar et al. (Contribution 4) found that different internal factors (e.g., agropreneurs' attitudes toward sustainability), external factors (e.g., family support, social networking), and subjective norms affect the sustainability of agricultural entrepreneurship in Malaysian rural settings. The study suggests that preparing a new generation of agri-entrepreneurs who are sustainability-minded requires considering the different internal, external, and psychological factors in their training and capacity building.

Finally, sustainable transitions in agri-food systems must also consider their impact on human well-being, particularly among marginalized communities. Pandey et al. (Contribution 5) investigate the effects of land use changes from traditional, so-called shifting cultivation to intensified mono-cropping on the psychological well-being of indigenous people across six states in Northeast India. Between 2000 and 2015, landscape changes were mainly due to external interventions, with increased green cover, access to education, and income. Cross-sectional data from almost 500 village respondents reported a decline in traditional cultivation, land ownership, diversity of cultivated and wild edible plants, and social cohesion, adversely affecting their psychological well-being. Interestingly, respondents were aware of the effects on their well-being as migration increased with decreased shifting cultivation, pointing to the necessity of considering the cultural needs of indigenous people for successful transformations.

Secondly, regarding environmental sustainability, there is a dual relationship between the food system and the natural environment. Indeed, food systems are shaped mainly by the natural environment in which they develop. At the same time, they affect the natural environment, either positively or negatively. At the farm level, Cruz et al. (Contribution 6) analyzed the sustainability of bovine production systems in Colombia's Cundinamarca Department, where diverse milk, beef, and dual-purpose farms operate across varying climates. Using the MESMIS methodology, they evaluated social, environmental, and economic indicators, finding that dairy systems excelled in productivity and environmental performance but scored lowest in social sustainability. In contrast, dual-purpose systems demonstrated stronger self-management and social resilience. Their findings highlight how economic sustainability improves with production intensification, particularly favoring dairy farms. These insights can help guide public policies that support sustainable agricultural development while balancing environmental and social considerations.

Expanding from farm-level sustainability to regional sustainability, Liang et al. (Contribution 7) evaluate the interplay of the low-carbon economy, agricultural products, and resource environment across eight Chinese regions, revealing significant imbalances in North, Northwest, and Northeast China. Using principal component analysis (PCA), they found strong explanatory power for agricultural and resource–environment systems. From 2010 to 2020, the national Economic–Agricultural–Resource–Environment (EARE) system advanced from sub-coordinated to coordinated growth, transitioning from resource growth lagging behind economics to economic growth lagging behind resource–environment growth. The findings highlight the need for targeted policies to promote balanced regional sustainability.

At the ecosystem level, Yadav et al. (Contribution 8) analyzed vegetation's responses to hydroclimatic factors in arid and semi-arid climates in Rajasthan (India). They found that the normalized difference vegetation index (NDVI), evapotranspiration (ET), and rainfall exhibited upward trends, while the rainfall and land surface temperature (LST) demonstrated a downward trend. The NDVI increase suggests vegetation improvement and a decrease in degraded lands despite increased cultivated land. The study suggests that the impacts of climate change are context-specific. Consequently, food system conceptualization and their sustainability assessment should consider the context in each territory/country.

Beyond direct environmental impacts, food waste is often seen as a symptom of unsustainable food systems. The COVID-19 pandemic was a significant stressor on global food supply, exposing vulnerabilities in waste management. Baya Chatti et al. (Contribution 9) postulated that food waste poses a significant challenge in the Near East and North Africa (NENA) region. The pandemic acted as a catalyst for a split in consumer behaviors with positive and negative trends regarding food wastage, and the application of the circular economy approach remains limited despite its potential. Overall, the pandemic highlighted the pressing need to address food waste while spurring innovative policy ideas and strategic planning, emphasizing the necessity of integrated policies to navigate post-pandemic recovery successfully.

Geopolitical conflicts are another major shock to food systems, which can disrupt food security at multiple levels. In this respect, Rabbi et al. (Contribution 10) explored how the ongoing Russia–Ukraine conflict impacts the pillars of food security (availability, access, use, stability) in Europe and examined possible strategies to mitigate these impacts. They postulated that the conflict differentially affected food security in Europe. Europe's food supply is not at risk, but the conflict could affect food accessibility/affordability and production costs. The paper concludes that enhancing food aid, improving access to affordable production factors (e.g., inputs, energy), shifting towards sustainable diets and food habits, and removing agri-food trade barriers can protect food security pillars and bolster the resilience of the European food system. The study shows that food system sustainability, resilience, and food security are strongly linked and should be addressed in an integrated and systemic way.

Finally, a holistic food systems approach is essential for understanding the complex interactions and dynamics within agri-food systems. In their systematic scoping review, Pryor et al. (Contribution 11) identified existing frameworks for analyzing the human and environmental outcomes of these systems. On this basis, a conceptual framework specific to modern industrialized agri-food systems, explicitly including policy and governance, was developed. According to the authors, users can apply the framework to specific goals, including identifying facilitators and barriers to effective policy, places to intervene in the system, and windows of opportunity for successful transformation. The framework highlights the importance of analyzing actors' interests and potential trade-offs in policy implementation.

Thirdly, regarding consumption patterns and food system dynamics, sustainable agri-food systems encompass various interconnected issues that often require cross-disciplinary approaches to uncover new insights and bridge existing knowledge gaps. These studies explore how cultural, material, and historical factors shape food consumption, valuation, and dietary transitions. One unique perspective on food presentation and consumer behavior is offered by Szmagara (Contribution 12), who examines the role of blue color and food coloring in the food industry. This qualitative assessment explores how economic, environmental, and socio-cultural dimensions—including health, history, and perception—shape the sustainability of natural and synthetic blue food colorants. The study highlights the complex relationship between food esthetics and consumer choices, discussing how both synthetic and natural coloring agents impact food quality control and appeal. By focusing on something as seemingly simple as food coloring, the research provides a lens through which broader issues of food system sustainability and consumer engagement can be better understood.

Extending this exploration of food perception and valuation, Aare et al. (Contribution 13) adopt a socio-material perspective to examine how actors in the agri-food system interact with food and attribute value to it. The gap explored here is the unquestioned central role of actors in everyday practices, often obscured by a focus on socio-technical transitions or their governance. This original research discusses valuing practices, specifically focusing on fresh grain legumes in Denmark, and how these practices influence a sustainable transition. The study emphasizes that multiple realities exist within the agri-food system, affecting how actors value practices. Valuing is portrayed as an active engagement that can lead to meaningful changes in the agri-food system. Food professionals are crucial in developing new ways to value food ingredients.

Beyond consumer perception and food valuation, historical shifts in agriculture and diet offer critical lessons for shaping future food system transitions. Ramenzoni et al. (Contribution 14) examined the impact of agricultural changes on food availability and dietary diversity in a farming and fishing community in Cuba over four decades. The original research integrates data from focus groups, nutritional surveys, and interviews conducted between 2016 and 2022 with the context of momentous economic and environmental challenges. Two major agroecological transitions are discussed: the first involves sugar mono-crop intensification, while the second emphasizes decentralization and diversification. The findings underscore the need for local comprehensive assessments of dietary and coping strategies to understand sustainable transformations in agroecological contexts.

Conflicts of Interest: The authors declare no conflicts of interest.

List of Contributions

1. Corubolo, M.; Meroni, A. Transitioning Design-Orienting Scenarios for Food Systems: A Design Contribution to Explore Sustainable Solutions and Steer Action. *Sustainability* **2024**, *16*, 9598. https://doi.org/10.3390/su16219598.
2. Acevedo-Ortiz, M.A.; Lugo-Espinosa, G.; Ortiz-Hernández, Y.D.; Pérez-Pacheco, R.; Ortiz-Hernández, F.E.; Granados-Echegoyen, C.A. Women's Leadership in Sustainable Agriculture: Preserving Traditional Knowledge Through Home Gardens in Santa Maria Jacatepec, Oaxaca. *Sustainability* **2024**, *16*, 9513. https://doi.org/10.3390/su16219513.
3. Nazifi, H.; Sabouri, M.S.; Allahyari, M.S.; Niknami, M.; Danaei, E. Exploring Extension Implications for Slow Food Development in Iran: A Comprehensive Analysis. *Sustainability* **2023**, *15*, 16538. https://doi.org/10.3390/su152316538.

4. Jaafar, M.; Jalali, A.; Suffarruddin, S.H.; Ramasamy, N. The Determinants of Becoming Sustainable Agropreneurs: Evidence from the Bottom 40 Groups in Malaysia. *Sustainability* **2023**, *15*, 8283. https://doi.org/10.3390/su15108283.
5. Pandey, D.K.; Dubey, S.K.; Verma, A.K.; Wangchu, L.; Dixit, S.; Devi, C.V.; Sawargaonkar, G. Indigenous Peoples' Psychological Well-being Amid Transitions in Shifting Cultivation Landscape: Evidence from the Indian Himalayas. *Sustainability* **2023**, *15*, 6791. https://doi.org/10.3390/su15086791.
6. Cruz, F.; Pardo, D.; Horcada, A.; Mena, Y. An Assessment of Sustainability of Dual-Purpose, Dairy and Beef Cattle Production Systems in the Cundinamarca Department (Colombia) Using the MESMIS Framework. *Sustainability* **2024**, *16*, 7054. https://doi.org/10.3390/su16167054.
7. Liang, X.; Xu, J. Accelerating Transition to a Low-Carbon Economy: A Coupling Analysis of Agricultural Products and Resource Environment. *Sustainability* **2024**, *16*, 6315. https://doi.org/10.3390/su16156315.
8. Yadav, B.; Malav, L.C.; Singh, S.V.; Kharia, S.K.; Yeasin, M.; Singh, R.N.; Nogiya, M.; Meena, R.L.; Moharana, P.C.; Kumar, N.; et al. Spatiotemporal Responses of Vegetation to Hydroclimatic Factors over Arid and Semi-Arid Climate. *Sustainability* **2023**, *15*, 15191. https://doi.org/10.3390/su152115191.
9. Baya Chatti, C.; Ben Hassen, T.; El Bilali, H. Closing the Loop: Exploring Food Waste Management in the Near East and North Africa (NENA) Region during the COVID-19 Pandemic. *Sustainability* **2024**, *16*, 3772. https://doi.org/10.3390/su16093772.
10. Rabbi, M.F.; Ben Hassen, T.; El Bilali, H.; Raheem, D.; Raposo, A. Food Security Challenges in Europe in the Context of the Prolonged Russian–Ukrainian Conflict. *Sustainability* **2023**, *15*, 4745. https://doi.org/10.3390/su15064745.
11. Pryor, S.; Casey, T.; Dietz, W.H. Conceptualizing Agri-Food Systems for a Healthy, Sustainable, and Just Transformation: A Systematic Scoping Review. *Sustainability* **2024**, *16*, 9862. https://doi.org/10.3390/su16229862.
12. Szmagara, A. Blue in Food and Beverages—A Review of Socio-Cultural, Economic, and Environmental Implications. *Sustainability* **2024**, *16*, 8142. https://doi.org/10.3390/su16188142.
13. Aare, A.K.; Hansen, S.R.; Kristensen, N.H.; Hauggaard-Nielsen, H. Valuing in the Agri-food System: The Case of Fresh Grain Legumes in Denmark. *Sustainability* **2023**, *15*, 2946. https://doi.org/10.3390/su15042946.
14. Ramenzoni, V.C.; Vázquez Sánchez, V.; Valdés Massó, D.; Rangel Rivero, A.; Borroto Escuela, D.Y.; Hoffman, D.J. When the Sugar Runs Out: Transitioning Agricultural Systems and Their Effect on Dietary Diversity in Yaguajay, Central Cuba. *Sustainability* **2023**, *15*, 13073. https://doi.org/10.3390/su151713073.

sustainability

MDPI

Article

Transitioning Design-Orienting Scenarios for Food Systems: A Design Contribution to Explore Sustainable Solutions and Steer Action

Marta Corubolo * and Anna Meroni

Polimi DESIS Lab, Department of Design, Politecnico di Milano, Via Durando 10, 20158 Milan, Italy; anna.meroni@polimi.it
* Correspondence: marta.corubolo@polimi.it

Abstract: This article explores how design, as a disciplinary field, can play a role in conceiving and supporting transition strategies within complex food systems where multiple actors are involved and sustainability is a priority. The work builds on the methodology of Design-Orienting Scenarios (DOS), which are future-oriented narratives motivated, illustrated, and visualized through specific solutions. DOS are applied here to contribute to the ongoing transformation of the Milano Food System, which is at the intersection of dynamics influencing the activities of its various 'nodes'—pivotal points in the supply chain. A specific scenario is then co-designed with relevant actors, combining two influencing factors: governance and sustainability strategy. The aim of this scenario is to highlight areas of multi-actor collaboration and spark transformative projects while also defining roles, values, and capabilities. This article further introduces the evolution of DOS into Transitioning Design-Orienting Scenarios (T-DOS), designed to facilitate outcome-oriented transitions. Characterized by a multi-actor and relational perspective, T-DOS engage stakeholders through a structured process, leveraging local challenges, resources, and actors to ensure the relevance and applicability of practical futures. The T-DOS methodology is finally discussed as a tool to guide systemic design-oriented conversations within the food system and, more broadly, within complex systems.

Keywords: food system; design-orienting scenario; service design; alternative food networks; codesign; transition; sustainability

Citation: Corubolo, M.; Meroni, A. Transitioning Design-Orienting Scenarios for Food Systems: A Design Contribution to Explore Sustainable Solutions and Steer Action. *Sustainability* **2024**, *16*, 9598. https://doi.org/10.3390/su16219598

Academic Editors: Hamid El Bilali, Tarek Ben Hassen and Carola Strassner

Received: 9 September 2024
Revised: 21 October 2024
Accepted: 25 October 2024
Published: 4 November 2024

1. Introduction: Tackling the Complexity of Food Systems

Where to start in making a food system more sustainable?

A radical transformation of food systems is claimed by several entities to be an indispensable step toward sustainability to achieve Agenda 2030 [1–4]. General policies that acknowledge the interconnectedness of different systems, prioritize synergistic collaboration over conflict, and implement strategies that address the intersections of various Sustainable Development Goals, as well as the impact of food systems on climate and natural resources, are considered to be essential for any effective action. At the same time, context-specific policy solutions tailored to address diverse challenges are recognized as being crucial.

Without claiming to solve such a complex issue with a single tool or perspective, this article presents a contribution from the discipline of design and discusses it in relation to a specific local food system.

1.1. *Local Food Systems: A Perspective to a Problem and Related Opportunities*

A food system is the combination of activities, actors, and elements involved in the production, processing, transport, and consumption of food within a given context, and the output of these activities, including socio-economic and environmental outcomes [5]. It is well known that the sustainability of (food) systems depends on several interconnected issues and requires, indeed, a systemic approach for highly complex situations [6–8].

Several intertwined trends, in fact, affect food systems and their outcomes, such as the following: climate change and resource degradation, agricultural and data-driven technologies, market expansion or disruption, concentration in supply chains, changing demand, limited access to resources for small-scale producers, increasing inequality and poverty, population change, and urbanization. Together, these trends drive food system transformations.

So, as are all systems, food systems are complex and adaptive. Complexity means that system's components are interdependent and that the interactions between them are dynamic. Adaptivity means that systems change behavior in response to their environment, but the behavior of the whole may not be predictable according to the behavior of its components.

In the effort to make any system more sustainable, these two characteristics lead to uncertainty in decision-making. Hence, "rehearsing plausible options" for the future [9] might be more meaningful and accurate than attempting to generate precision results with early and uncertain data. For these kinds of "wicked problems" (namely, issues that are ill-formulated, confusingly intertwined within systems, and are subject to conflicting interests and indeterminacy), design, as a discipline, aims to be an *integrative* factor. That is, to quote a well-known essay by Buchanan, a discipline that explores the relationships between "signs, things, actions and thoughts" [10] and that moves forward through experimental problem-solving, where knowledge emerges as a step-by-step interaction among players.

Design, thus, addresses food systems through an integrative and relational approach that begins with interpreting ongoing situations, aims at sense-making, and ends up with solutions. The inspiration may come from what is observed in the present, is guided by values and aspirations, and leads to generating visions for the future [11–13]. Assuming that tomorrow will result from what we produce starting now, designers start imagining the future by selecting and giving coherence to the present signals considered to be most favorable. Then, they define an image of the world as it would be "if" possible futures were realized, even when this seems to be a leap from fragile foundations. This design practice is called scenario building, where scenarios are 'rehearsing spaces' to "highlight central elements of possible futures and draw attention to important key aspects that will affect future developments" [9] (p. 2145).

1.2. Research Hypothesis and Objectives

The research presented in this article, coordinated by the Polimi DESIS Lab of the Design Department of Politecnico di Milano in collaboration with scholars from other departments and disciplines (Involved universities: OnFoods' project SCIN_GO (Scientific Innovation, Technology and Sustainability: Governance and Regulation) Università degli Studi di Milano, Università di Pisa, Università di Catania, Università degli Studi di Parma; On Foods' project FAI_FRU (Fair and efficient wholesale market for improving fruit and vegetable consumption) Università di Catania, Università degli Studi di Parma. In such projects, Politecnico di Milano in involved through the Departments of Design and the Department of Management, Economics and Industrial Engineering), aims to investigate, through scenarios, the possible evolutions of the food system of the City of Milano in Italy, toward environmental, social, and economic sustainability. For doing so, it highlights and discusses areas of opportunity for innovation and collaboration between the different stakeholders, and co-designs, orients, and supports a transitioning strategy of some specific actors. The research operates within the framework of a national research program titled titled "OnFoods—Taking Action on Food Systems, Focused on Sustainability, Working on Safety, Security and Health" and, in particular, its sub-focus on "Scientific Innovation, Technology and Sustainability: Governance and Regulation".

The research group has an extensive track record of projects on sustainable food systems and food services, applying strategic and service design methodologies to the field of food. The project Nutrire Milano (Feeding Milan), which ran from 2009 to 2015 in collaboration with Slow Food Italia and the University of Gastronomic Sciences, was a pioneering experience in applying design to the field of food [14]. Design thinking was employed to envision a future where short food supply chains could become effective alternatives to the conventional industrial system in Milan. An ambitious narrative of the future was co-created with key stakeholders, connecting people and places of local food production in an urban and peri-urban vision. Accordingly, several specific food chains were considered, and various stakeholders, including citizens, were engaged to co-design and experiment with new, interconnected services. These services were then prototyped and tested over time. Some of them became established, such as a farmers' market (named 'Earth Market'), which has since expanded and grown.

The experience of this project generated significant momentum in designing for the food system, producing various outcomes. More recently, adopting the same systemic approach, an applied project focused on the redistribution of surplus food for charity, while also providing real support to local groceries and harnessing the potential of neighborhood solidarity (www.sospesanolo.it).

The methodology of designing specific interconnected solutions within a vision that embraces the whole system has various roots. One of them traces back to Gregory Bateson, who, in his seminal work on ecology and evolution [15], interprets innovation as something that can only emerge from "chaos". He claims that, since evolution is the learning of a species and a perpetual innovation based on trial and error, what matters is the power of an idea and its potential to work, not its current numerical relevance. Therefore, a small accidental fact emerging from chaos can create a discontinuity and become, if it fits into a particular environment, the driver of the system's evolution. In other words, no matter how few people are doing something today, if it is made appealing and feasible, it can shape the future. He also argues that the minimum unit of survival in evolution is never simply an individual organism or species, but always species-plus-environment.

This research is based on two hypotheses that stem from Bateson's studies:

- The first one is that seizing weak yet promising signals of sustainable ways of producing, processing, or consuming food (namely, the Alternative Food Networks—AFN), and elaborating on them can be a way to shape the future, if properly designed.
- The second one is that players' efforts to innovate can be driven not only by selfish reasons, but also by understanding that favoring the system's interests can strategically benefit their own ones.

Strategic designers are in the position of facilitating this evolutionary learning by building scenarios that activate conversations among the system's players and with wider society [11,16,17].

These hypotheses lay the basis of a method and a process to build a contextualized scenario for the transition of the Milanese food system to a more sustainable future and to develop a vision that emphasizes the relationships between the actors of the system in view of a common interest.

1.3. A Need for Change in a Food System

The work on the scenario comes at a time when the Milano food system has expressed a need for change within a broader framework of policy transformations. It must be noted that the city has a Food Policy and a Food Policy Pact since 2015, when the mayor launched an international protocol aimed at tackling food-related issues at the urban level, to be adopted by as many world cities as possible. The Pact was signed during the Milan international EXPO 2015 by more than 100 cities (https://www.milanurbanfoodpolicypact.org/). It is a working tool to implement sustainable food policies, and has brought in to implement a specific food policy for the city of Milano, too. After a decade, this policy has brought several projects and pilot actions involving different public and private actors across the city (https://www.milanurbanfoodpolicypact.org/mufpp-projects/, accessed on 25 October 2024).

Recently, two transformation trajectories under the umbrella of the food policy have been affecting the entire system and involve some of its main actors: the wholesale market and the network of neighborhood food waste hubs, an infrastructure established in 2019 to combat food waste by redistributing surplus food.

The wholesale market of the city is undergoing a radical and extensive renovation to update its spatial and technological infrastructures, accommodate the municipal school's catering kitchen, modernize logistics, optimize circular processes for surplus food recovery and redistribution, and create space for food labs and training initiatives (https://www.sogemispa.it/progetto_foody_2025, accessed on 25 October 2024). These transformations do not happen in isolation and have an impact on the entire ecosystem. Additionally, the wholesale market company is gradually taking on the responsibility of managing the network of indoor neighborhood markets on behalf of the Municipality. The new responsibility represents a significant challenge for the company, requiring not only a vision for the consumer markets, but also new organizational competencies.

The food waste hubs, following the successful proof of concept demonstrating their effectiveness in reducing food waste and redistributing it to the most vulnerable populations, are now in the process of consolidation, evolution, and expansion [18]. To this end, the Municipality initiated an extensive co-design and co-planning process with key stakeholders, not only to optimize processes and logistics, but also to better integrate the hubs into the neighborhoods, train managing actors, and complement food aid with social policies to avoid the risk of welfare dependency. Ultimately, one goal is also to achieve medium- to long-term economic sustainability. This evolution is envisioned as being closely connected to other actors in the system, namely neighborhood indoor and street markets, large-scale retail distribution, and the wholesale market.

These two strategies are, per se, drivers for the actors to engage in a systemic process of rethinking their activities within a shared vision for the future. The work presented in this article is situated within this context.

2. Background: Scenarios and Design-Orienting Scenarios

In all fields, scenarios are conjectural artifacts widely used to think about the future evolution of some hypothetical situation, the alternatives to it, and the process to get there [19]. They may take different forms of narrative description of a possible state of development over time [20,21], often integrated with visual elements and other supporting information. They are aimed at stimulating and framing some strategic conversation on the future, elicit feedback, and stimulate imagination by involving different parties, considering different perspectives, connecting different issues, and several variables [22,23]. The literature on scenarios is vast and falls under the umbrella of "future studies".

According to Börjeson et al. [23], scenarios can be broadly classified into three main typologies, each corresponding to different techniques, and offering different usefulness: explorative, predictive, and normative.

Explorative scenarios respond to the question "What can happen?", they explore what might happen in the future, regardless of beliefs or desires. They consider, from various perspectives, situations that could occur. These scenarios are typically organized in sets, that is, reasonable numbers of possibilities in the medium to long term. Then, they explicitly explore structural and deep transformations that may affect a target group, starting from a present situation. Thus, they allow for the exploration of the consequences of alternative developments.

Predictive scenarios respond to the typical question "What will happen (if. . .)?", where the response is conditional to a certain fact happening.

Normative scenarios respond to the question "How can a specific target be reached?" and take a target as a starting point to be, in fact, achieved.

Almost all these typologies might be both quantitative and qualitative; additionally, some of them might consider internal or external influencing factors, which are factors controllable (or not) by the actor(s) in question.

Scenario building, then, is a well-known method for engaging multiple and diverse stakeholders in commonly relevant projects and securing their commitment [24–26]. For instance, public administrations can engage social parties in scenario co-design to commit to new visions and converge social creativity and innovation.

When it comes to design, scenarios are intended as narrative and visual stories of the future, characterized by distinctive factors, forces, and values that shape alternative possible directions. Scenarios, thus, are qualitative and actionable tools to enable speculative or pragmatic thinking, aimed at identifying and exploring design opportunities. They are neither predictions nor forecasts, but explorations aimed at achieving some value. Therefore, scenarios are design proposals generated through abductive thinking [27] and result from so-called "productive reasoning" [28], which builds on observed characteristics, previous knowledge, and models. They are parts of wider creative processes that trigger design conversations about the future, and thus they are often based on a 'relational worldview' [8], namely, they shift focus from things and materials to relationships and structures within the considered contexts and systems.

Design-Orienting Scenarios (DOS) [11] are stories of the future that are motivated, illustrated, and visualized through specific solutions. Based on actionable opportunities organized in a consistent way, DOS can help to identify, define, and co-design transformative projects, while outlining roles, values, and capabilities of the different actors. Therefore, they are processes rather than fixed artifacts, and are collaborative processes. The nature of DOS is intrinsically explorative, yet they are processes often complemented by predictive parts linked to specific "what if questions", and integrated by normative parts, whose aim is to define specific targets to reach. The scenario described in this article is precisely a mixed typology in which the sequence of types responds to the reason why for the different parts in the process, oriented towards a sustainable transition of the system.

Regardless of the field of application, scenarios have meta-features—transversal common traits (sometimes referred to as 'aspects' or 'characteristics')—that can be used to describe them and are influenced by their typology. Based on an analysis of the literature and case studies, these meta-features can be summarized into ten points (Table 1) that provide a quick comparative overview of different scenarios. The methodology for identifying the meta-features of scenarios was based on a twofold approach involving a review of the literature and an analysis of case studies. The literature review spanned among three main disciplinary fields, futures studies, scenario building, and design research, with a focus on methodologies like Design-Orienting Scenarios, to identify recurring meta-features and the structural components of scenarios. These fields were chosen because they offer insights into a scenarios' role, short-, medium-, and long-term perspectives, and innovative approaches to scenario (co-)creation, particularly in contexts where human-centered and sustainability-oriented factors are key. This interdisciplinary approach ensured a broad understanding of the meta-features that consistently appear across different scenario typologies. Simultaneously, an extensive analysis of existing case studies was conducted, including projects developed by the authors' research group and a wide array of initiatives from the DESIS network (The Design for Social Innovation and Sustainability (DESIS) network consists of 68 DESIS Labs around the world: academics, researchers and students belonging to higher education institutions or universities in the field of design, who orient their design and research activities towards social innovation.), offering insights and validating the identified meta-features across various contexts.

The ten points presented in Table 1 lay the groundwork for comparing different scenarios, so as to help understand which types can effectively aid in a food system toward environmental and social sustainability.

As an expansion of the list of meta-features, the scenario's structure can be further detailed. However, the aforementioned cases allow the authors to find recurring elements in the way scenarios are structured and presented:

- The title and key words, which briefly explain the contents.
- The narrative, which provides a description of the contents.

- The trends, which refers to the macro/micro external or internal factors considered when building the scenario.
- The presence of pioneering solutions, seeds, or weak signals, which refer to cases and solutions existing in the present time that can be seen as anticipations of the scenario and/or their inspirations.
- The opportunities the scenario identifies for innovative solutions.
- The enablers, which might be factors, people, or organizations that may favor the scenario to happen.

Table 1. Scenario's meta-features as transversal common traits.

Scenario's Meta-Features	Explanation
Approach	The system's main structure, contemplating (or not) alternatives
Scale and scope	The extension and the reach of the scenario, including the focus on a systemic or a specific topic
Timeframe	Short (<10 years), medium (10–30 years), or long (30–50 years)
Actors involved	Who is involved in the generation, co-design, and development of the scenario
Actors targeted	The scenario's intended users and, therefore, the perspective that the scenario adopts
Reason why	The purpose and usefulness of the scenario for the target users
Method and process	The method used to gather data, generate ideas, elaborate them, and check them with contexts, people, and relevant factors
Focus on internal or external factors	What is within or beyond the control of the relevant actors
Structure	The way the scenario is organized to present contents clearly and effectively
Distinctive and original contents	The knowledge the scenario conveys and the message it intends to give; this feature is intrinsically connected to the previous one

The following paragraph presents an analysis and a comparison of two food system scenarios selected for their alignment with the mentioned design approach and systemic perspective. This comparison aims to highlight elements that underscore the distinctiveness of the designer's approach in creating food scenarios and their potential to drive system transformations. These elements are then used to present the DOS developed for the Milano food system, discuss similarities and differences, and describe the specific evolutions of DOS for transitioning towards sustainable futures.

3. Scenarios in and for the Food Systems

The two scenarios, "Preferable Future of Food" and the "MUSAE" project, were selected through a targeted research process focused on identifying food system scenarios where design played a pivotal role in shaping their development. A key criterion for selection was their emphasis on sustainability within food chains and systems, aligning with the broader goal of addressing pressing environmental and social challenges. An additional criterion was that they were developed in the recent period, following the COVID-19 pandemic, which introduced new challenges, exacerbated existing ones, and significantly influenced how we envision the future of food systems. Moreover, the two analyzed scenarios on the future of food have been selected because:

- Their value lays in the exploration of thought-provoking possible alternative directions, generated through an abductive design approach, with a clear involvement of design experts and methodologies and in using design tools;
- Their focus is on systems, thus understanding and addressing the complex interrelationships within a system rather than just individual components, focusing on how parts interact and influence each other. In the context of food systems, a systemic approach would aim at considering the entire food supply chain from production and distribution to consumption and waste management.

The selected scenarios are initially presented through their main characteristics and are then compared in terms of meta-features and structure.

3.1. Preferable Future of Food

The first selected scenario, named the "Preferable Future of Food" [29], was developed by SALLY–EY Doberman's future lab, in collaboration with Gullspång Re investment firm, to address pressing issues in the food system like sustainability, food security, and health. The initiative focuses on inspiring people in creating a more sustainable, localized, and community-oriented food system. Part of a bigger initiative by the future manifestation lab SALLY, it runs around creating positive change within the food industry by showing an emerging system that has yet to come to fruition and by manifesting "these preferable futures through the lens of digital products, services, and business models that could enable and accelerate key transformational shifts across business and society" [29].

Structured as a story from the future looking back in time to 2023 when the old, broken food system still was the main source of food, it introduces three primary shifts bringing into life preferable alternatives to the status:

- "One-hour food system" for localized food production proposes a shift from industrialized global supply to food circles, de-intermediating the relation with producers, enabling local food economies, increasing the access to fresh foods nutritionally matched to the individual, and valuing waste.
- "Community food revolution" boosts urban agriculture and social connections, adopting data-driven urban planning to reveal spaces and synergies for food production, and imagining a new ecosystem of tech-driven services and tools that allows everyone to produce food.
- "The impact plate" utilizes technology to promote health and environmental consciousness in food choices as AI-supported tools showing the true impact of food and integrating data to detect sustainable patterns and draft personalized services.

Each shift presents a series of concepts illustrating future products and services using the same narrative structure: a leap into the past to highlight unsustainable behaviors and processes, an explanation of the innovative solution, a series of enablers in the form of events, behavioral changes and technological advancements that have occurred to achieve this, and finally a set of existing case studies, named pioneers.

The scenarios are set in a near future that is not explicitly stated, nor is the region or place for which they are designed, although a European context seems the most plausible one. The target group is generically people working in the food system: farmers, entrepreneurs, academia, and businesspeople. This is in line with the purpose of the scenarios, which serve as a source of inspiration and as a manifestation of possible innovations that, if amplified, could generate the imagined change in an ideal food system with common and generic elements of unsustainability.

3.2. MUSAE Project

The second selected scenario is within the "MUSAE" (https://musae.starts.eu/) project (funded by S+T+ARTS initiative, European Commission, 2022–2025), part of the S+T+ARTS initiative, which envisions a future where digital and industrial technologies are ethically developed to enhance food systems and human well-being. This ongoing project, run by a consortium that includes Politecnico di Milano and other European institutions, adopts the Design Future Art-driven (DFA) method [30], an approach that combines elements of design, future thinking, and art to envision and explore possible future scenarios. This method leverages artistic creativity and design principles to create immersive, thought-provoking representations of the future and serves as a tool for artists and SMEs to stimulate the innovative and creative uptake of technologies in society.

The overall project is organized in two art-tech residency calls and a prototyping phase. The first phase involved 12 artists who produced 12 scenarios and corresponding artworks based on identified trends: (1) reducing the carbon footprint in dietary behavior,

(2) the role of food in holistic human well-being, and (3) rethinking the food chain in our environment. The second art-tech residency program will pair the artists with 12 SMEs to collaboratively develop concepts based on the previously created scenarios and on the use of one or more of these technologies: artificial intelligence, robotics, or wearables. Finally, the prototyping phase will focus on mentoring the teams to develop industrial prototypes of their concepts. During the first phase, artists went through a defined sequence of step that included a scenario building's training phase, a thematic and technological immersion to explore opportunities, trends, and potentialities, an ideation moment, and a series of mentoring and assessment meetings with the consortium partners.

The 12 scenarios cover a timeframe between 7 and 20 years from now (2030–2040), even though the content and esthetics of AI-generated visualizations and proposed solutions suggest a more distant future. Although the scenarios take the European context as the background scene, only a few of them identify a specific place, while the majority refer to a context depicted through its generalist features and unsustainable patterns. The focus is on emerging opportunities for companies (SMEs and startups, not only in the food system) in terms of available technologies and scientific advances that enable new solutions, interactions, and behaviors.

Each scenario includes a narrative, key words, images, opportunities for companies, emerging trends, and a set of ad hoc designed elements, such as artifacts, services, and personas, that contribute to defining the future landscape. Each one is also accompanied by a video that guides the viewer into the future and by an artwork, being physical or digital, that acts as a touchpoint for the scenario.

3.3. Comparison of the Scenarios

Table 2 presents a succinct comparison of the scenarios through their meta-features, making emerge commonalities and distinctive factors.

Looking at these scenarios, some common elements and peculiar features of the two projects can be noticed and provide an initial interpretation on how the diverse meta-features can orient and address the use of scenarios.

The first element is the exploratory character of both scenarios, which look to the future as a field of possibilities and opportunities to be seized, enabled by a series of mainly technological solutions that envision a change towards a more sustainable system. In the case of the Preferable Future of Food (PFoF), the imagined future is made available by the integration or adoption of technologies that are already present or rapidly spreading and act mainly as a response to unsustainable patterns, behaviors, or external events that took place in the past (in 2022). Conversely, looking at the MUSAE project, the technology is much more pervasive and outlines the features of both the scenarios and the opportunities presented to companies. In addition, existing solutions and the adoption of such emerging technologies push the future much further ahead, while claiming a timeframe of 10 years. Each MUSAE scenario, in fact, while imagining a strong evolution on the technological side, represents this shift in images and artworks generated using AI, thus reproducing contexts, tools, and spaces that appear far from the present time, even esthetically. Conversely, the PFoF project presents touchpoints and solutions (in the form of outlined apps, websites, services, and stories) whose esthetic and design sound familiar and immediately available. This aligns with the inspirational goal of the scenario that aims at "manifesting" change as an initial spark of a possible strategic conversation.

Another common trait is that both projects chose not to specify a particular geographical context. Indeed, both scenarios are not situated and lack detailed elements that might include specific actors, resources, and regulations or cultural norms at play. On one hand, this abstraction allows for the themes to be broadly relevant to a wide range of stakeholders within a hypothetical food system. On the other hand, it places the effort on the potential stakeholders themselves to adapt the proposed content to their own specific contexts and system of relationships and to foresee a roadmap for the adoption of the solutions. An effort that, for the PFoF project, is initially supported by the link to existing pioneers, which are selected case studies that exemplify a practical avenue for change, while, for the MUSAE project, the second and third phase will match artists and companies to explore relevant opportunities and interests and to develop prototypes within the chosen scenario, thus moving from a wider systemic scope to a more focused one, related to the selected company and context.

Table 2. Comparison of the two scenarios throughout their meta-features and structure.

Scenarios' Meta-Features	The Preferable Future of Food	MUSAE Scenarios
Approach	Structured in three key transformational shifts across business and society that could accelerate change towards a more sustainable food system. The shifts thoroughly inform different elements of each vision.	Three thematic areas and three technologies guiding the scenario generation in the shape of twelve alternative futures. Each scenario is independently developed by an artist, focused mostly on a specific technology, a specific topic, and solution.
Scale and scope	Regional scale. Systemic scope: outline of a whole system in its general elements + illustrative solutions.	Local and regional scale. Transversal scope: combination of technological systems and food systems for a main topic + illustrative solutions.
Timeframe	Short (<10 years).	A claimed timeframe of 10 years (short), but solutions and visualization target a medium/long timeframe.
Actors involved	Design experts. Experts in different fields.	Artists. Design experts for scenario methodology. Supported by generative AI.
Actors targeted	People operating in the food system: farmers, entrepreneurs, academia, and businesspeople.	Small–medium enterprises and startups.
Reason why	Manifesting and showing an emerging system to inspire and accelerate change.	Presenting new forms of transdisciplinary collaboration aimed at helping SMEs and startups explore future technology applications of TRL5, through artistic practice.
Method and process	Speculative design. Developed by the design agency Sally leveraging on internal data. No evidence of co-design actions.	DFA method (Design Futures + Art): training on scenario building, thematic immersion, ideation, mentoring and assessment with consortium partners, scenario showcase.
Focus on internal or external factors	Internal and external factors.	Internal factors to each scenario. External factors are mainly embedded in thematic areas, common to more than one scenario.
Structure	Three shifts, each one with three or four concepts as illustrative solutions, related enablers and selected pioneers among existing solutions.	Twelve alternatives, expressed with a narrative and video, emerging opportunities (specific technologies, contexts of application, industries), embedded trends, and distinctive elements (artifacts, objects, personas) that outline solutions.
Title and key words	A general title and three evocative subtitles for each shift.	A title and a set of keywords for each scenario.
Narrative	Flashback to 2023 as a corrupt system and flashforward to today's sustainable (future).	Flashforward to 10/20 years describing a future context and related solutions. Complemented by a video.
Trends, which refers to the macro/micro external or internal factors considered in building the scenario	Technological and digital solution (AI, 3D printing, matching and trading platforms, APIs, precision technologies, and more) became mainstream and available.	Three thematic areas considered as emerging trends to be coupled with technologies (AI, robotics, wearables). An additional series of topic related and micro trends have been added by artists in each scenario.
Presence of pioneering solutions, seeds or weak signals	A set of three or four examples of pioneering solutions for each concept and shift.	Existing case studies related to technologies and solutions are included in each scenario and often made explicit in the narrative.
Opportunities the scenario identifies for innovative solutions	Elaborated in the form of concepts.	Elaborated in form of potential innovation opportunities and strategic development for companies mainly in tech or food sectors.
Enablers, which might be factors, people or organizations that may favor the scenario to happen	Enablers emerged in the past (2022/23) as technological and digital advancements, but also policies and norms, behavioral changes, products, and services.	Enablers as digital and technological solutions, expressed within the written and video narrative.
Distinctive features of the scenario that make it original and thought-provoking	The connection with available and almost known digital tools and technologies encourages an immediate action and identification within the future situation.	The combination of art and advanced technologies in the development of future scenarios generates futuristic visions. Visualizations, artifacts, and artworks are presented in a suggestive manner.

4. The Design-Orienting Scenario (DOS) for the Milano Food System

As discussed, scenarios can facilitate open conversations about visions and solutions among system's actors. One goal of the OnFoods is to specifically use scenarios to catalyze strategic conversations among local actors and to investigate emerging collaborative actions for further designs and prototypes.

In the following paragraphs, a DOS for the Milano food system is presented; named "Milano Sustainable Food System Scenario", it is described through the same meta-features of the comparative scenarios, highlighting its distinctive contents.

4.1. The Milano Sustainable Food System Scenario

Approach. The overall approach adopted to generate the scenario emphasizes a systemic view, connecting individual actors' perspectives with the broader context. This approach integrates various scales, from individuals, local communities, and stakeholders to broader systemic impacts and trends. Likewise, it also considers different possible strategies toward sustainability at the city and regional scale so that the totality of services it considers can be seen as a food service masterplan [24] for the city. By doing so, the scenario aims to reflect on the interdependence and complexity of food systems, acknowledging how local actions and decisions can influence and be influenced by larger socio-economic, environmental, and technological forces. This perspective, which has generated four alternative directions, helps to identify leverage points for achieving systemic impacts and recognize cause-and-effect linkages that influence different parts of the system.

Scale and the scope. The scenario is contextualized within the Milanese food system, embracing both urban and peri-urban scales. For the main relevant stakeholders, it analyzes challenges and barriers, as well as relationships, interdependencies, and potential converging interests. In so doing, it outlines collaborative, integrative, and inclusive solutions.

At the micro level, the focus is on local practices, community engagement, and behavior changes. At the macro level, the emphasis is on policy frameworks, national and international trends, and global environmental changes. At the meso level, the focus is on the actors and organizations populating the local food system and on their system of relationships. By integrating these perspectives, the scenario offers insights into how local actions can align with and support broader goals, such as sustainability, resilience, and social equity. This integration highlights the importance of multi-level governance and the need for coordinated efforts across different scales.

Timeframe. The scenario envisions Milan in 2035. A 10-year timeframe allows for innovative ideas while maintaining a connection with the present time. This timeframe also aligns with local strategies and policies on climate neutrality, mobility, and participative processes outlined by the municipality.

Actors involved. The scenario has been generated by design experts in collaboration with experts in various other fields and disciplines from to the authors' institution.

Actors targeted. The targeted actors are local stakeholders, identified as 'nodes' of the food system. A node is a pivotal point in the food supply chain (a combination of spatial, digital, physical, and human elements) where significant activities and interactions related to food production, transformation, distribution, and consumption occur [31]. Some nodes in the scenario are part of Alternative Food Networks—AFNs—whereas others are conventional actors of the industrial food system. Examples of the nodes are as follows: the wholesale market, indoor and outdoor markets, farmers' markets, and food waste neighborhood hubs [32].

Reason why. The scenario aims to steer and inspire the food system's nodes in transitioning to a more sustainable, fair, accessible, and healthy food system by identifying priorities and solutions in terms of integrative and collaborative product service systems, governance models, and related roadmaps.

Method and process. The scenario's method and process can be summarized in three macro-phases: (1) the scenario generation—explorative; (2) the scenario development—predictive; (3) the scenario prototyping—normative.

1. Phase 1. The scenario-generation phase is explorative, abductive, and diverging, and is comprised five main steps:
   - Context analysis: Through desk and field research, interviews, internal problem-framing workshops, and a series of local case studies, the output was a Milanese Food System Map describing the relevant nodes in the food sector and a series of challenges for each of the node.
   - Desk research around trends, drivers, and policies related to the challenges and critical topics emerging from the previous phase related to both the food sector and to sustainable practices (as punctual solutions) and domains.
   - Generation of the DOS, with the method of the 2 × 2 matrix, through the identification of polarities and the generation of four alternative directions.
   - Validation and refinement of the scenarios with researchers from OnFoods and disciplinary experts, collection of local case studies, ongoing projects or initiatives, and gatekeepers and unusual actors to be involved in the scenarios.
   - Design of a series of draft service concepts that populate each alternative direction as future solutions to be delivered by and with actors involved in codesign sessions. Each concept emerged by combining an alternative direction with the nodes and the food chain steps (from production to waste management).

This initial generative phase brought about the definition of the full set of four alternatives as possible directions of transformation and their articulation in illustrative solutions.

2. Phase 2. Then, the scenario moved into development, becoming the focus of strategic conversations and co-design workshops with the actors of the relevant nodes, such as the wholesale market and the network of the food waste neighborhood hubs. This following phase is a predictive one, that is, a progressively converging process in which design experts started to discuss alternative directions with stakeholders and policymakers. To do this, designers used the "what if" method that questions participants, and thus local actors, on what might happen on the condition of "some specified near future events of great importance for future development" [23]. This article presents the development of the scenario up to this phase, which is key to create, or not, the basis for the progressive transformation of the food system, since it works on the opportunities for the engagement and collaboration of the stakeholders. As an output, solutions are developed in-depth with service design methods and tools, while the scenario is re-oriented or refined. This development is aimed at growing awareness in actors of the possible future transformations of their activities and of the entire system around them.
3. Phase 3. The final phase is planned as a progressive convergence towards the implementation of some solution that makes use of roadmaps and pre-prototyping activities, which are draft and partial field-tests of the solutions, involving stakeholders, users, and policymakers. This phase is a normative one that investigates how to reach the targets set in the scenario by adjusting or transforming the current situation. Therefore, the focus of interest is on the expected future situations and how these could be realized.

Focus on Internal or External Factors. The external factors are common to the four alternatives of the scenario and have been embedded in the chosen polarities, deriving from policy frameworks, national and international trends, driving forces, and global environmental changes.

The internal factors relate to the characteristics of the individual actors and existing collaborations and emerge from the analysis of the context and node. They mostly refer to resources, competences, relationships, and technology available to each actor.

Both internal and external factors were identified in close alignment with the actual conditions and constraints local actors are or will be facing. This decision was made to anticipate their potential dilemmas.

Structure. The structure of the Design-Orienting Scenario is organized around a 2 × 2 matrix (Figure 1), which defines four quadrants to be considered as four alternative futures for the Milano Food System.

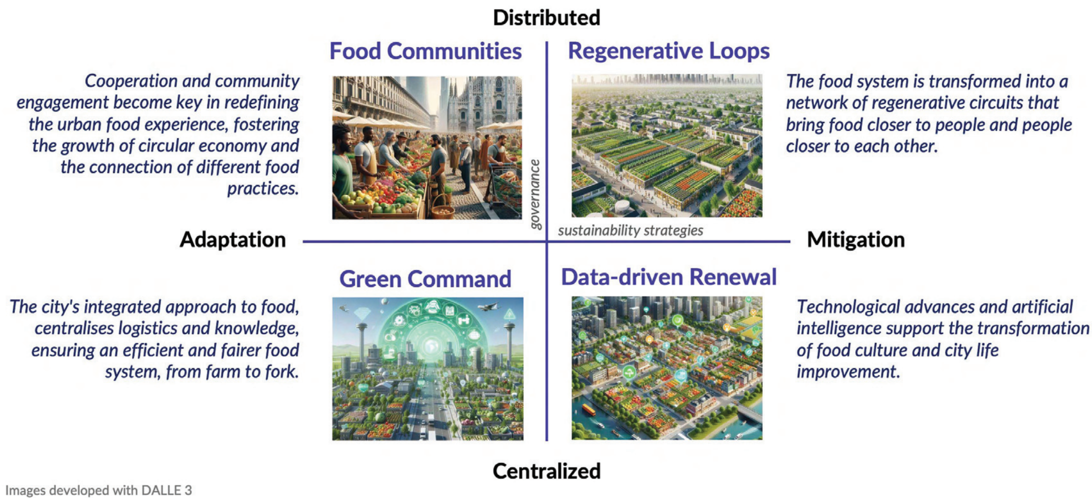

Figure 1. DOS for the Milanese Food System. The 2 × 2 matrix and related polarities define four alternative quadrants described through a title, a visualization, and a short narrative.

The first axis refers to governance structures, focusing on the distribution of power and decision-making processes, thus reflecting mainly an internal factor or strategy. This leads to two polarities:

- Centralized governance, where power and the management of infrastructures and technologies are concentrated in a single point or a limited group. This can lead to more uniform policies and regulations, potentially enabling the swift implementation of strategies and ensuring compliance across a broader area. However, it can also result in a lack of local adaptability and responsiveness to specific community needs, and often leads to top-down approaches.
- Distributed governance, spreading decision-making authority and control across various levels/units within the system or node. This structure encourages autonomy and decision-making, often leading to more flexible and responsive operations. It empowers local actors to take ownership of food system initiatives and supports tailored solutions that are more responsive to local contexts and needs, but may face challenges in the coordination and consistency of policy implementation.

The second axis focuses on societal and institutional approaches to environmental issues, thus considering a combination of external factors/policies and internal strategies, therefore distinguishing between the following:

- Adaptation strategies that address the effects of phenomena and focus on enhancing resilience and reducing vulnerability by adjusting existing systems to the impacts of climate change;
- Mitigation strategies that tackle their root causes, preventing effects and exploring regenerative practices, thus necessitating a more comprehensive and systemic change and a significant shift in production practices, consumption patterns, and technological innovations.

These alternative strategies might be regarded as macro trends that are likely to be progressively introduced by local and global policies to tackle climate change.

Accordingly, the scenario comprises four interconnected alternatives: the combination of the two axes generates four directions of "meaning", developed through abductive reasoning from observed characteristics of the system, promising practices of Alternative Food Networks (AFNs), case studies, and previous knowledge.

Social sustainability was integrated into the scenario through inputs from selected regenerative practices of AFNs, which can be regarded as pioneering solutions proven to benefit both people and the environment [33–35]. As for the initial hypothesis, these AFNs are valued for their promising nature and inspiring capacity rather than for their actual diffusion.

Each alternative direction is described by a title, an AI generated evocative image, a narrative describing the future context, and a set of keywords. To make sure to emphasize the social and environmental sustainability qualities of the scenario, an additional set of design criteria was considered in the generation and development phases; these were connected to social innovation qualities and circular economy strategies, while technology was regarded as an enabler (Table 3) [35].

Table 3. Main description and elements of each alternative direction.

	Food Communities	**Regenerative Loops**	**Green Command**	**Data-Driven Renewal**
	Adaptation approach + Distributed governance	Mitigation approach + Distributed governance	Adaptation approach + Centralized governance	Mitigation approach + Centralized governance
Description of the alternative directions	Cooperation and community engagement are key for redefining the urban food experience, fostering the growth of circular economies and closing the loop in food practices	The food system transforms into a web of regenerative loops that bring food closer to people and people closer to each other; food-related practices are used to address urban challenges, aiding in city healing and revitalization	The city's integrated approach to food centralizes logistics and insights, ensuring a streamlined and fairer food system from farm to table	Technological advancements and AI transform the food culture and improve city living
Keywords	Bottom-up initiatives, neighborhood-scale, engaged citizens, low-tech, sharing	Production, care, capillarity and connection, specialization, future generations, 15 min city	Technology-driven, normative, monitoring and tracking, optimization	High-tech, prediction, anticipation, rapid response
Integration of the services between each other	High	High	High	High
Capacity building across the society	Medium	High	High	Medium
Collaboration among actors	Medium	High	Low	High
Engagement and self-organization of actors	High	High	Low	Medium
Technology integrated in the solutions	Low	Low	High	High
Relevant nodes	Farmers market, food waste hubs, indoor markets	Farmers market, indoor markets, food waste hubs	Wholesale market, farmers	Wholesale market, farmers, food waste hubs

For each node of the food system, an evolved role is drafted, describing its transformation in terms of purpose, activities, and relationships enabled by the scenario. Accordingly, and considering the relationships with the other actors, opportunity areas and connected possible solutions are drafted to explore how the scenario translates into viable solutions that match identified nodes and food chain steps (from production to redistribution, transformation, consumption, waste management, education and training).

The distinctiveness of this scenario lies in the balance between the leap ahead in the sustainable qualities of the proposed innovative solutions and their adherence to the local context and actors. The tension between these features makes the scenario perceived as not too far from being achievable via a proper strategy. This perception is, then, leveraged to engage stakeholders in a conversation about their future.

5. The Co-Design of the DOS with Stakeholders, and Its Outputs

The Milano Sustainable Food System Scenario was conceived as an envisioning tool, an "interaction platform", and a springboard for generating design-driven conversations with different food system actors through co-design workshops (Figure 2). These conversations, on the one side, helped to identify opportunities and enablers for enhancing food access and sustainability in the city from various perspectives; on the other hand, they acted as catalysts for envisioning potential solutions to be prototyped, thus highlighting possible evolutions of the Milanese food system.

Figure 2. Co-design sessions with local stakeholders.

The following paragraphs describe the outputs of these co-design conversations, conducted with some of the nodes of the local food system, namely the wholesale market and some food waste hubs, with their network of actors.

5.1. Emerging Directions of Possible Actions

During the co-design workshops conducted in separate sessions with different actors, the Milano Sustainable Food System Scenario was discussed through the following sequence of interactive activities: After a brief presentation of the scenario and its alternatives, participants were engaged to review and discuss the specific draft solutions, adding comments or brand new solutions. For each one, a "what if" reflection was carried out, figuring out how to adopt and make it. Additionally, for the most-relevant ones, the dialog was steered toward identifying the drivers that might enable the practice, the barriers that might hinder it, and its gatekeepers.

Each solution was then contextualized within the scenario, its external and internal factors, and thoroughly discussed moving forward and backward from the scenario to the challenges of the local food system and nodes. This allowed the authors to connect sustainability strategies, governance logics, and food-related opportunities for each actor of the network.

Although reviewing the co-design process around the Milano Sustainable Food System Scenario is beyond the scope of this article, it is worth introducing some elements of the debate. While, as expected, not all solutions were considered to be plausible by the actors, all of them raised an issue and provided the chance to discuss an opportunity that was not, or was seldom, considered in the past. Viability issues related to economic and organizational factors and social issues connected to the social purpose of the initiatives, besides the environmental one, were the foremost arguments that emerged. The former is tied to the governance factors and business models of the different stakeholders. In addressing this, one goal was to avoid prioritizing a business-as-usual logic in favor of more evolutionary perspectives, emphasizing future inevitable constraints and opportunities from a systemic viewpoint before engaging in a specific business model design. The latter relates to the principles of mitigation and adaptation used in the scenario, borrowed from the European framework strategy against climate change. Despite being aware of the limitations of these principles, which mainly concern environmental issues, researchers decided to adhere to them to comply with a broader and systemic logic, while also agreeing to embrace a more comprehensive approach that considers social and ecological aspects together.

For both arguments, co-designers converged on the need to embrace a wider perspective where different actors might collaborate and complement each other in carrying out their missions within a shared vision. This collaborative approach is seen as essential for the transition of the entire system toward more sustainable performance, as individual efforts alone can only have a smaller impact compared to the creation of a collaborative design infrastructure between the different nodes. Further co-design workshops are planned to extend the conversation to other actors of the local food system and to design a more comprehensive strategy for its sustainability. This will include the public administration and the local food policy team to converge on what might happen if common strategies were undertaken.

As an outcome of the co-design workshops with the stakeholders, the two strategic directions described below emerged.

5.1.1. A Widespread and Capillary System for Distributing and Selling Fresh Food

The first direction points to a widespread fresh food distribution and sales system that integrates and connects the wholesale market to the 21 indoor municipal markets scattered around the city, leveraging the forthcoming political strategy of shifting governance from a fragmented and uneven logic to a more centralized one.

This outlines an integrated, connected, and optimized system that sees the wholesale market organization (a public company) as the system's managing and enabling actor and the markets as a new, hybrid, proximity node that combines the following:

- Service functions: from sales to Business to Business—B2B—and Business to Consumer—B2C—transactions, shared distribution platforms, and catering, cultural, and social activities.
- Local governance and involved actors: producers, intermediaries, vendors, restaurateurs, associations, activists, and citizens.
- Social and environmental strategies: adaptation, mitigation, and regeneration.

This vision emerged in relation to the wholesale market, together with three priorities:

1. A service model for innovative, hybrid, and diffuse accessibility of fresh food integrated into the market's food system;
2. A collaborative micro-logistics platform for preventing and reducing emissions, and for improving the traceability of produce;
3. An exploration of hydro/aeroponic food production technologies for indoor markets and the wholesale market.

In a nutshell, this strategic direction is characterized by the following:

- Sustainability strategies: a transition from adaptive to mitigation strategies.
- Governance: a tension between a centralized system (the organization of a wholesale market) and a distributed one (the indoor municipal markets network).
- Addressed challenges: (i) sustainable intra-city transportation solutions for food recovery, distribution, and delivery to prevent and reduce food waste in all steps of the food chain; (ii) setup of a widespread and proximity B2C and B2B distribution system for fresh food, integrated with businesses and social, cultural, and welfare services; (iii) zero-mile production and distribution.

- Actors involved and targeted in co-design and co-production: the wholesale market, indoor markets, food producers, social delivery ventures, local food shops, local organizations, and citizens.

5.1.2. An Efficient System for Regenerating Food and People

The second direction points to a collaborative service to regenerate surplus food and to empower individuals and local communities. Its objective is to strengthen the collaboration between the system actors for the common purpose of recovering food, places, and people. Accordingly, stakeholders, businesses, and NGOs are called to innovate their service delivery and to develop solutions for the inclusion and integration of beneficiaries.

This strategy follows the principle that empowering beneficiaries, and, more generally, people, could be a way to mobilize them and take them out of a welfare-oriented service [36], therefore facilitating job placement and learning processes. Practically, this could happen involving the people assisted by a service in its co-design and co-production, as experimented in some virtuous AFNs [37].

Additionally, this direction aims to optimize the collection and redistribution processes within and between hubs, enabling the experimentation with new services, such as food processing and provision, and the use of shared platforms.

This vision emerged in relation to the food waste neighborhood hubs, together with three priorities:

1. An upskilling and training service for job inclusion, tailored to the food recovery and redistribution system;
2. A collaborative micro-logistics platform for improving the collection of surplus food;
3. A collaborative and co-produced service of food redistribution and sale (food cooperative).

In a nutshell, this strategic direction is characterized by the following:

- Sustainability strategies: A transition from adaptive to mitigation strategies.
- Governance logic: distributed.
- Addressed challenges: (i) Integration of food redistribution initiatives with relevant and complementary services, such as welfare and social services; (ii) provision of quality food to vulnerable people while ensuring fair treatment of all actors; (iii) increases and improvements in the collection and redistribution of surplus/end-of-life food for charity and social purposes.
- Actors involved and targeted in co-design and co-production: food waste hubs, welfare organizations, beneficiaries, indoor markets, social delivery ventures, grocery stores, local shops, and canteens.

6. Discussion: The Distinctiveness of the Milano Sustainable Food System Scenario and the Transitioning DOS

The comparative analysis of the three scenarios raises a first set of reflections on the role of likewise processes and outcomes to drive systemic change towards sustainability. The analysis, moreover, helps to focus the purpose of the Milano ones and crafts its method accordingly by envisioning possible evolutions of the local food system and co-designing with stakeholders potential pathways toward sustainability. Unlike the other two scenarios, it targets specific actors within a specific context and ecosystem, aiming to collaboratively design a food service masterplan for the city that can integrate the urban masterplan through a service-oriented approach.

6.1. Key Elements of the Scenario Structure and Targeted Actors

Specific and actual challenges. A first reflection concerns the general approach to the scenario-building and its structure; the DOS for the Milano Food System is generated around governance and sustainability challenges, which are relevant factors stakeholders must deal with in the present time or soon. Both are less about technologies and more about the organization's strategy in dealing with top-down/bottom-up forces. Technology, instead, is an element that can enable this strategy. Given the nature of the actors targeted by the scenario and their role at the intersection of public and private sector and welfare within the local institutional landscape, this approach was considered to be more likely to spur action than a more future-oriented one. The PFoF and MUSAE scenarios, instead, privilege a more visionary approach that moves from general principles, business models, technological opportunities, and artistic sensitivity. They depict alternative futures as tangible opportunities to "reduce the pain and increase the speed of change" [29]. As a result, the proposed scenarios are highly suggestive and intrinsically detached from any local cultural and institutional landscape with its urgencies, rules, and constraints.

Following Morelli [38], the 'institutional landscape', is a system of values, rules, and social, cultural, economic, and political foundations that guide change, promoting developments that align with this framework while obstructing those that do not. The more actors are intertwined with one another and connected to the public system, the more they must navigate this landscape, which evolves very slowly and through gradual changes influenced by concurrent factors. For service designers, working at this level involves addressing a large and systemic scale of intervention, which entails geographical and operational variability. As such, the researchers involved in the project have shaped their role as steering agents toward more integrated actions for the sustainability of the entire food system by transforming the behavior and relationships of the stakeholders.

Although recognizing the impossibility of kicking-off actual action or controlling any resulting transformation, the research agenda was to explore and visualize potential changes in which each actor could see their role within the larger system, both at the place-scale and in relation to others. Reflecting on the evolution of their current best practices, integrating them with prospective illustrative solutions was a key part of this transformation scenario. A timeframe of ten years was then considered to be the most appropriate, being not too far from today's actions. Likewise, technologies were introduced with a progressive approach, from re-considering recent, discarded, experimentations to introducing established or low-tech solutions (digital and more) in conventional processes.

Multi-actor and relational perspective. Another set of reflections concerns the targeted actors. The scenario identified specific actors within a specific place, allowing each to recognize themselves and others in the local ecosystem. Conversely, the PFoF and MUSAE scenarios generically target people operating in the food system or/and small–medium enterprises and startups that can find inspiration in the scenario and take over some challenges and opportunities. MUSAE envisions a second stage of research to collaborate with SMEs in transforming one scenario into future-driven concepts and prototypes at Technology Readiness Level 5 (TRL5) [30] (p. 2). Yet, there is no mention or intention to leverage the collaboration of the targeted actors.

While the approach used for the Milano Sustainable Food System Scenario ensures greater stakeholder activation and reduces resistance, it may limit visionary breakthroughs and revolutionary changes, perpetuate a conservative stare, and result in incremental innovations, it can also reveal new opportunities for collaboration and synergy among stakeholders, as well as help identify potential partnerships and understand relational opportunities.

In circular strategies, such synergy is essential to make the outputs of one process the inputs of another, compensating emissions and integrating decarbonization technologies—all within a proximity logic. For example, surplus food from the wholesale market can support solidarity redistribution chains. Similarly, social sustainability can be achieved by combining conventional food services with social impact actions by third-sector actors, such as including vulnerable people in transformation or delivery services.

Through this explicit relational and collaborative strategy, this research aims to inspire the food system's nodes to uplift their sustainability by identifying common priorities, integrating strategies, and sharing solutions. It also aims to initiate a multi-actor and design-driven commoning process, a collective decision-making dialog that can bring about value for the system and generate interest in starting-up initiatives [24]. This process can also bring about collaborations with external actors, whose competencies are required to meet emerging needs and opportunities. The competencies, ambitions, and motivations of stakeholders are indeed crucial factors that can either hinder or drive transformation. Given the transformation trajectories outlined by the Milano Food Policy and described in the introduction of this article, the system's nodes are in a position where rethinking their activities and addressing new challenges is necessary. Innovating processes and services are not in question; it is already happening, and this research aims to subtly integrate into this process and critically contribute to it.

Contextualization. Both of these distinctive elements in the Milano Sustainable Food System Scenario, the compliance with actual challenges and the consideration of the actual system's nodes, are intended to make the scenario contextualized and therefore more relevant to the targeted actors, tailoring it to the specific cultural, social, economic, and environmental conditions. The scenario is then built leveraging local and international AFNs as seeds of change that can inspire, work, and, finally, scale. This approach involves extensive fieldwork, stakeholder engagement, and local data analysis, resulting in solutions that are relevant, co-designed, and likely co-produced by local stakeholders, and, therefore, are also flexible enough to adapt to emerging local conditions and changes. In contrast, the PFoF and MUSAE scenarios rely on broader, generalized frameworks that do not consider the granularity of specific local challenges, potentially missing out on unique local actors, needs, and resources. This can make the scenario more malleable to different conditions, yet be perceived as distant from what really matters for a local system.

As mentioned, the idea behind the Milano Sustainable Food System Scenario is to simulate interactions between different nodes and spur changes in the behaviors of actors within the system by "rehearsing plausible options" for the future. It is also argued that this scenario is a mixed typology [23]; an explorative phase generating different plausible alternatives is followed by a predictive one in which specific "what if" developments are deployed in a conversation with the actors. The final step will be designing context-specific roadmaps for the implementation of improved or new services. Given the transformation targets, roadmaps should outline how the current situation can be adjusted or changed.

Outcome orientation. Compared to the PFoF and MUSAE scenarios, the Milano Sustainable Food System Scenario can be defined as explicitly outcome-oriented, committed to initiating the transition from a known present situation to some preferable alternatives in the future. In this effort, the different scenario typologies are articulated in a sequence, each one theoretically effective in moving from the exploration of possibilities to their selection, development, and prototyping in a relational logic that requires field work, early stakeholder engagement, and co-design. Despite the importance of the process of transition as a collective and relational journey of the actors (not only the targeted ones, but also those involved in the development), the Milano Sustainable Food System Scenario places emphasis on making things happen in a specific system, place, and institutional landscape. Thus, it reaches an outcome by building on observed facts, the characteristics of a system, and on previous knowledge.

6.2. Transitioning Design-Orienting Scenarios

The last reflection on the comparison of the scenarios in the effort to drive a systemic change towards sustainability regards the three-phases method adopted for building and developing the scenario presented in Section 4.1. This reflection, together with the distinctive elements abovementioned, led us to formulate an evolution of a DOS into a Transitioning DOS (T-DOS) specifically designed to facilitate outcome-oriented sustainability transitions within a particular context or system and in a medium-term perspective. Characterized by a multi-actor and relational perspective, T-DOS engage stakeholders through a structured, contextualized process, leveraging local challenges, resources, and actors to ensure the relevance and applicability of practicable sustainable futures and roadmaps, attainable within existing institutional landscapes.

The T-DOS can be streamlined as in Figure 3, briefly showing the stages of the process, each one articulated in the following:

- Research activities that cut across the three phases;

- Scenario's content generation, discussion, and development;
- Relevant actors.

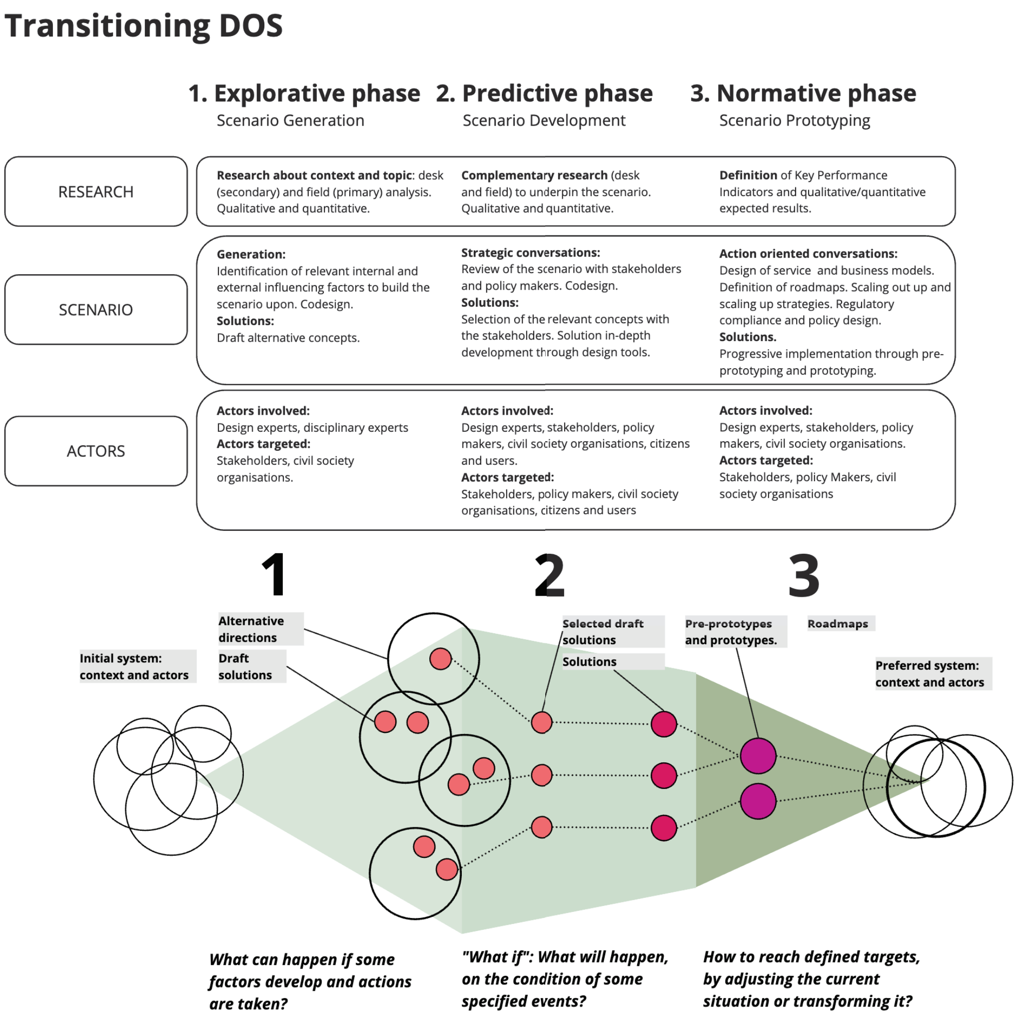

Figure 3. Transitioning Design-Orienting Scenarios' main phases and structure.

The figure highlights, also, the main elements and artifacts that are designed for and within each phase, and supporting codesign activities, such as alternative directions, draft solutions, prototypes, and roadmaps.

7. Conclusions

This article presents and discusses the use of scenarios to steer outcome-oriented sustainability transitions in a local food system. The following paragraphs present a summary of the main finding discussed, as well as the limits and future steps of this work.

7.1. Summary of the Findings

This article proposes the ways in which design can play a role in developing, orienting, and supporting transitioning strategies within complex and adaptive food systems, and how scenarios can be considered both as creative processes and actionable tools that facilitate strategic conversations and steer outcome-oriented sustainability transitions. Building on these premises, this work defines a set of ten transversal meta-features, along with recurring elements in the scenarios' structure and presentation formats, that describe key elements, laying the foundation for building scenario types that can effectively contribute to environmental and social sustainability, regardless of the field of application.

Within this framework, the Design-Orienting Scenarios (DOS) methodology proves instrumental in co-designing transformative solutions while maintaining a systemic perspective. DOS enable a comprehensive understanding of the complexities involved, offering future-oriented narratives visualized through specific solutions. Applied to the Milano Food System, the DOS here presented contribute to ongoing transformations by engaging relevant actors in co-design processes that integrate governance and sustainability strategies, aiming to foster multi-actor collaboration and launch transformative projects.

The evolution of DOS into Transitioning Design-Orienting Scenarios (T-DOS) offers a framework for creating innovative and contextually relevant solutions that account for both the specific characteristics of local food systems and broader sustainability goals. In particular, the development of scenarios tailored to the Milanese food system highlights the importance of fostering relationships among stakeholders, ensuring that the proposed solutions are meaningful as well as operational and capable of activating local assets and actors, and are thus designed to support outcome-oriented transitions.

In addition to their relevance for food systems, the applicability of T-DOS extends to broader complex systems. When applied in different contexts, the multi-actor and relational approach of T-DOS offers a promising framework for navigating complexity. By bringing together diverse stakeholders, these scenarios facilitate the exploration of innovative systemic solutions that can address a wide range of societal challenges. The focus on collaboration and co-design, combined with the adaptability of T-DOS to various contexts, makes them a tool for fostering transformative change across different domains.

7.2. Limits of the Study and Future Steps

The research presented in this article is still ongoing; it is intended as a process in which the scenario is a design artifact to steer a medium-term transition. The present stage of the research corresponds to phase 2 of the T-DOS, in which different alternative directions and relevant possible solutions are co-designed with the actors targeted. From this phase, which is progressively addressing specific "what if" questions, two strategic directions have emerged through co-design and now serve as starting points for future progress. While there is no guarantee that the process will continue as hoped, there is evidence that multi-actor conversation groups have formed around the inputs of this scenario.

The next challenges for the project are to develop phase 2 and, therefore, a range of possible solutions that engage the system's actors, ultimately leading to the pre-prototyping of services (approximately five) to verify their validity. Depending on the outcomes, this could result in the definition of key performance indicators and creation of implementation roadmaps.

Given the project's assumptions and its emphasis on a multi-actor and relational perspective, for the positive outcome of the project, ensuring a series of cross-cutting milestones throughout the whole process will be crucial. These milestones will be collective moments of debate, involving multiple nodes of the system, such as workshops of mutual update, system adaptation, and alignment of the behaviors, which involve also external experts and new actors. Likewise, aligning the local food policy and regulations with on-the-ground practices will be key, since social and business innovativeness often collides with current regulations and policies [39].

Besides the challenge of the continuation of the project, the main questions about the T-DOS concern the scalability of its method and of the food directions that have come out from the Milano context.

This method is a design process that can be replicated with the involvement of professional designers who are familiar with creative abduction, employ envisioning techniques, conduct field research, and possess thematic knowledge, in this case about sustainable food practices. This is part of the design culture and of what Manzini defines as "expert design" [40]. Yet, design knowledge and systemic thinking can become relevant only if activated by institutional agents, being actors of the system or governments, through regional or local policies [41]. The T-DOS for the Milano Food System was developed in a city recognized internationally for its Food Policy, with a dedicated Food Policy Office that, over the years, has implemented several actions and won several grants. The city has started to be pivotal across the world for sustainable food policies [17,41,42], designed under the key principles of evidence-based, multi-actor collaboration, and cross-sectoral synergies, and with the involvement of established local institutions.

While this may not apply to all contexts, a food T-DOS has better chances of success in environments where resources are directed toward activities supporting sustainable practices and participatory food governance. Particularly, the food sustainability directions (namely, *A widespread and capillary system for distributing and selling fresh food* and *An efficient system for regenerating food and people*) can be scaled under certain conditions, which are primarily policy conditions that enable actors to share knowledge, collaborate, and act effectively. Among these conditions, the key ones include the presence of the following: an institutional landscape that has *infrastructured* a dialog among the local system's actors; participatory food governance structures that can enhance ownership, relationships, collaboration, and co-investment among multiple stakeholders; a city or regional policy that encourages circular economy and social innovation that require multi-actor collaboration; a favorable environment for alternative food networks, counterbalancing the large retail system; and finally, a culture of innovation and experimentation with a systemic perspective, where multiple stakeholders (including research bodies and citizens) are engaged in food initiatives and policy-making processes [42–45].

The specific contents of the Milano Sustainable Food System Scenario cannot be directly replicated elsewhere, unless they are streamlined and shaped as theoretical service models, which are structures of interaction between service providers, users, and supporting processes to deliver a solution for a need. Yet, the distinctive internal and external factors chosen to build the scenario (Governance—centralized/distributed, and Sustainability strategies—adaptation/mitigation) are scalable in other contexts where multi-actor systems are faced with the need of transitioning, together, to more sustainable configurations.

Research on design scenarios is vast and fascinating, as it deals with the future and the imagination of what the future could be. Despite the T-DOS presented in this article being limited in terms of visionary breakthroughs, they are designed to be operational and pragmatic in activating stakeholders and assets. The effectiveness of this approach needs to be measured and demonstrated through multiple applications and over the long term, especially in comparisons with more visionary and thought-provoking scenario methodologies. Further research should address this issue and explore the conditions that can effectively increase the success of their application, including the accountability of designers in engaging with and influencing systemic innovation processes.

Author Contributions: Both authors participated in equal manner to the research, definition and development of the article, yet Sections 1 and 2 were written by A.M., and Sections 3–5 by M.C., while Sections 6 and 7 were written jointly. All authors have read and agreed to the published version of the manuscript.

Funding: Research funded under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3—Call for tender No. 341 of 15 March 2022 of Italian Ministry of University and Research funded by the European Union—NextGenerationEU; Project code PE00000003, Concession Decree No. 1550 of 11 October 2022 adopted by the Italian Ministry of University and Research, Project title "ON Foods—Research and innovation network on food and nutrition Sustainability, Safety and Security—Working ON Foods".

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained withing the article.

Acknowledgments: We thank our colleagues from Polimi DESIS Lab and especially Daniela De Sainz Molestina and Lucia Viganego Ballesteros for their precious contribution, as well as all the local actors for their active participation to the co-design processes.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Intergovernmental Panel on Climate Change. Summary for Policymakers. In *Climate Change 2022: Impacts, Adaptation and Vulnerability*; Pörtner, H.-O., Roberts, D.C., Poloczanska, E.S., Mintenbeck, K., Tignor, M., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2022; pp. 3–33. [CrossRef]
2. Food and Agriculture Organization of the United Nations; International Fund for Agricultural Development; United Nations Children's Fund; World Food Programme; World Health Organization. *The State of Food Security and Nutrition in the World 2023: Urbanization, Agrifood Systems Transformation and Healthy Diets Across the Rural–Urban Continuum*; FAO: Rome, Italy, 2023; Available online: https://openknowledge.fao.org/handle/20.500.14283/cc3017en (accessed on 30 August 2024).
3. Bornemann, B.; Weiland, S. New Perspectives on Food Democracy. *Politics Gov.* **2019**, *7*, 1–7. [CrossRef]
4. Sonnino, R. The New Geography of Food Security: Exploring the Potential of Urban Food Strategies. *Geogr. J.* **2016**, *182*, 190–200. [CrossRef]
5. Edwards, F.; Sonnino, R.; Cifuentes, M.L. Connecting the Dots: Integrating Food Policies Towards Food System Transformation. *Environ. Sci. Policy* **2024**, *156*, 103735. [CrossRef]
6. High Level Panel of Experts on Food Security and Nutrition. *Food Security and Nutrition: Building a Global Narrative Towards 2030*; A Report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security; High Level Panel of Experts on Food Security and Nutrition: Rome, Italy, 2020.
7. Clayton, T.; Radcliffe, N. *Sustainability: A Systems Approach*; Routledge: London, UK, 1996.
8. Vezzoli, C. *System Design for Sustainability in Practice*; Maggioli Editore: Santarcangelo di Romagna, Italy, 2022.
9. Bisinella, V.; Christensen, T.H.; Astrup, T.F. Future Scenarios and Life Cycle Assessment: Systematic Review and Recommendations. *Int. J. Life Cycle Assess.* **2021**, *26*, 2143–2170. [CrossRef]
10. Buchanan, R. Wicked Problems in Design Thinking. *Des. Issues* **1992**, *8*, 5–21. [CrossRef]
11. Manzini, E.; Jégou, F. *Sustainable Everyday: Scenarios of Urban Life*; Edizioni Ambiente: Milano, Italy, 2003.
12. Parasecoli, F. *Food*; The MIT Press: Cambridge, MA, USA, 2019.
13. Castanho, A.; Brites, C.; Oliveira, J.C.; Cunha, L.M. Food Design Thinking: A Systematic Review from an Evolutionary Perspective. *Foods* **2024**, *13*, 2446. [CrossRef] [PubMed]
14. Koskinen, I.; Meroni, A. Convivial Aesthetic in Social Innovation: A Nested Framework from Three Projects in Milano. *CoDesign* **2023**, 1–18. [CrossRef]
15. Bateson, G. *Mind and Nature: A Necessary Unity*; Bantam Books: New York, NY, USA, 1979.
16. Ogilvy, J.A. *Creating Better Futures: Scenario Planning as a Tool for a Better Tomorrow*; Oxford University Press: New York, NY, USA, 2002.
17. Van Der Heijden, K. *Scenarios, the Art of Strategic Conversation*; Wiley: New York, NY, USA, 2005.
18. Milano Food Policy. *Report Workshop Coprogrammazione Hub di Quartiere*; Comune di Milano: Milano, Italy, 2023.
19. Kahn, H.; Wiener, A.J. *The Year 2000: A Framework for Speculation on the Next Thirty-Three Years*; Macmillan: New York, NY, USA, 1967.
20. Warfield, J. An overview of futures methods. In *The Knowledge of Future Studies*; Slaughter, R., Ed.; DDM Media: Melbourne, Australia, 1996.
21. Neuvonen, A.J. Re-Focusing on the Future. Backcasting Carbon Neutral Cities. Doctoral Dissertation, Tampere University, Tampere, Finland, 2022.
22. Masini, E. *Why Future Studies?* Grey Seal Books: London, UK, 1993.
23. Börjeson, L.; Höjer, M.; Dreborg, K.-H.; Ekvall, T.; Finnveden, G. Scenario Types and Techniques: Towards a User's Guide. *Futures* **2006**, *38*, 723–739. [CrossRef]
24. Selloni, D.; Meroni, A. Exploring Service Design as a Commoning Approach: The Engaging Strategy of the Service Master Planning. *Sustainability* **2023**, *15*, 16067. [CrossRef]
25. Andersen, P.D.; Hansen, M.; Selin, C. Stakeholder Inclusion in Scenario Planning—A Review of European Projects. *Technol. Forecast. Soc. Chang.* **2021**, *169*, 120802. [CrossRef]
26. Villari, B. Community-Centered Design: A Design Perspective on Innovation in and for Places. *Int. J. Des. Soc.* **2021**, *16*, 47–58. [CrossRef]
27. Dorst, K. The Core of 'Design Thinking' and Its Application. *Des. Stud.* **2011**, *32*, 521–532. [CrossRef]
28. March, L. The logic of design and the question of value. In *The Architecture of Form*; March, L., Ed.; Cambridge University Press: Cambridge, UK, 1976; pp. 1–40.
29. Preferable Future of Food (No Date). Available online: https://food.preferablefutures.com (accessed on 30 August 2024).

30. MUSAE Scenario Booklet (No Date). Available online: https://musae.starts.eu/wp-content/uploads/sites/3/2024/04/booklet_scenarios_musae.pdf (accessed on 30 August 2024).
31. Aucoin, M.; Fry, M. Growing Local Food Movements: Farmers' Markets as Nodes for Products and Community. *Geogr. Bull.* **2024**, *56*, 1.
32. Milano Food Policy Office; Fondazione Cariplo; ESTÀ. The Food System in Milan Five Priorities for a Sustainable Development. Food Policy Milano. 2018. Available online: https://www.comune.milano.it/aree-tematiche/food_policy/obiettivi-e-priorita-della-food-policy-di-milano (accessed on 30 August 2024).
33. Wang, F.; Harindintwali, J.-D.; Wei, K.; Shan, Y.; Mi, Z.; Costello, M.J.; Grunwald, S.; Feng, Z.; Wang, F.; Guo, Y.; et al. Climate Change: Strategies for Mitigation and Adaptation. *Innov. Geosci.* **2023**, *1*, 100015. [CrossRef]
34. Intergovernmental Panel on Climate Change. *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II, and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Lee, H., Romero, J., Eds.; IPCC: Geneva, Switzerland, 2023. [CrossRef]
35. Corubolo, M.; De Sainz Molestina, D.; Viganego Ballesteros, L.; Meroni, A. Food Forward: Design Futures to Support Alternative Food Systems in Urban Areas. In Proceedings of the Cumulus P/REFERENCES OF DESIGN, Budapest, Hungary, 15–17 May 2024; forthcoming.
36. Hochgerner, J. Empowerment, Co-Creation and Social Innovation Ecosystems. In *Atlas of Social Innovation–New Practices for a Better Future*; Howaldt, J., Kaletka, C., Schröder, A., Zirngiebl, M., Eds.; Sozialforschungsstelle, TU Dortmund University: Dortmund, Germany, 2018; pp. 218–221. Available online: www.socialinnovationatlas.net (accessed on 29 July 2024).
37. Corubolo, M.; De Sainz Molestina, D.; Meroni, A.; Viganego Ballesteros, L. Urban and Peri-urban Food Systems: Exploring Proximity and Care in Alternative Food Networks. In *DRS2024: Boston, Proceedings of the Resistance, Recovery, Reflection, Reimagination Conference, Boston, MA, USA, 23–28 June 2024*; Gray, C., Ciliotta Chehade, E., Hekkert, P., Forlano, L., Ciuccarelli, P., Lloyd, P., Eds.; Design Research Society: London, UK, 23–28 June 2024. [CrossRef]
38. Morelli, N.; de Götzen, W.; Simeone, L. *Service Design Capabilities*; Springer Nature: Cham, Switzerland, 2021. [CrossRef]
39. Mulgan, G. Social Innovation—The Last and Next Decade. In *Atlas of Social Innovation—New Practices for a Better Future*; Howaldt, J., Kaletka, C., Schröder, A., Zirngiebl, M., Eds.; Sozialforschungsstelle, TU Dortmund University: Dortmund, Germany, 2018; pp. 194–197. Available online: www.socialinnovationatlas.net (accessed on 29 July 2024).
40. Manzini, E. *Design, When Everybody Design*; MIT Press: Cambridge, MA, USA, 2015.
41. De Cunto, A.; Tegoni, C.; Sonnino, R.; Michel, C. Food in Cities: Study on Innovation for Sustainable and Healthy Production, Delivery, and Consumption of Food in Cities. First Report: Mapping Innovative Urban Food Strategies Designed to Promote the Production, Delivery, and Consumption of Sustainable and Healthy Food; Working Document. Available online: https://www.milanurbanfoodpolicypact.org/wp-content/uploads/2021/08/Eurocities-Food-in-Cities.pdf (accessed on 14 October 2024).
42. Food and Agriculture Organization of the United Nations. The Milan Urban Food Policy Pact: Monitoring Framework. Available online: https://www.milanurbanfoodpolicypact.org/resources/the-milan-urban-food-policy-pact-monitoring-framework-handbook-and-resource-pack/ (accessed on 14 October 2024).
43. Moragues-Faus, A.; Battersby, J. Urban Food Policies for a Sustainable and Just Future: Concepts and Tools for a Renewed Agenda. *Food Policy* **2021**, *103*, 102124. [CrossRef]
44. Monciardini, D.; de Melo Cartaxo, T. The Milan Food Policy: Six Lessons for Local Food Strategies. 2022. Available online: https://ssrn.com/abstract=4596638 (accessed on 30 August 2024).
45. Mattioni, D.; Milbourne, P.; Sonnino, R. Destabilizing the Food Regime "from within": Tools and Strategies Used by Urban Food Policy Actors. *Environ. Innov. Soc. Transit.* **2022**, *44*, 48–59. [CrossRef]

sustainability

Article

Women's Leadership in Sustainable Agriculture: Preserving Traditional Knowledge Through Home Gardens in Santa Maria Jacatepec, Oaxaca

Marco Aurelio Acevedo-Ortiz [1,*], Gema Lugo-Espinosa [1], Yolanda Donají Ortiz-Hernández [2,*], Rafael Pérez-Pacheco [2], Fernando Elí Ortiz-Hernández [3] and Carlos Alejandro Granados-Echegoyen [1]

[1] Consejo Nacional de Humanidades, Ciencias y Tecnologías (CONAHCYT)-Instituto Politécnico Nacional, CIIDIR Unidad Oaxaca, Santa Cruz Xoxocotlán 71230, Oaxaca, Mexico; glugoe@ipn.mx (G.L.-E.); cgranadose@ipn.mx (C.A.G.-E.)
[2] Instituto Politécnico Nacional, CIIDIR Unidad Oaxaca, Santa Cruz Xoxocotlán 71230, Oaxaca, Mexico; rperezp@ipn.mx
[3] Instituto Politécnico Nacional, ESIME Culhuacán, Coyoacán, Ciudad de México 04440, Mexico; fortizh@ipn.mx
* Correspondence: macevedoo@ipn.mx (M.A.A.-O.); yortiz@ipn.mx (Y.D.O.-H.); Tel.: +52-9511726274 (M.A.A.-O.); +52-9515170610 (ext. 82723) (Y.D.O.-H.)

Abstract: Rural communities in Oaxaca face challenges such as food insecurity, economic instability, and the loss of traditional agricultural knowledge. Home gardens, once essential for food production and income generation, have declined due to migration, environmental degradation, and modern agricultural pressures. This study evaluated how community-driven models, supported by crowdfunding, can revitalize home gardens to improve food security, build community resilience, and promote economic empowerment. A mixed-methods approach, including household surveys, interviews, and focus groups, was used to assess the impact of these gardens. The results showed that over 70% of households experienced improved food security and reduced reliance on external food sources. Home garden production also led to a 20% reduction in food expenses, and the sale of surplus crops provided additional income, enhancing household economic stability. Women's involvement in agricultural decision-making increased, fostering empowerment within both family and community contexts. Traditional practices, such as seed saving and organic pest control, were maintained, contributing to the ecological sustainability of the gardens. Crowdfunding was an effective tool for financing home gardens, boosting community engagement and strengthening social bonds. The findings highlight the potential of integrating traditional knowledge with modern funding strategies to create resilient, sustainable agricultural systems in rural Oaxaca.

Keywords: home gardens; food security; community resilience; crowdfunding; rural development; SDGs

Citation: Acevedo-Ortiz, M.A.; Lugo-Espinosa, G.; Ortiz-Hernández, Y.D.; Pérez-Pacheco, R.; Ortiz-Hernández, F.E.; Granados-Echegoyen, C.A. Women's Leadership in Sustainable Agriculture: Preserving Traditional Knowledge Through Home Gardens in Santa Maria Jacatepec, Oaxaca. *Sustainability* **2024**, *16*, 9513. https://doi.org/10.3390/su16219513

Academic Editors: Hamid El Bilali, Tarek Ben Hassen and Carola Strassner

Received: 25 September 2024
Revised: 29 October 2024
Accepted: 31 October 2024
Published: 31 October 2024

1. Introduction

Home gardens have long been a cornerstone of small-scale agricultural systems in rural Mexico, particularly in Oaxaca, where they are crucial for food security, biodiversity conservation, and the preservation of traditional agricultural knowledge [1–3]. These biodiverse plots, typically located near homes, provide households with fresh food, medicinal plants, and small-scale livestock production [2]. Beyond their immediate contributions to household sustenance, home gardens play a vital role in promoting food sovereignty by enabling families to control their food production and maintain agricultural practices deeply rooted in local cultural traditions [4,5].

However, despite their numerous benefits, home gardens have been steadily declining across rural Mexico in recent decades [6]. One of the primary drivers of this decline is rural-to-urban migration, particularly among younger generations seeking better economic opportunities [7,8]. This migration has disrupted the intergenerational transmission of traditional agricultural knowledge, weakening the continuity of home garden practices [9]. At the same time, the rise of industrial agriculture—favoring monoculture and large-scale production—has marginalized home gardens, pushing aside their more sustainable, biodiversity-friendly practices in favor of commercial crops [10]. Furthermore, environmental degradation and shifting land-use priorities have compounded these pressures, making it increasingly difficult for rural communities to maintain these once-essential systems [11].

In Oaxaca, women have historically been at the forefront of both household and agricultural activities, particularly in managing home gardens that provide essential food and medicinal plants for their families [12]. Despite their central role in ensuring household food security, women's contributions are often undervalued, seen as extensions of domestic responsibilities rather than formal agricultural work [13,14]. Traditionally, men have dominated public agricultural decision-making, while women's roles have remained confined to the private sphere, limiting their participation in community leadership and economic activities [15]. Yet, women's involvement in home gardens is not only essential for household sustenance but also for preserving agricultural biodiversity and transmitting traditional knowledge across generations [16]. Recognizing and overcoming these cultural and structural barriers is critical to unlocking the full potential of women's contributions to rural agricultural systems [17–19].

As home gardens decline and women continue to face barriers in agricultural leadership, innovative solutions are needed to revitalize these systems and promote equitable participation. One promising approach is social crowdfunding, which provides a decentralized and accessible means of financing community-driven projects, particularly in regions where traditional financial institutions are less accessible [20–23]. For indigenous and rural communities in Oaxaca, crowdfunding offers a valuable opportunity to secure resources for restoring home gardens, purchasing seeds, and improving infrastructure [24]. More than just a financial tool, crowdfunding connects local initiatives with broader networks of support, fostering social cohesion and collective ownership of agricultural projects [22]. By giving communities control over their development projects, crowdfunding empowers marginalized groups, allowing them to bypass institutional barriers and align agricultural initiatives with their cultural and ecological values [25,26].

This context of declining home gardens and marginalized communities highlights the case of Vega del Sol, a small area within the municipality of Santa María Jacatepec, which was classified as a priority attention zone due to its high levels of marginalization and socio-economic underdevelopment [27,28]. Approximately 30% of the population identifies as Afro-Mexican, adding to the region's rich cultural diversity [29]. However, despite this cultural richness, the community faces significant challenges: nearly 29% of the population lives in extreme poverty, a result of limited access to essential services, educational opportunities, and economic mobility [30]. The region's rugged terrain and relative isolation exacerbate these socio-economic issues, restricting access to markets, healthcare, and education, thereby contributing to the high levels of social vulnerability.

Vega del Sol serves as an ideal location for studying the complex interplay between cultural, environmental, and economic factors. This region provides a critical case study for examining the challenges and opportunities related to rural development, food security, and environmental conservation. In particular, the community's experience highlights the potential of home gardens not only as tools for subsistence and cultural preservation but also as a means to address socio-economic challenges through sustainable agricultural practices [31].

This study aims to address these gaps by exploring how community-driven initiatives, supported by crowdfunding, can revitalize home gardens in Oaxaca as a sustainable approach to improving food security, community resilience, and economic empowerment. The specific objectives are to assess the impact of home gardens on food security and household economic stability in rural communities, evaluate the effectiveness of crowdfunding as a financial mechanism for sustaining home gardens, explore the role of women in agricultural decision-making within home garden projects, focusing on their contributions to community leadership and empowerment, and examine how traditional agricultural knowledge is preserved and transmitted through home gardens, and its role in sustaining rural livelihoods.

By focusing on these objectives, this research seeks to demonstrate the potential of home gardens as a sustainable solution to contemporary socio-economic and environmental challenges. The findings will contribute to broader discussions on sustainable development, with particular relevance to the Sustainable Development Goals (SDGs), including SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 5 (Gender Equality), and SDG 13 (Climate Action).

2. Materials and Methods

2.1. Study Site Location

The study was conducted in La Chinantla, Oaxaca, one of the most biologically diverse regions in Mexico [32,33]. This region's extraordinary biodiversity has made it a focal point for conservation efforts and sustainable agricultural practices [31,34], which are critical for the livelihoods of indigenous and rural communities [34]. Agricultural activities, particularly the cultivation of traditional crops in home gardens, are closely linked to the cultural identity and environmental stewardship of the indigenous population, who rely on these practices for both subsistence and the preservation of their cultural heritage [31,34–36].

The specific study area focused on the ejido of Vega del Sol, located within La Chinantla in the municipality of Santa María Jacatepec (Figure 1). Vega del Sol is a rural community with a population of 1225 residents, composed of 658 women and 567 men. Among these, 6.29% of women and 2.78% of men are illiterate. Additionally, 96.41% of the population identifies as indigenous, with 72.73% speaking Chinantec as indigenous language, underscoring the community's deep-rooted cultural traditions that continue to shape everyday life [37]. Of the total population, 693 individuals fall within the working-age range of 15 to 59 years, playing a key role in supporting subsistence farming and local economic activities.

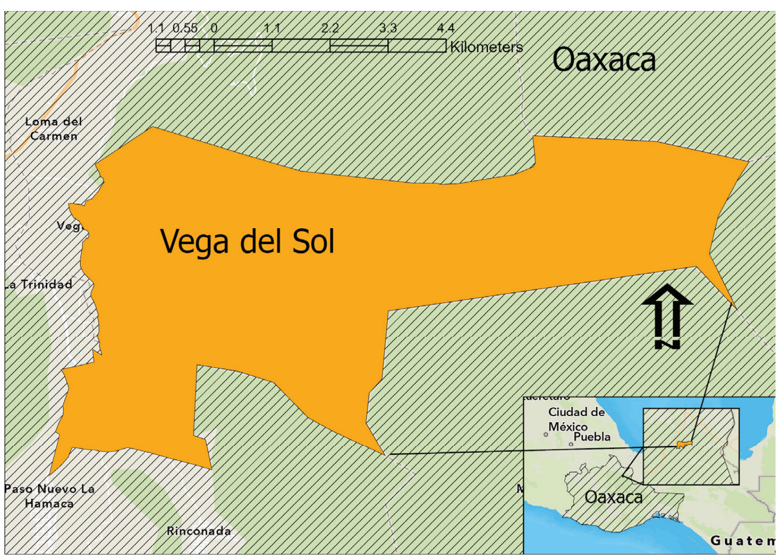

Figure 1. Geographical location of Vega del Sol in la Chinantla, Oaxaca.

2.2. Research Design

A mixed-methods approach was employed to address the research objective, integrating both quantitative and qualitative data to assess the revitalization of home gardens in Oaxaca. The study, conducted from 2020 to 2022, focused on three primary areas: (a) food security and sustainability, (b) community resilience and empowerment, and (c) the preservation of traditional agricultural knowledge. A theoretical model (Figure 2) was developed to support the long-term sustainability and adaptability of home gardens, specifically through community-driven efforts and crowdfunding initiatives.

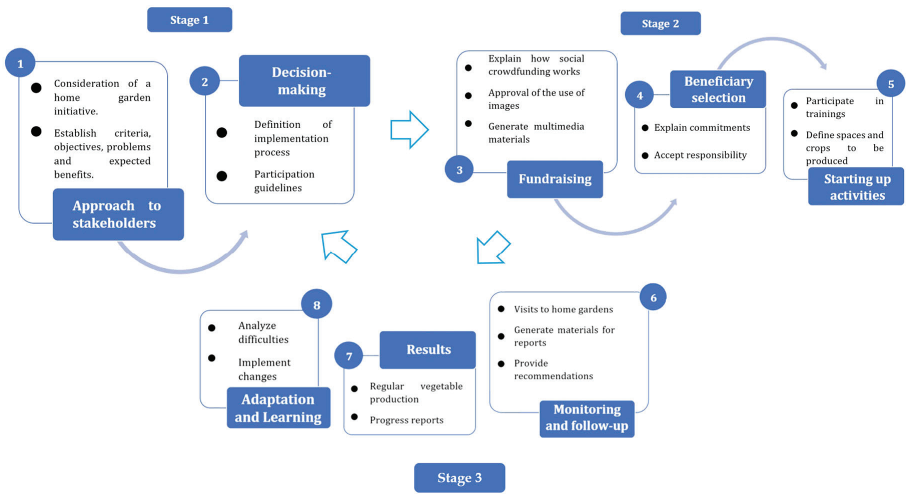

Figure 2. Theoretical model for home garden adoption.

2.2.1. Household Surveys

Quantitative data were collected through structured household surveys (Figure A1) conducted with 30 households in Vega del Sol, selected using a non-probabilistic snowball sampling method. While the sample size may appear modest, it was deemed appropriate given the rural and isolated nature of the community, allowing for an in-depth exploration of household-level impacts. The survey included sections on demographics (age, gender, income), the use of home gardens, crop diversity, and their impact on food security. Additionally, it focused on agricultural practices, such as types of crops grown and methods used, to assess how home gardens contributed to household sustenance. Special attention was paid to the economic benefits of home gardens, including cost savings on food and any income generated from surplus produce. This approach provided a comprehensive understanding of both the socio-economic and food security dynamics in the community, helping to evaluate the viability and effectiveness of home garden initiatives in improving local livelihoods.

2.2.2. Interviews and Focus Groups

Qualitative data were collected through semi-structured interviews (Figure A2) with a total of 30 participants, consisting of community authorities and key stakeholders actively involved in home gardening. These interviews aimed to gather insights into traditional agricultural practices, gender roles, decision-making processes, and the challenges faced by women in taking on leadership roles within the agricultural sector. The selection of participants was purposeful, targeting individuals who held significant influence in the community or were directly engaged in managing home gardens.

Additionally, focus group discussions (FGDs) were conducted with women and community leaders to explore the cultural significance of home gardens and to assess the potential of crowdfunding as a tool for supporting community-driven agricultural projects. Participants were also asked to rate their perceptions of home gardens on a 5-point Likert scale, evaluating their contributions to food security, household resilience, and income generation [38].

2.2.3. Food Security and Economic Data

Food security was assessed using an adapted methodology [39,40], tailored to the local context incorporating 5-point Likert scales [38], to measure food availability and accessibility. Data on the economic benefits of home gardens included reductions in food expenses, income generation from surplus sales, and market participation, focusing on how home gardens provide economic relief for households. Key socioeconomic indicators such as income, savings from self-sufficiency, and local market involvement were measured to analyze the gardens' economic impact on household livelihoods.

2.2.4. Crowdfunding Experiment

An experimental component was integrated into the study to assess the viability of social crowdfunding as a tool for financing home garden initiatives. Social crowdfunding, in this context, involves raising funds by appealing to a broad audience, typically through online platforms, to support specific community-driven projects. The crowdfunding campaign was carefully designed in collaboration with community members, with the primary goal of generating financial resources for expanding or improving home gardens [24,41].

The process began with the creation of a narrative that highlighted the importance of home gardens for food security, sustainability, and community resilience. This narrative was shared with potential donors through digital platforms and local networks, emphasizing the specific financial goals and timelines set for the campaign. The strategy involved engaging the community directly, both in the design and promotion phases, to foster local ownership and ensure active participation.

The pilot crowdfunding campaign aimed to raise funds specifically for the establishment of 30 home gardens. Key metrics for assessing the success of the crowdfunding approach included the total funds raised, the level of community engagement, and external support from broader networks. This campaign provided a framework for evaluating the potential of social crowdfunding as an ongoing resource for supporting future agricultural initiatives.

Crowdfunding was intended to be a flexible and adaptable tool, capable of being used in the long term whenever additional funding was required. Its implementation in this study was aimed at determining not only its immediate financial viability but also its potential for sustained community engagement and donor involvement over time.

2.3. Data Analysis

Quantitative data from the household surveys were analyzed using Microsoft Excel 2021 to identify trends in food security, crop diversity, and economic impact. Key socioeconomic indicators, such as income from home gardens and savings from self-sufficiency, were analyzed to assess the economic benefits to households. Qualitative data from interviews and FGDs were analyzed thematically to highlight the role of women in agricultural decision-making, community participation, and the preservation of traditional agricultural knowledge.

3. Results and Discussion

3.1. Evaluation of the Conceptual Model for Home Garden Adoption and Community Engagement

The conceptual model for home garden adoption and community engagement (Figure 2) was implemented in a structured manner, divided into three distinct phases. This approach was designed to ensure the long-term sustainability and success of home gardens within the community of Vega del Sol. The model focused on fostering active participation, particularly among women, in decision-making processes. By doing so, it aimed to enhance the overall functionality of home gardens and strengthen community engagement, setting the foundation for the subsequent phases.

3.1.1. Stage One: Organizational Foundations

In the initial phase, the model laid the groundwork by assessing family structures and community dynamics [42,43]. This stage was critical in identifying the space each family could allocate for the gardens, which ranged in size from 15 to 30 square meters, and understanding women's roles in decision-making. Traditionally, women have had limited involvement in agricultural decisions [44], but this phase established the importance of including them in the planning process [44–47]. A baseline of male and female beneficiaries' perceptions toward home gardens was generated (Table 1), highlighting the initial challenges women faced. Notably, of the 21 women participating, 38.10% rated their experience as "Bad" and "Very Bad", and 28.57% as "Regular". However, 33.33% perceived their involvement as "Good" or "Very Good", indicating that despite traditional barriers, many women saw the potential benefits of home gardens from the beginning [42]. These baseline perceptions were crucial in guiding gender inclusivity efforts and ensuring women's participation in the subsequent phases [12].

Table 1. Initial perception of home gardens based on gender.

Gender of the Beneficiary	Initial Perception	Counts	Percentage of Total (%)
Female (21)	Very bad	2	9.52
	Bad	6	28.57
	Regular	6	28.57
	Good	5	23.81
	Very good	2	9.52
Male (9)	Very bad	1	11.11
	Bad	1	11.11
	Regular	1	11.11
	Good	6	66.67
	Very good	0	0

3.1.2. Stage Two: Inclusive Planning and Strategy Development

During this phase, the model (Figure 3) emphasized active participation from all family members, particularly women. The participants who became directly involved were between the ages of 29 and 45, which facilitated the transmission of indigenous agricultural practices to younger generations. This active engagement helped ensure the preservation of traditional knowledge while integrating modern strategies. Women were involved in selecting crop varieties that would best suit local climatic conditions and meet household consumption needs [4,48].

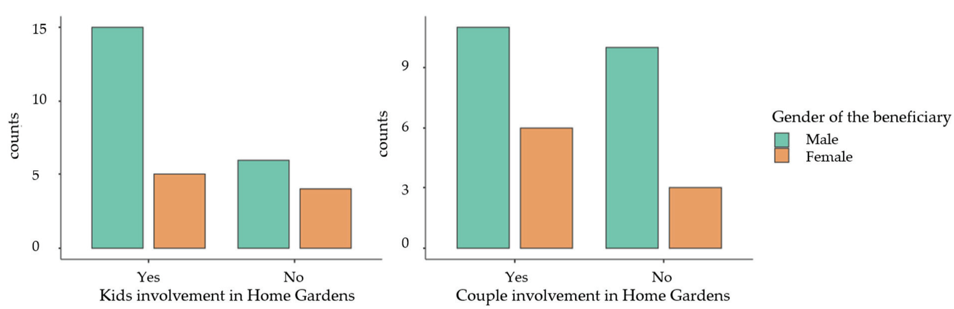

Figure 3. Participation and involvement of family members in home gardens.

In addition, financial strategies were developed to support long-term sustainability [24], with workshops on fundraising and financial management playing a pivotal role in the model's success [18,49,50]. The introduction of the crowdfunding component during this phase further strengthened community involvement, as it encouraged collective participation in raising funds for the development and expansion of home gardens [16,24,51].

3.1.3. Stage Three: Implementation and Community Empowerment

The final stage was focused on the actual implementation of home gardens. Women's roles in managing the gardens were strengthened and recognized by the community

(Figure 4), illustrating the shift in women's involvement from supportive tasks to taking leadership in decision-making processes at both the family and community levels. This empowerment of women not only enhanced their participation but also ensured that the gardens were effectively managed and sustained over time [52–54].

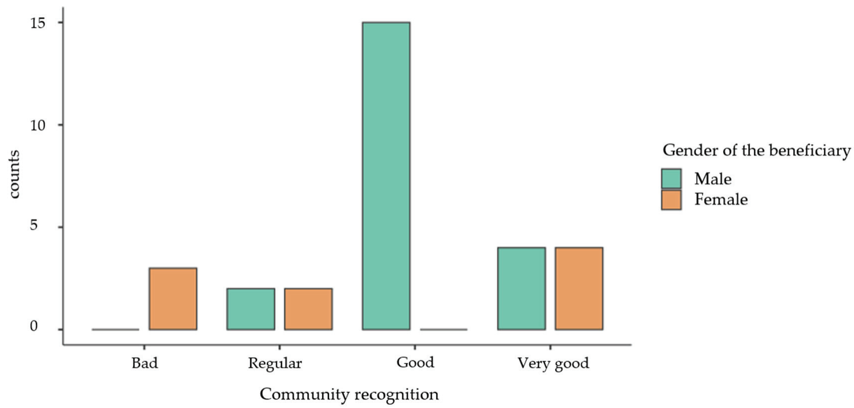

Figure 4. Recognition from the community for implementing home gardens.

The model incorporated a monitoring aspect to track the home garden activities and facilitated self-assessment, enabling participants to reflect on their progress, exchange experiences, and address challenges collectively. The community's ability to adapt and support each other played a crucial role in ensuring the long-term success of these gardens [19,47].

3.2. Impact of Home Gardens on Food Security and Economic Benefits

The analysis showed that 42.33% of households rated their access to food as "Good" and 23.33% rated it as "Very Good" highlighting the significant positive impact (70%) of home gardens on food security. Additionally, 46.67% of households reported that they experienced "Good" levels of savings due to home garden production, further reducing financial pressure from food expenses. These findings underscore the vital role that home gardens played in improving both food availability and economic stability for the surveyed households.

This shift allowed these families to reduce their reliance on external food sources. By providing consistent access to fresh, nutritious produce throughout the year, home gardens also strengthened household resilience, particularly during times of economic instability and fluctuating food prices [3,40].

Furthermore, improvements in food security were accompanied by notable economic benefits. A total of 76.67% of households (HH) reported successful crop harvests during the growing cycle, with many producing surplus vegetables that were sold in local markets. This not only supplemented household income but also strengthened the local food system, fostering sustainability and economic resilience within the community (Table 2).

Additionally, home gardens helped reduce food expenses by an average of 19.72%, as families relied less on external food sources. For simplicity, this reduction was rounded to approximately 20% in the text. Surplus produce sold in local markets generated extra income, which further contributed to the economic stability of these households [39,40]. Table 3 shows a notable increase in the percentage of households generating income from surplus sales compared to the initial stages of implementation, where few families reported any economic benefit from home gardens. This additional income not only provided families with the means to invest in other household needs, such as education or healthcare but also created a buffer against economic uncertainties, ultimately improving livelihoods.

Table 2. Contribution of home gardens to household food security and economic stability.

Measure	Level	HH Count Over *	Percentage of Total (%)
Availability of goods	Bad	3	10
	Regular	7	23.33
	Good	13	42.33
	Very good	7	23.33
Access to Healthy food	Bad	3	10
	Regular	7	23.33
	Good	14	46.67
	Very good	6	20
Savings due to production	Very bad	4	13.33
	Bad	3	10
	Regular	9	30
	Good	14	46.67
Harvest obtained during the cycle	Yes	23	76.67
	No	7	23.33

* Number of households exhibiting the specified characteristics. $n = 30$ households.

Table 3. Relation of income and expenditure per family for food needs.

HH	ANIH * (MXN $)	MFEH * (MXN $)	MVEH * (MXN $)	IIH * (MXN $)	SFPI * (MXN $)	ISSL * (MXN $)	CIHI * (MXN $)
1	11,236	10,716	1530	1400	130	347	477
2	11,008	10,644	1479	1400	79	438	517
3	10,913	10,356	1492	1400	92	313	405
4	10,947	9804	1582	1400	182	427	609
5	10,800	9612	1384	1400	−16	136	120
6	10,410	9828	1600	1400	200	274	474
7	11,389	10,098	1331	1400	−69	256	187
8	10,397	10,788	1306	1400	−94	265	171
9	10,009	9750	1555	1400	155	-	155
10	10,156	9816	1393	1400	−7	153	146
11	11,068	10,188	1561	1400	161	266	427
12	9987	10,122	1444	1400	44	458	502
13	10,458	10,776	1338	1400	−62	-	−62
14	11,449	9804	1593	1400	193	-	193
15	11,192	9780	1413	1400	13	378	391
16	11,005	10,104	1491	1400	91	399	490
17	11,468	9936	1368	1400	−32	352	320
18	10,073	9810	1419	1400	19	308	327
19	10,009	10,596	1439	1400	39	-	39
20	11,034	10,512	1320	1400	−80	426	346
21	10,766	10,188	1465	1400	65	381	446
22	10,765	10,122	1516	1400	116	243	359
23	11,472	10,140	1457	1400	57	-	57
24	10,508	9984	1534	1400	134	428	562
25	10,867	9732	1357	1400	−43	425	382
26	10,004	10,614	1475	1400	75	257	332
27	10,265	9762	1339	1400	−61	-	−61
28	11,016	10,416	1412	1400	12	-	12
29	10,129	10,308	1436	1400	36	250	286
30	10,837	10,242	1507	1400	107	-	107

* ANIH = Average Net Income per Household; MFEH = Monthly Food Expenses per Household; MVEH = Monthly Vegetable expenses per Household; IIH = Initial investment per Home Garden; SFPI = Savings from production after Investment; ISSL = Income from Surplus Sales in Local Market; and CIHI = Contribution or improvement to Household income. Household income calculations are based on a family size of six people. Amounts are in Mexican pesos (MXN).

Furthermore, the practice of selling surplus produce strengthened local market participation, fostering stronger connections within the local economy. This dynamic reinforced community ties, as households became active contributors to the local food system. It also promoted sustainability through localized food production, reducing dependency on external food sources and encouraging circular economies within the community [2,55]. The economic benefits, combined with improved food security, highlight the holistic impact of home gardens on both household and community well-being, as shown in Table 3.

Crop diversity was also noted as a key factor, with households cultivating a variety of fruits (Table 4), vegetables, and medicinal plants. This diversity not only improved household nutrition but also reduced reliance on external food sources, further contributing to food security [38,41]. The inclusion of medicinal plants such as plants such as Blackberry herb (*Solanum nigrescens*) and Acuyo or hierba santa (*Piper auritum*) was particularly important, as it allowed families to access natural remedies, which could in turn reduce healthcare costs and enhance overall well-being [56]. Additionally, the cultivation of a wide range of crops such as staple grains like corn (*Zea mays*) and beans (*Phaseolus* spp.) provides resilience against seasonal changes and climate variability, ensuring that households have a consistent food supply throughout the year. This diversity also fostered the preservation of local plant species such as sweet potato (*Ipomea batata*), cassava (*Manihot esculenta*), and chayote (*Sechium edule*) and agricultural knowledge, further promoting sustainable agricultural practices within the community.

Table 4. Identified crops at the community level for home gardens.

Category	Common Name	Scientific Name	Plant Number
Fruit trees	Citrus fruits (sweet lemon and sweet orange)	*Citrus* spp.	+++
	Citrus (sour orange)	*Citrus* sp.	++
	Mango	*Mangifera indica*	++
	Jinicuil	*Inga jinicuil*	++
	Guava	*Psidium guajava*	++
	Papaya	*Carica papaya*	+
	Soursop	*Annona muricata*	+
	Mamey	*Pouteria sapota*	+
	Anona	*Annona reticulata*	+
	Tamarind	*Tamarindus indica*	+
	Mexican avocado	*Persea* sp.	++
	Plum	*Spondia*	++
	Carambola	*Averrhoa carambola*	+
	Lychee	*Litchi chinensis*	+
	Pink Poma	*Syzygium jambos*	+
	White cocoa	*Theobroma bicolor*	+
	Cocoa	*Theobroma cacao*	+
	Purple plantain	*acuminata/balbisiana*	+
	Annatto	*Bixa orellana*	+
	Coffee	*Coffea arabica* *Coffea robusta*	+
	Posole leaf	*Calathea lutea*	+
	Jicara	*Crescentia cujete*	+
	Chikal	*Lagenaria siceraria*	+
Plants (edible or medicinal)	Blackberry herb	*Solanum nigrescens*	++
	Fitolaca	*Phytolacca icosandra*	+
	Smells at night	*Cestrum nocturnum*	+
	Quintonil, white quelite	*Amaranthus hybridus*	++
	Quelite de venado	*Ipomea* sp.	+
	Chipil or Chepil	*Crotalaria* sp.	++
	Purslane	*Portulaca oleracea*	+
	Chayote	*Sechium edule*	+
	Pumpkin	*Cucurbita moschata*	+
	Passion fruit or Palau	*Passiflora edulis*	+
	Watermelon	*Citrullus lanatus*	+
	Coconut	*Cocos nucifera*	+
	Tepejilote	*Chameadora tepijilote*	+
	Huasmole, Huele mole	*Renealmia alpinia*	+
	Nopal tres lobos or pitaya	*Hylocereus undatus*	+
	Tomato	*Solanum lycopersicon*	+
	Guaje	*Luecaena esculenta*	+
	Acuyo or hierba santa	*Piper auritum*	+
	Mint or spearmint	*Mentha viridis*	+
	Oregano orejón or vaporub plant	*Ocinum* sp.	++
	Chile	*Capsicum annuum*	+
	Chives	*Allium* sp.	+
	Epazote	*Dysphania ambrosioides*	+
	Basil	*Ocimum basilicum*	+
	Cilantro de monte or bull's coriander	*Eryngium foetidum*	+
	Cinnamon	*Cinnamomum verum*	+
	Coriander	*Coriandrum sativum*	+
Grains	Corn	*Zea mays*	+++
	Beans	*Phaseolus coccineus* *Phaseolus vulgaris*	+++
Roots	Malanga	*Colocasia esculenta*	++
	Sweet potato	*Ipomea batata*	++
	Cassava	*Manihot esculenta*	++
	Jicama	*Pachyrhizus erosus*	+

(+++) more than 20 plants per home garden, (++) between 6 and 19 plants per home garden, (+) one to 5 plants per home garden.

3.3. Role of Women in Agricultural Management and Decision-Making

The implementation model (Figure 2) was particularly effective in transforming the role of women within agricultural management. Prior to the initiative, women had limited involvement in agricultural decision-making, as these roles were typically reserved for men [52–54]. However, through the model's inclusive planning and training efforts, women became more actively involved in selecting crops, organizing garden maintenance, and managing finances related to surplus produce sales [18,52,57].

A notable shift in women's roles and perceptions was observed when comparing the initial perceptions in Table 1 to the final results in Table 5. Initially, Table 1 showed that 38.10% of 21 women rated their involvement in agricultural decision-making as "Bad" or "Very Bad", while only 33.33% viewed their participation as "Good" or "Very Good". However, after the implementation, Table 5 reveals a marked improvement: the percentage of women rating their involvement as "Bad and Very Bad" dropped to 4.76%, while those rating it as "Regular" increased to 38.10%. Notably, 57.14% of women now rated their involvement in agricultural management as "Good" or "Very Good", highlighting the success in empowering women.

Table 5. Final perception of home gardens based on gender.

Gender of the Beneficiary	Final Perception	Counts	Percentage of Total (%)
Female (21)	Bad	1	4.76
	Regular	8	38.10
	Good	10	47.62
	Very good	2	9.52
Male (9)	Bad	0	0
	Regular	1	11.11
	Good	3	33.33
	Very good	5	55.56

This shift in gender roles and increased engagement in decision-making contributed significantly to the women's sense of empowerment and their ability to lead agricultural initiatives, not only within the household but also at the community level [12]. The improved perception of women regarding their roles in home gardens demonstrates the model's effectiveness in fostering inclusive agricultural management and leadership.

Beyond the household, women also became more engaged in community meetings where key agricultural and development decisions were made. The model emphasized the importance of women's participation in these forums, ensuring that they had the opportunity to voice their opinions and contribute to collective decision-making processes [57]. As a result, women began to take on more visible leadership roles within the community, influencing broader agricultural policies and community planning efforts. Their involvement in these meetings not only expanded their influence but also strengthened community cohesion by ensuring that a wider range of perspectives was considered in the decision-making process as mentioned in similar studies related to gender [18,54].

This increased participation allowed women to advocate for resources, training, and support that aligned with their families' needs, particularly in terms of food security and sustainable agricultural practices. The ability to speak in community assemblies and influence agricultural policies is a critical step toward gender equity in the community. Furthermore, this engagement contributed to a more inclusive and resilient community structure, where women's contributions were recognized as vital to both the economic and social development of the community [12,45,52,58].

3.4. Preservation of Traditional Agricultural Knowledge

The initiative played a crucial role in preserving and transmitting traditional agricultural knowledge, particularly through the active participation of elder community members. One key practice passed down was seed saving. Elders shared techniques for selecting, storing, and maintaining seeds from one season to the next, ensuring the availability of resilient, locally adapted varieties. This practice reduced dependence on external seed sources and contributed to maintaining biodiversity within the home gardens [59,60].

The involvement of both men and women in these seed recovery efforts was significant, as illustrated in Figure 5, which shows the participation of male and female household members in the recovery of local seeds and plants. The figure highlights that women played a crucial role in ensuring the continuity of these practices. This collaborative effort between genders emphasizes the collective responsibility to preserve biodiversity and maintain the resilience of home gardens.

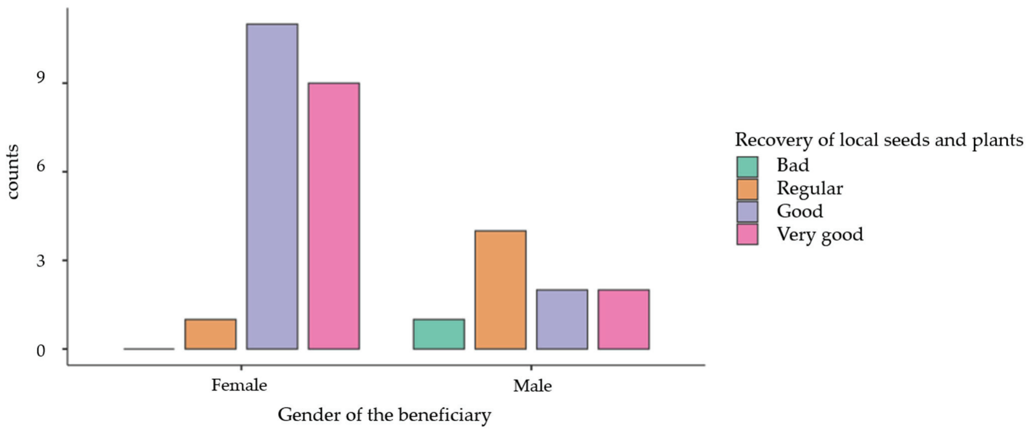

Figure 5. Involvement of males and females in recovery of local seeds.

Women were particularly essential in integrating traditional seed-saving practices into modern agricultural activities, facilitating the transmission of knowledge to younger generations. This intergenerational transfer of knowledge not only helped to maintain the genetic diversity of crops but also contributed to the long-term ecological resilience of the community's agricultural systems [15,61,62]. Through their active participation, women helped safeguard both the cultural heritage and environmental sustainability of their home gardens.

Moreover, the involvement of women in this process was essential. Women played a key role in ensuring that seed-saving traditions were integrated into modern agricultural practices and shared with younger generations, thereby contributing to both the cultural sustainability of the community and the ecological resilience of the home gardens.

Another significant contribution was the knowledge of organic pest control methods [63–65]. Elders passed down techniques to younger generations on how to use natural ingredients like herbs in biocompounds and companion planting to manage pests without relying on chemical pesticides. These organic practices promoted ecological balance and soil health in the home gardens, while also reducing costs for families by eliminating the need for expensive chemical treatments.

The use of biocompounds in home gardens, classified by the gender of the person responsible within the household, highlights the notable involvement of women in adopting and applying these organic methods (Figure 6). The data reveal that a significant proportion of women-led households were responsible for the use of biocompounds, illustrating their central role in implementing sustainable pest control practices. This gender-based analysis reflects how women's participation in agricultural management has expanded beyond traditional roles, contributing directly to the ecological health of the home gardens.

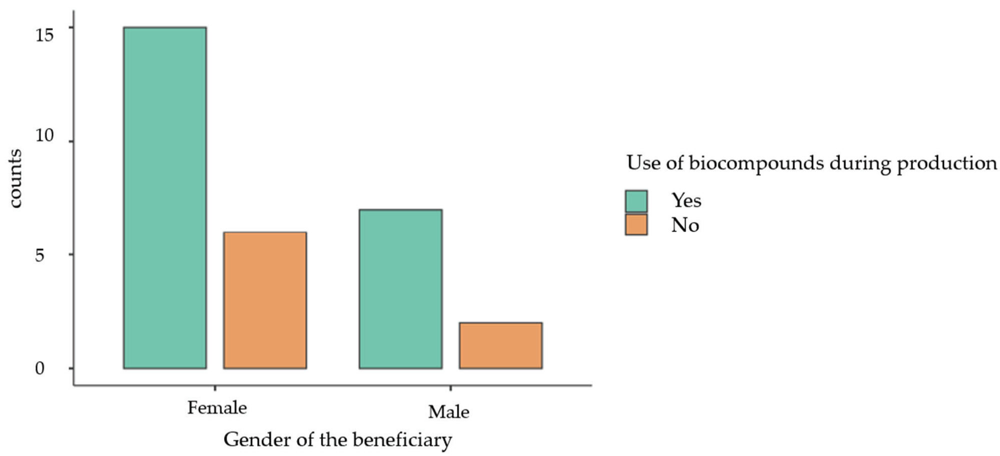

Figure 6. Inclusion of biocompounds in home gardens.

The widespread adoption of biocompounds underscores the importance of these organic methods [63,66,67] in maintaining soil quality and reducing pest infestations (Figure 6). Women, who were primarily responsible for daily garden activities, were integral in ensuring the success of these practices. Their involvement not only strengthened their leadership in agricultural decision-making but also fostered a more sustainable and cost-effective approach to pest management within the community [52,58].

3.5. Crowdfunding Experiment and Community Resilience

The pilot crowdfunding campaign was successful in raising sufficient funds to establish 30 home gardens [24]. It demonstrated that crowdfunding is a viable tool for financing community-led agricultural projects and increasing participation in local initiatives [68]. The community actively contributed both financially and through in-kind support, such as labor for garden construction and maintenance [51]. This collective involvement strengthened a sense of ownership, with the gardens being viewed as a shared community resource rather than individual family assets.

The campaign also fostered collective responsibility and resilience within the community [69]. Working together to raise funds and implement the gardens created trust and solidarity, as the shared goal of improving food security united participants in mutual support and collaboration [70]. By relying on internal resources and reducing dependence on external institutions, the crowdfunding initiative overcame traditional barriers to funding in rural communities [21,71].

Additionally, the campaign raised awareness of food security issues and attracted external supporters interested in sustainable agricultural practices [25,68]. This external involvement expanded the community's network and brought new resources, fostering connections with organizations interested in food sovereignty and sustainability [72].

Managing the funds and implementing the gardens promoted transparency and strengthened social bonds, as community members worked side-by-side, sharing knowledge and troubleshooting challenges. The success of this initiative not only improved food security and economic opportunities but also laid the foundation for future collaborative initiatives in the community.

4. Conclusions

This study demonstrates that home gardens play a critical role in enhancing food security, economic stability, and the preservation of traditional agricultural knowledge in rural Oaxaca. By integrating community-driven initiatives with modern crowdfunding mechanisms, the project empowered women to take on more active leadership roles in agricultural decision-making, thus contributing to sustainable rural development. The increased involvement of women in managing home gardens not only improved household food production but also enhanced their influence on broader agricultural policies within the community, aligning with the objectives of SDG 5 (Gender Equality) by promoting greater inclusivity and equity.

The revitalization of home gardens resulted in notable improvements in household food security, with over 70% of households reporting improved access to fresh and nutritious produce, alongside a 20% reduction in food-related expenditures. Furthermore, the surplus production of crops offered families additional income streams, thus contributing to economic stability and resilience, in support of SDG 1 (No Poverty) and SDG 2 (Zero Hunger). The findings highlight the utility of crowdfunding as an effective financial mechanism for rural communities, enabling them to overcome traditional barriers to funding while fostering social cohesion and collective ownership of agricultural initiatives.

Moreover, the project facilitated the preservation of traditional agricultural practices, such as seed saving and organic pest control, which contributed not only to ecological sustainability but also to the safeguarding of cultural heritage. These practices, alongside the fostering of intergenerational knowledge exchange, reinforced the long-term resilience of home gardens, supporting the objectives of SDG 15 (Life on Land), which emphasizes biodiversity conservation through sustainable land-use practices.

While the study is focused on rural Oaxaca, the results offer valuable lessons with broader international implications. Rural and indigenous communities worldwide face similar challenges, such as food insecurity, environmental degradation, and the marginalization of women in agricultural leadership. The integration of traditional agricultural practices with crowdfunding presents a replicable model for addressing these global challenges. Communities in diverse settings could benefit from applying the strategies demonstrated in this study, making this research relevant not only in Mexico but also on an international scale. By implementing these strategies, communities across the globe can address contemporary socio-economic and environmental challenges while preserving cultural heritage and promoting resilience.

However, this study is not without limitations. Conducted as a pilot project in a geographically isolated and marginalized community, the scope and sample size were constrained, which limits the generalizability of the findings to other regions with differing socio-economic or environmental conditions. Additionally, the relatively short duration of the study limited the ability to assess the long-term sustainability of home gardens. Future research should address these limitations by undertaking larger-scale, longitudinal studies across diverse rural settings, incorporating a broader range of socio-economic and environmental variables to provide a more comprehensive understanding of the role of home gardens in achieving sustainable development goals.

In conclusion, this research highlights the transformative potential of home gardens in promoting food security, empowering women, and supporting sustainable agricultural practices. By leveraging community-driven initiatives and crowdfunding, rural communities worldwide can address contemporary socio-economic and environmental challenges, while preserving cultural heritage and fostering long-term resilience.

Author Contributions: Conceptualization, M.A.A.-O. and Y.D.O.-H.; Data curation, C.A.G.-E.; Formal analysis, M.A.A.-O. and Y.D.O.-H.; Funding acquisition, F.E.O.-H.; Investigation, M.A.A.-O., G.L.-E., F.E.O.-H. and C.A.G.-E.; Resources, Y.D.O.-H. and R.P.-P.; Supervision, R.P.-P.; Validation, G.L.-E.; Writing—original draft, M.A.A.-O.; Writing—review and editing, M.A.A.-O., G.L.-E. and Y.D.O.-H. All authors will be informed about each step of manuscript processing including submission, revision, revision reminder, etc. via emails from our system or assigned Assistant Editor. All authors have read and agreed to the published version of the manuscript.

Funding: This research was financed by EcoLogic Development Fund 2021-2022 on the GlobalGiving platform 36387 with social crowdfunding. The first author received a postdoctoral fellowship 216103 from CONAHCYT, at the Instituto Politécnico Nacional CIIDIR Oaxaca SIP20220404.

Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Secretaría de Investigación y Posgrado of the Insituto Politénico Nacional with the reference number SIP20220404.

Informed Consent Statement: The consent of the participants was obtained to carry out the study and gather information.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: We acknowledge the backing of the EcoLogic Development Fund, Fondo Ambiental Regional de la Chinantla, Oaxaca, A.C., and the Instituto Politécnico Nacional for their support; as well as Consejo Nacional de Humanidades Ciencias y Tecnologías (CONAHCYT) and Sistema Nacional de Investigadoras e Investigadores (SNII-CONAHCYT).

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Household Survey: Home Gardens and Economic Benefits in Vega del Sol

Section 1: Demographics

1. **How many people live in your household?**
   ☐ 1–2 ☐ 3–5 ☐ 6–8 ☐ +8
2. **What is the gender of the head of the household?**
   ☐ Male ☐ Female
3. **What is the primary source of income for your household?**
   ☐ Agriculture ☐ Wage labor ☐ Business ☐ Remittances ☐ Other
4. **Average monthly household income (MXN):**
   ☐ 0–2000 ☐ 2000–5000 ☐ 5001–10,000 ☐ +10,000

Section 2: Home Garden Use

5. **Do you have a home garden?**
   ☐ Yes ☐ No
6. **How long have you had your home garden?**
   ☐ 0–1 year ☐ 1–3 years ☐ 3–5 years ☐ +5 years
7. **What types of crops do you grow?**
   ☐ Vegetables ☐ Fruits ☐ Medicinal plants ☐ Herbs ☐ Other
8. **What percentage of your food comes from the garden?**
   ☐ 0–25% ☐ 25–50% ☐ 50–75% ☐ +75%

Section 3: Economic Impact

9. **How much do you save on food due to the home garden (MXN/month)?**
   ☐ 0–500 ☐ 500–1000 ☐ 1000–2000 ☐ +2000
10. **Do you sell surplus produce?**
    ☐ Yes ☐ No
11. **If yes, how much additional income do you generate (MXN/month)?**
    ☐ 0–500 ☐ 500–1000 ☐ 1000–2000 ☐ +2000

Section 4: Household Resilience

12. **Has your home garden helped during times of food shortage?**
    ☐ Yes, significantly ☐ Yes, slightly ☐ No
13. **Has the home garden improved your household's financial stability?**
    ☐ Yes ☐ No ☐ Not sure

Figure A1. Format for Structured Household Surveys.

Focus Group Questionnaire: Home Gardens and Community Leadership

---

Section 1: Demographics

1. **Age:**
☐ 18–30 ☐ 31–45 ☐ 46–60 ☐ +60

2. **Gender:**
☐ Male ☐ Female

3. **Role in the Community:**
☐ Community leader ☐ Home Garden manager ☐ Other (specify) _________

Section 2: Home Gardens and Food Security

4. **How do home gardens contribute to your household's food security?**

---

5. **To what extent do home gardens reduce your household's need to buy food?**
☐ Very Bad ☐ Bad ☐ Regular ☐ Good ☐ Very Good

6. **How would you rate the impact of home gardens on the quality of food (e.g., diversity, freshness)?**
☐ Very Bad ☐ Bad ☐ Regular ☐ Good ☐ Very Good

Section 3: Economic Impact of Home Gardens

7. **Have you been able to sell surplus produce from your garden?**
☐ Yes ☐ No

8. **If yes, how much income do you generate from surplus sales in a typical growing cycle?**

---

9. **How would you rate the overall economic benefit of your home garden?**
☐ Very Bad ☐ Bad ☐ Regular ☐ Good ☐ Very Good

Section 4: Leadership and Decision–Making

10. **Has your role in managing a home garden increased your participation in household decision–making?**
☐ Yes ☐ No ☐ Not Sure

11. **How would you rate the involvement of women in agricultural decision–making within your community?**
☐ Very Bad ☐ Bad ☐ Regular ☐ Good ☐ Very Good

Section 5: Crowdfunding and Community Initiatives

12. **Are you familiar with crowdfunding as a tool to support agricultural projects?**
☐ Yes ☐ No

13. **How would you rate crowdfunding's potential to expand home garden initiatives in your community?**
☐ Very Bad ☐ Bad ☐ Regular ☐ Good ☐ Very Good

Figure A2. Questionnaire Format for Semi-Structured Focus Groups.

References

1. Korpelainen, H. The Role of Home Gardens in Promoting Biodiversity and Food Security. *Plants* **2023**, *12*, 2473. [CrossRef]
2. Montagnini, F. Homegardens of Mesoamerica: Biodiversity, Food Security, and Nutrient Management. In *Tropical Homegardens. Advances in Agroforestry*; Kumar, B.M., Nair, P.K.R., Eds.; Springer Netherlands: Dordrecht, The Netherlands, 2006; Volume 3, pp. 61–84. [CrossRef]
3. Galhena, D.H.; Freed, R.; Maredia, K.M. Home Gardens: A Promising Approach to Enhance Household Food Security and Wellbeing. *Agric. Food Secur.* **2013**, *2*, 8. [CrossRef]
4. Aguilar-Støen, M.; Moe, S.R.; Camargo-Ricalde, S.L. Home Gardens Sustain Crop Diversity and Improve Farm Resilience in Candelaria Loxicha, Oaxaca, Mexico. *Hum. Ecol.* **2009**, *37*, 55–77. [CrossRef]
5. Castañeda-Navarrete, J. Homegarden Diversity and Food Security in Southern Mexico. *Food Secur.* **2021**, *13*, 669–683. [CrossRef] [PubMed]
6. Niñez, V. Household Gardens: Theoretical and Policy Considerations. *Agric. Syst.* **1987**, *23*, 167–186. [CrossRef]
7. Gil-García, Ó.F.; Akalin, N.; Bové, F.; Vener, S. Understanding the Mobilities of Indigenous Migrant Youth across the Americas. *Soc. Sci.* **2024**, *13*, 91. [CrossRef]
8. Selod, H.; Shilpi, F. Rural-Urban Migration in Developing Countries: Lessons from the Literature. *Reg. Sci. Urban Econ.* **2021**, *91*, 103713. [CrossRef]
9. Meza-Jiménez, M.D.L.; Pacheco-Cruz, R. Aspectos Socioeconómicos y de Seguridad Alimentaria En Comunidades de Muy Alta Marginación Pertenecientes a Oaxaca, México. *Salud Adm.* **2021**, *8*, 3–14.
10. Calvet-Mir, L.; Riu-Bosoms, C.; González-Puente, M.; Ruiz-Mallén, I.; Reyes-García, V.; Molina, J.L. The Transmission of Home Garden Knowledge: Safeguarding Biocultural Diversity and Enhancing Social–Ecological Resilience. *Soc. Nat. Resour.* **2016**, *29*, 556–571. [CrossRef]

11. de Grammont, H.C. La evolución de la producción agropecuaria en el campo mexicano: Concentración productiva, pobreza y pluriactividad. *Andamios* **2010**, *7*, 85–117. [CrossRef]
12. Cruz-Yáñez, L.A. El Papel de Las Mujeres En Los Huertos Familiares. *Altern. Psicol.* **2016**, *4*, 46–60.
13. Alberti-Manzanares, P.; Hernandez, M.Z.; Salcido-Ramos, B.; Real-Luna, N. Género, Economía Del Cuidado y Pago Del Trabajo Doméstico Rural En Jilotepec, Estado de México. *Agric. Soc. Desarro.* **2014**, *11*, 379–400. [CrossRef]
14. Ruiz-López, P.; Pullas-Tapia, P.; Parra-Parra, C.A.; Zamora-Sánchez, R. La Doble Presencia En Las Trabajadoras Femeninas: Equilibrio Entre El Trabajo y La Vida Familiar. *Rev. Comun. SEECI* **2017**, *1*, 33–51. [CrossRef]
15. Reina-Aoyama, L. Las Mujeres Zapotecas Del Istmo de Tehuantepec—México En El Siglo XIX. Available online: https://journals.openedition.org/nuevomundo/68503 (accessed on 20 August 2024).
16. Lugo-Espinosa, G.; Acevedo-Ortiz, M.A.; Ortiz-Hernández, Y.D.; Aquino-Bolaños, T. Huertos Familiares y Participación Comunitaria Para La Generación de Medios de Vida Sostenibles. In *Los Objetivos del Desarrollo Sostenible Versus la Pandemia de la COVID-19*; Tavera-Cortés, M.E., Ed.; ASMIIA: Texcoco, México, 2023; pp. 125–138. ISBN 978-607-596-753-0.
17. Castro-Apreza, I. La Participación Política de Las Mujeres Indígenas En México: Oportunidades y Desafíos. *Desacatos* **2011**, *1*, 215–221.
18. El Khateeb, S.; Saber, M.; Shawket, I.M. Urban Reflections through Home Gardening; Does Gender Matter? *Ain Shams Eng. J.* **2023**, *14*, 101885. [CrossRef]
19. Gripenberg, L. Social Change of an Indigenous Community: A Case Study of the Community-Based Cooperative "Millennial Women" in Oaxaca, Mexico. Bachelor's Thesis, Lund Universitet, Lund, Sweden, 2019.
20. Filimonova, N.G.; Ozerova, M.G.; Ermakova, I.N.; Miheeva, N.B. Crowdfunding as the Way of Projects Financing in Agribusiness. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *315*, 022098. [CrossRef]
21. Hamlin, N.; Lake, B. An Initial Investigation into GlobalGiving's Impact on Nonprofit Organizations. Available online: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3252703 (accessed on 24 September 2024).
22. Li, Y.M.; Wu, J.D.; Hsieh, C.Y.; Liou, J.H. A Social Fundraising Mechanism for Charity Crowdfunding. *Decis. Support Syst.* **2020**, *129*, 113170. [CrossRef]
23. Motylska-Kuzma, A. Crowdfunding and Sustainable Development. *Sustainability* **2018**, *10*, 4650. [CrossRef]
24. Acevedo-Ortiz, M.A.; Lugo-Espinosa, G.; Ortiz-Hernández, Y.D.; Pérez-Pacheco, R. Construyendo Capacidades Locales Para Obtener Financiamiento Colectivo e Implementar Huertos Familiares En La Chinantla, Oaxaca. In *Los Objetivos del Desarrollo Sostenible Versus la Pandemia de la COVID-19*; Tavera-Cortés, M.E., Ed.; ASMIIA: Texcoco, México, 2023; pp. 112–124. ISBN 978-607-596-753-0.
25. Iniesta, J.M.E.; Peñalver, A.J.B.; Gómez, E.H. La Financiación Del Emprendimiento Social: Estudio de La Comunicación y El Uso de Las Redes Sociales En La Plataforma de Crowdfunding "Goteo". *CIRIEC-Esp. Rev. Econ. Pública Soc. Coop.* **2022**, *1*, 199–233. [CrossRef]
26. Sánchez, W.M.; Tonon, L.B. Señalización y El Éxito de Las Campañas de Crowdfunding Latinoamericano. *RETOS Rev. Cienc. Adm. Econ.* **2020**, *10*, 99–116. [CrossRef]
27. Estados Unidos Mexicanos DECRETO Por El Que Se Formula La Declaratoria de Las Zonas de Atención Prioritaria Para El Año 2023. Available online: https://dof.gob.mx/nota_detalle.php?codigo=5672639&fecha=28/11/2022#gsc.tab=0 (accessed on 30 June 2023).
28. Pueblos América. Santa María Jacatepec. Vega Del Sol. Available online: https://mexico.pueblosamerica.com/i/vega-del-sol/ (accessed on 30 October 2024).
29. DataMéxico Santa María Jacatepec: Economía, Empleo, Equidad, Calidad de Vida, Educación, Salud y Seguridad Pública. Data México. Available online: https://www.economia.gob.mx/datamexico/es/profile/geo/santa-maria-jacatepec (accessed on 30 October 2024).
30. MIDO-Sistema de Monitoreo de Indicadores de Desempeño de Oaxaca. Available online: https://mido.oaxaca.gob.mx/home/ (accessed on 21 July 2024).
31. Acevedo-Ortiz, M.A.; Lugo-Espinosa, G.; Ortiz-Hernández, Y.D.; Pérez-Pacheco, R.; Ortiz-Hernández, F.E.; Martínez-Tomás, S.H.; Tavera-Cortés, M.E. Nature-Based Solutions for Conservation and Food Sovereignty in Indigenous Communities of Oaxaca. *Sustainability* **2024**, *16*, 8151. [CrossRef]
32. Cedeño-Valdiviezo, A.; Torres-Lima, P. La Chinantla Oaxaqueña: La Historia de Un Patrimonio Perdido. *Diseño Soc.* **2015**, *1*, 54–61.
33. Hernández-Montiel, J.L. La Chinantla, Fuente de Agua, Fuente de Vida. Available online: https://agua.org.mx/biblioteca/la-chinantla-fuente-de-agua-fuente-de-vida-sp-5128/ (accessed on 10 October 2024).
34. Berget, C.; Duran, E.; Bray, D.B. Participatory Restoration of Degraded Agricultural Areas Invaded by Bracken Fern (Pteridium Aquilinum) and Conservation in the Chinantla Region, Oaxaca, Mexico. *Hum. Ecol.* **2015**, *43*, 547–558. [CrossRef]
35. Acevedo-Ortiz, M.A.; Lugo-Espinosa, G.; Ortiz-Hernández, Y.D. Percepciones Comunitarias Sobre Mecanismos de Conservación de Recursos Naturales Bajo Un Enfoque Paisajístico En Tres Ejidos de La Chinantla, Oaxaca. In *Aproximaciones Teórico-Metodológicas para el Análisis Territorial y el Desarrollo Regional Sostenible*; Martínez-Pellegrini, S.E., Sarmiento-Franco, J.F., Valles-Aragón, M.C., Eds.; Recuperación transformadora de los territorios con equidad y sostenibilidad; Universidad Nacional Autónoma de México, Instituto de Investigaciones Económicas y Asociación Mexicana de Ciencias para el Desarrollo Regional: Ciudad de México, Mexico, 2021; Volume 1, pp. 1–18. ISBN 978-607-30-5332-7.

36. Lugo-Espinosa, G.; Acevedo-Ortiz, M.A.; Aquino-Bolaños, T.; Ortiz-Hernández, Y.D.; Ortiz-Hernández, F.E.; Pérez-Pacheco, R.; López-Cruz, J.Y. Cultural Heritage, Migration, and Land Use Transformation in San José Chiltepec, Oaxaca. *Land* **2024**, *13*, 1658. [CrossRef]
37. Evso Estadísticas de Vega Del Sol, Santa María Jacatepec, Oaxaca. Available online: https://mexico.pueblosamerica.com/i/vega-del-sol/ (accessed on 30 June 2023).
38. Matas, A. Diseño Del Formato de Escalas Tipo Likert: Un Estado de La Cuestión. *Rev. Electron. Investig. Educ.* **2018**, *20*, 38–47. [CrossRef]
39. Aguilar-Estrada, A.E.; Caamal-Cauich, I.; Barrios-Puente, G.; Ortiz-Rosales, M.A. ¿Hambre En México? Una Alternativa Metodológica Para Medir Seguridad Alimentaria. *Estud. Soc. Rev. Aliment. Contemp. Desarro. Reg.* **2019**, *29*, 2–26. [CrossRef]
40. Shamah-Levy, T.; Mundo-Rosas, V.; Flores-De la Vega, M.M.; Luiselli-Fernández, C. Food Security Governance in Mexico: How Can It Be Improved? *Glob. Food Secur.* **2017**, *14*, 73–78. [CrossRef]
41. Home Gardens for 100 Families, Oaxaca, Mexico. Available online: https://www.objective.earth/Home_Gardens_for_100_Families,_Oaxaca,_Mexico/ (accessed on 30 October 2024).
42. Acevedo-Ortiz, M.A.; Lugo-Espinosa, G.; Ortiz-Hernández, Y.D.; Ortiz-Hernández, F.E. *Herramientas Metodológicas En Procesos Participativos En Comunidades Rurales Para La Conservación de Recursos Naturales*; Tavera-Cortés, M.E., Ed.; Editorial ASMIIA: Texcoco, Estado de México, 2022; pp. 93–106. ISBN 978-607-99921-0-1.
43. González, B.; Peña, M.; Rincón, N.; Bustillo, L.; Urdaneta, F. Formulación de Lineamientos Estratégicos Para El Desarrollo Rural, Basado En Una Metodología Participativa. *Rev. Fac. Agron.* **2004**, *21*, 398–414.
44. Jayachandran, S. Social Norms as a Barrier to Women's Employment in Developing Countries. *IMF Econ. Rev.* **2021**, *69*, 576–595. [CrossRef]
45. Anand, M.; Mecagni, A.; Piracha, M. *Practical Tools and Frameworks for Measuring Agency in Women's Economic Empowerment*; SEEP Network: Camberwell, Australia, 2019.
46. Cronkleton, P.; Evans, K.; Addoah, T.; Dumont, E.S.; Zida, M.; Djoudi, H. Using Participatory Approaches to Enhance Women's Engagement in Natural Resource Management in Northern Ghana. *Sustainability* **2021**, *13*, 7072. [CrossRef]
47. Kirkwood, E.K.; Dibley, M.J.; Khatun, W.; Ara, G.; Khanam, M.; Bokshi, A.; Li, M.; Alam, N.A. Can a Combined Agriculture and Nutrition Behaviour Change Intervention Improve Women's Empowerment? A Mixed Methods Feasibility Study in Rural Bangladesh. *Qual. Rep.* **2022**, *27*, 2905–2922. [CrossRef]
48. Alesina, A.; Giuliano, P.; Nunn, N. On the Origins of Gender Roles: Women and the Plough. *Q. J. Econ.* **2013**, *128*, 469–530. [CrossRef]
49. Calvet-Mir, L.; March, H.; Corbacho-Monné, D.; Gómez-Baggethun, E.; Reyes-García, V. Home Garden Ecosystem Services Valuation through a Gender Lens: A Case Study in the Catalan Pyrenees. *Sustainability* **2016**, *8*, 718. [CrossRef]
50. Howard, P.L. Gender and Social Dynamics in Swidden and Homegardens in Latin America. In *Tropical Homegardens. Advances in Agroforestry*; Kumar, B.M., Nair, P.K.R., Eds.; Springer Netherlands: Dordrecht, The Netherlands, 2006; Volume 3, pp. 159–182. [CrossRef]
51. EcoLogic Home Gardens for 200 Families, Oaxaca, Mexico. Available online: https://www.globalgiving.org/projects/home-gardens-protecting-forests-in-oaxaca-mexico/ (accessed on 20 September 2024).
52. Patalagsa, M.A.; Schreinemachers, P.; Begum, S.; Begum, S. Sowing Seeds of Empowerment: Effect of Women's Home Garden Training in Bangladesh. *Agric. Food Secur.* **2015**, *4*, 24. [CrossRef]
53. Schreinemachers, P.; Patalagsa, M.A.; Uddin, N. Impact and Cost-Effectiveness of Women's Training in Home Gardening and Nutrition in Bangladesh. *J. Dev. Eff.* **2016**, *8*, 473–488. [CrossRef]
54. Syhre, J.-A.; Brückner, M. The Garden Has Improved My Life: Agency and Food Sovereignty of Women in Urban Agriculture in Nairobi. In *Feminist Political Ecology and the Economics of Care*; Routledge: London, UK, 2018; pp. 189–210. [CrossRef]
55. Mekonnen, A.; Mekuria, A.; Zemede, A. The Role of Homegardens for in Situ Conservation of Plant Biodiversity in Holeta Town, Oromia National Regional State, Ethiopia. *Int. J. Biodivers. Conserv.* **2014**, *6*, 8–16. [CrossRef]
56. Santos, M.; Moreira, H.; Cabral, J.A.; Gabriel, R.; Teixeira, A.; Bastos, R.; Aires, A. Contribution of Home Gardens to Sustainable Development: Perspectives from a Supported Opinion Essay. *Int. J. Environ. Res. Public Health* **2022**, *19*, 13715. [CrossRef] [PubMed]
57. Fárez-Jiménez, M.-Á.; Cañizares-Medina, A.E.; Tapia-Segarra, J.I.; Robalino-Peña, E.M. Organización Comunitaria En La Producción de Huertos. *Cienciamatria* **2022**, *8*, 2168–2176. [CrossRef]
58. Duflo, E. Women Empowerment and Economic Development. *J. Econ. Lit.* **2012**, *50*, 1051–1079. [CrossRef]
59. Lugo Espinosa, G.; Acevedo Ortiz, M.A.; Ortiz Hernández, Y.D. Conservación de semilla criolla y control biológico, resguardo del patrimonio biocultural de la Chinantla Oaxaca. In *Nuevas Territorialidades-gestión de los Territorios y Recursos Naturales con Sustentabilidad Ambiental*; Sarmiento-Franco, J.F., Ed.; UNAM-AMECIDER: Ciudad de México, México, 2023; Volume 1, pp. 221–236. ISBN 978-607-30-8314-0.
60. Salazar, L. *Semillas Para La Seguridad Alimentaria En América Latina y El Caribe (ALC)*; Banco Interamericano de Desarrollo: Washington, DC, USA, 2023.
61. Darby, K.; Hinton, T.; Torre, J. The Motivations and Needs of Rural, Low-Income Household Food Gardeners. *J. Agric. Food Sys. Community Dev.* **2020**, *9*, 55–69. [CrossRef]
62. Molina, C.L. La Familia Ante La Pandemia Del COVID-19. *Ius Prax.* **2020**, 23–29. [CrossRef]

63. Haspolat, G. The Usage of Ultra Dilutions in Agriculture. *Allg. Homöopath. Ztg.* **2023**, *268*, 4–10. [CrossRef]
64. Kumar, S.; Dhruw, S.; Porte, D.P.; Verma, N.K.; Kashyap, P.; Tiwari, R.K.S.; Bhattacharyya, A. Plant Extracts as an Alternative to Synthetic Chemicals: A Review. *Biol. Forum–Int. J.* **2023**, *15*, 24–29.
65. Prieto-Méndez, J.; Prieto-García, F.; Hernández-Pérez, A.D.; Quijada-Morales, L.M.; Aquino-Torres, E.; Acevedo-Sandoval, O.A. Agrohomeopathy: New Tool to Improve Soils, Crops and Plant Protection against Various Stress Conditions. Review. *Hortic. Argent.* **2021**, *40*, 43.
66. Foley, J.A.; Ramankutty, N.; Brauman, K.A.; Cassidy, E.S.; Gerber, J.S.; Johnston, M.; Mueller, N.D.; O'Connell, C.; Ray, D.K.; West, P.C.; et al. Solutions for a Cultivated Planet. *Nature* **2011**, *478*, 337–342. [CrossRef]
67. Yang, Q.; Al Mamun, A.; Naznen, F.; Masud, M.M. Adoption of Conservative Agricultural Practices among Rural Chinese Farmers. *Humanit. Soc. Sci. Commun.* **2024**, *11*, 1–14. [CrossRef]
68. Regner, T.; Crosetto, P. The Long-Term Effects of Self Pledging in Reward Crowdfunding. *Technol. Forecast. Soc. Chang.* **2021**, *165*, 120514. [CrossRef]
69. Borrero-Domínguez, C.; Cordón-Lagares, E.; Hernández-Garrido, R. Crowdfunding Para Organizaciones de Economía Social: Factores de Éxito. *REVESCO. Rev. Estud. Coop.* **2022**, *140*, 79940. [CrossRef]
70. Ljumović, I.; Hanić, A.; Kovačević, V. The Role of Reward-Based Crowdfunding in Farm Financing: What Characterises Successful Campaign? *Ekon. Poljopr.* **2021**, *68*, 773–788. [CrossRef]
71. Greenberg, M.D.; Hui, J.; Gerber, E. Crowdfunding: A Resource Exchange Perspective. In Proceedings of the CHI '13 Extended Abstracts on Human Factors in Computing Systems, Paris, France, 27 April–2 May 2013; Association for Computing Machinery: New York, NY, USA, 2013; pp. 883–888.
72. Behrendt, G.; Peter, S.; Sterly, S.; Häring, A.M. Community Financing for Sustainable Food and Farming: A Proximity Perspective. *Agric. Hum. Values* **2022**, *39*, 1063–1075. [CrossRef]

sustainability

Article

Exploring Extension Implications for Slow Food Development in Iran: A Comprehensive Analysis

Hassan Nazifi [1], Mohammad Sadegh Sabouri [1], Mohammad Sadegh Allahyari [2,*], Mehrdad Niknami [1] and Elham Danaei [1]

1 Department of Agricultural Extension Education, Garmsar Branch, Islamic Azad University, Garmsar 3581631167, Iran; nazifi.hassan2@gmail.com (H.N.); m.sabouri@semkarshenas.ir (M.S.S.); m.niknami@iau-garmsar.ac.ir (M.N.); e.danaee@iau-garmsar.ac.ir (E.D.)
2 Department of Agricultural Management, Rasht Branch, Islamic Azad University, Rasht 4147654919, Iran
* Correspondence: allahyari@iaurasht.ac.ir

Abstract: This research aimed to ascertain the prerequisites for the advancement of the slow food movement in Iran. Employing both quantitative and qualitative methods, it adopted a descriptive and survey-oriented design. Semi-structured interviews were conducted with 15 experts well-versed in the extension of slow food, employing a snowball sampling technique. The interview data underwent coding and analysis employing open coding, axial coding, and selective coding methods. The study encompassed experts and managers in agricultural extension and education across the nation. For statistical analysis, a structural equation model and confirmatory factor analysis were employed, utilizing SMART PLS 3 and SPSS 26 software. The goodness-of-fit index (GoF) was utilized to evaluate the comprehensive validity of the research model. From a qualitative perspective, six primary facets of the slow food model emerged: 1. Extension strategies in harmony with slow food principles; 2. Methods of extending the slow food movement; 3. Supportive policies for slow food propagation; 4. Intervening conditions; 5. Causal conditions (triggers and applications) of the slow food paradigm; and 6. Outcomes resulting from the adoption of the slow food ethos. These facets collectively comprised a total of 38 sub-components. Through analysis of the structural equation model, key facets with substantial operational weight and significant influence on the promotion of slow food were identified. These prominent components encompass disease prevention, the organization of festivals and exhibitions, the revision of laws, the shaping of individuals' lifestyles, the enhancement of food tourism capacity, and the optimization of human resources.

Keywords: slow food; good; clean; fair; gastronomy; advisory system; sustainability

Citation: Nazifi, H.; Sabouri, M.S.; Allahyari, M.S.; Niknami, M.; Danaei, E. Exploring Extension Implications for Slow Food Development in Iran: A Comprehensive Analysis. *Sustainability* **2023**, *15*, 16538. https://doi.org/10.3390/su152316538

Academic Editor: Michael S. Carolan

Received: 10 October 2023
Revised: 25 November 2023
Accepted: 2 December 2023
Published: 4 December 2023

1. Introduction

Food plays a vital role in human existence, representing cultures and nations and fostering connections among individuals [1,2]. Across societies, varying food preferences, dining customs, and cultural traditions shape personal and collective identities [3]. The global nutritional transition reflects evolving patterns in food consumption [4]. The slow food movement's emergence is significant, advocating for quality, clean, and equitable food for a promising future, supporting sustainability and local agriculture [5,6].

Proponents of the slow food movement advocate a return to traditional, community-based, and organic food production for sustainability amid global population growth. They prioritize fostering food knowledge for health and environmental harmony [7]. Slow food, now a sociopolitical initiative, challenges corporate dominance and values small enterprises, cultural diversity, and biodiversity. It emphasizes social and environmental responsibility, supporting local employment and safeguarding traditional industries, small farms, food diversity, and the ecosystem [8]. This comprehensive approach encompasses economic, social, cultural, and environmental dimensions, with a focus on educating about agricultural practices and ecological preservation [9].

The slow food movement is intricately linked to SDG2, Zero Hunger. Slow food seeks to establish sustainable and resilient food systems that actively contribute to the realization of SDG2. The movement champions the principles of "good, clean, and fair" food, emphasizing quality, sustainability, and social justice in food production and consumption. Through initiatives that encourage the revival of local food and traditional cooking, support small-scale producers, and advocate for the conservation of cultural and biological diversity, slow food aligns itself with the objective of zero hunger while fostering local socio-environmental sustainability [10]. Agricultural extension is crucial for sustainable development and advancing the slow food movement's objectives [11–15]. It plays a pivotal role in propelling agriculture and disseminating technological progress beyond technical aspects, necessitating adept resource management [16]. With responsibilities in fostering growth, alleviating poverty, and addressing economic and social dimensions [17], agricultural extension is integral to establishing sustainable agriculture. However, practical models for agricultural extension in areas like wholesome nutrition are lacking. The current agricultural extension system faces challenges in policy formulation, organization, target clientele, and funding [14], hindering its capacity to fulfill various roles, including nutritional guidance. The lack of effective accountability results in predicaments diminished productivity, and reduced well-being for agricultural users and their households. Given Iran's rich cultural, climatic, and culinary diversity, coupled with the global expansion of cultural tourism, the nation has the potential to be a significant participant in the slow food movement [18]. Iran's expansive geographical expanse, diverse array of agricultural products, and culturally abundant tapestry directly influence local cuisine. Therefore, researching the constituents and elements of the slow food movement, while identifying efficacious extension methodologies, is imperative [19].

The development of a comprehensive model, considering economic, social, and cultural contexts, along with cultural sensitivities and the consequences of slow food consumption on the environment, culture, and health, is of paramount importance. Additionally, the absence of a well-defined developmental framework and the accompanying uncertainties regarding the components and elements of the slow food paradigm underscores the necessity for addressing these gaps through further investigation. Consequently, the primary research question guiding this study was the following: How can a comprehensive model be effectively designed for advancing slow food through the extension system, and which components and elements should this model encompass?

Slow food embodies dimensions promoting biodiversity, adopting a noble philosophy, championing ecologically mindful practices, preserving traditional methods, and advocating for wholesome eating. These dimensions are explored in many studies [20–27].

Numerous studies have explored the impacts of slow food development, covering aspects, such as disease prevention and ecological conservation [25,27,28]. Concurrently, conditions fostering slow food's evolution, including disorder, inadequate communication, steep costs, and a feeble public culture, have been identified [27–31]. Government policies, incentives, and heightened oversight are seen as pivotal in advancing slow food [21,32–34]. Strategies for cultivating slow food's progress have been discussed in studies by [22,32,35,36]. In Aşkin Uzel's [37] investigation, a conclusive determination was reached: slow food represents a valuable and sustainable approach to nourishment, holding the potential to alleviate illnesses stemming from suboptimal nutrition and enhance overall well-being. The propagation of slow food practices can also drive economic and societal progress in regions reliant on food production. To effectively advance slow food, education and the cultivation of wholesome eating habits, particularly among the younger demographic, are critically important. In the study by Bashiri et al. [38], the authors observed a significant reduction in the risk of cardiovascular diseases, diabetes, obesity, and digestive ailments through the adoption of slow food. This dietary approach further exerts favorable influences on cognitive health, diminishing anxiety and stress, augmenting concentration, and enhancing memory. Slow food reinforces the immune system, preempting related maladies. Thus, as a salubrious and sustainable dietary paradigm, slow food occupies a pivotal role in the preservation and enhancement of human health.

Abbasi et al. [39] study explores the impact of slow food on sustainable development, emphasizing its relevance as the global population grows. Slow food is an environmentally conscious approach, reducing waste, managing resources efficiently, and as Shujaei et al. [40] noted promoting healthful food generation. It fosters economic and social progress in food-dependent regions, holding promise for societal advancement. Zerehposh et al. [41] found slow food significantly affects both physical and mental well-being, while Hafizi et al. [42] delved into its principles and methodologies, highlighting sustainability in production and consumption. Integrating slow food tenets, such as consuming natural and seasonal products and adopting health-conscious cooking techniques, promotes sustainable food practices. Ghorbani [43] demonstrated that implementing slow and low-fat food methodologies can improve health outcomes, reduce waste, stimulate local production, and generate employment. Facing challenges, Habibi et al. [44] emphasized the potential for slow and low-fat food principles to enhance community health and local progress. Masoudi et al. [45] underscored the positive influence of slow food on societal well-being, while Hafizi et al. [42] outlined challenges and proposed remedies, such as heightened awareness and education. Table 1 summarizes perspectives of previous scholars on effective factors in the slow food concept.

Table 1. Slow food concepts and key influencing factors.

Key Influencing Factors	Authors
Slow food development strategies.	[20,22,29,36,37]
Government incentives, support policies, and the slow food movement.	[21,33–35]
The absence of planning, inadequate communication, high costs, and a deficient public culture serve as background conditions for the development of slow food. These encompass both background and causal conditions.	[25,27–31,35]
Consequences of slow food development include disease prevention and environmental protection.	[25,27–29,35]
Components supporting biodiversity, fostering a noble philosophy, embracing environmentally friendly food practices, reverting to ancestral traditions, and promoting healthful eating.	[20–22,24–27]
The utilization of local traditional foods in food and nutrition policies can stabilize food systems. However, the scarcity of authentic local cuisine in regions, coupled with the rise of foreign eateries, impacts the availability of healthful nutrition and contributes to the long-term risk of cardiovascular diseases. Irregular eating habits and excessive fluid consumption during meals are linked to increased odds of general and abdominal obesity. Dietary patterns, healthy eating profiles, and traditional cardiovascular disease risk factors are interconnected. Additionally, the consumption of high-calorie foods, such as fatty dairy products and red meats, highlights the importance of food tourism, nutritional habits, health education, and traditional approaches. The dynamic between traditional, sustainable food systems and contemporary dietary preferences is influenced by culture and convenience.	[18,46–52]

2. Research Methodology

This research takes an applied, non-experimental approach, focusing on understanding the perspectives and insights of experts in slow food extensional prerequisites. Using a mixed methods design that combines qualitative and quantitative paradigms, this study aims to provide comprehensive results. To address the research questions, a descriptive survey strategy was employed. The qualitative sampling methodology in this research employs a comprehensive approach to ensure a nuanced understanding of slow food extensional prerequisites. The selection of participants involves a dual strategy, integrating both theoretical and purposive sampling techniques with a specific emphasis on the snowball method. Theoretical sampling enables the identification of individuals possessing theoretical knowledge and expertise in slow food extensional requirements, ensuring a well-rounded representation. Simultaneously, purposive sampling allows for the intentional selection of participants based on their relevance and significance to the research objectives. The snowball method, a key component of this sampling strategy, facilitates the expansion of the participant pool. Starting with an initial set of participants, additional individuals are identified through referrals from the initial participants. This iterative process helps uncover hidden expertise and ensures a diverse range of perspectives within the domain of slow food extension. In the initial phase of the study, fifteen semi-structured interviews were carefully conducted. This number was determined based on the principle of theoretical saturation, indicating the point at which new information ceases to emerge, ensuring a thorough exploration of the subject matter. The semi-structured nature of the interviews allows for flexibility, enabling the exploration of unexpected insights and ensuring a holistic understanding of slow food extensional prerequisites. The results of this interview and the identified concepts for slow food extension requirements are presented in Table 2 and Figure 1. The results of this stage were considered for the quantitative phase.

Referring to the statistical population, it encompasses experts and managers extensively involved in agricultural extension and education. Affiliated with coordination management offices, agricultural research, and education centers nationwide, the sample size for this research consists of 218 actively engaged individuals in agricultural extension.

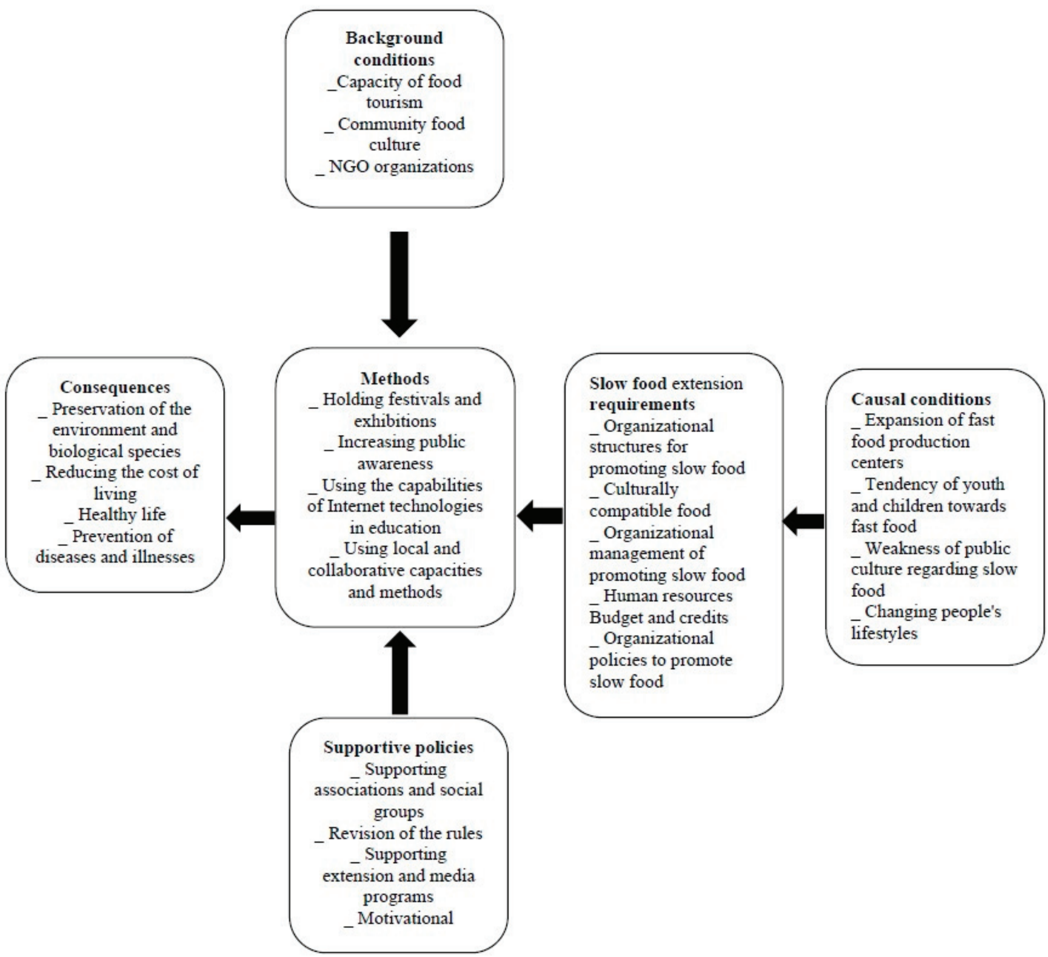

Figure 1. Main and major components of slow food extension.

Table 2. Identified concepts for slow food extension implications from semi-structured interviews.

Identified Relevant Key Concept	Main Construct
Conformity with values and traditions, matching with morals, believing in the philosophy of good (delicious) food, promoting the taste of native and local foods, and financial and human structures.	Extension of slow food
Obtaining opinions from family members, obtaining opinions from relatives and friends, consulting slow food experts, obtaining opinions from teachers, and introducing and extension a suitable lifestyle.	Extension methods of slow food
Increasing government investment in education and extension of slow food and government support for popular and non-governmental organizations in the field of slow food.	Supportive policies (intervening conditions)
Existence of extension facilities in urban and rural environments, the existence of extension guidelines and instruction, and the existence of educational and extension centers and institutions.	Background conditions
Reducing the costs of treating diseases, reducing cardiovascular diseases, more communication between family members, and improving human health due to eating slow food.	Consequences of slow food extension
Air pollution in food production, use of polluted water in food production, and excessive use of chemical inputs in agriculture.	Challenges facing the use of slow food

In the subsequent quantitative stage, descriptive research methodology was employed alongside a structural equation model. The initial use of factor analysis assists in discerning pivotal components and their corresponding significance coefficients. Subsequently, the structural equation model serves as a robust tool to unravel the intricate relationships among these components. Ultimately, this model culminates in presenting the definitive framework for slow food extensional prerequisites.

In this stage, the primary research tool was a researcher-made questionnaire consisting of two main sections based on the results of the qualitative phase. The initial section captured respondents' demographic characteristics, encompassing age, gender, level of education, field of education, organizational position, and work experience. The second section of the questionnaire focused on the promotional aspects of slow food. Comprising 75 items presented in a 5-level Likert scale format, this part aimed to gauge respondents' opinions on various dimensions. These dimensions encompassed Extension of Slow Food, Methods for Promoting Slow Food, Supportive and Motivational Policies, Background Conditions, Consequences of Slow Food, and the Causal Conditions of Slow Food.

To assess construct validity, we computed the average variance extracted index (AVE), indicating the extent to which the indicators contribute to the variance of the studied construct. AVE serves as a metric for construct validity, also recognized as convergent validity (Table 7). On the quantitative side, reliability was evaluated using both the Cronbach's alpha test and composite reliability for the items designed to measure the variables. It is important to note that the pre-test stage had a smaller sample size, making it inadequate for calculations within a structural equation model. Therefore, for assessing reliability during the pre-test stage, we employed Cronbach's alpha (Table 3). In contrast, during the model test stage, we adopted the CR method. Notably, the main questionnaires provided a more substantial sample size, enabling the determination of reliability through the CR approach.

Table 3. Cronbach's alpha coefficient for questionnaire dimension.

Row	Questionnaire Dimensions	Number of Items	Cronbach's Alpha Coefficients
1	Extension of slow food	14	0.781
2	Methods of promoting slow food	21	0.698
3	Supportive policies	10	0.895
4	Background conditions	10	0.887
5	Consequences of slow food	8	0.741
6	Causal conditions of slow food	12	0.952

The general fit index was introduced to check the fit of the model. The overall criterion of fit (GoF) (Equation (1)) can be obtained by calculating the geometric mean of the shared mean and R^2.

$$\text{GoF} = \sqrt{\text{average (Commonalities)}} \times R^2 \quad (1)$$

In order to assess the suitability of the data for factor analysis, it is necessary to conduct a test of sampling adequacy. This test is measured using the Kaiser-Meyer-Olkin (KMO) indicator (Table 4).

Table 4. Sample size adequacy test.

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		0.876
Bartlett's Test of Sphericity	Approx. chi-square	6151.33
	d.f.	217
	p-value	0

3. Results

The analysis of the subjects' age revealed the highest frequency in the "41–50 years" age group, comprising 86 individuals (39.5%) with an average age of 42.69. The majority of participants were male, accounting for 172 individuals (78.9%). Examining the subjects' education level, the most common category was "master's degree" with 100 individuals (45.8%), while the field of "agricultural engineering" had the highest frequency at 119 individuals (54.6%). Regarding agricultural experience, the most frequent range was "11–15 years" with 144 individuals (36.6%), and the average experience was 12.99 years. In terms of organizational positions, the highest frequency was observed among "experts" with 109 individuals (50%), whereas "academic faculty" had the lowest frequency of 24 individuals (11%) (Table 5).

Table 5. Respondents demographic characteristics (*n* = 218).

Feature	Group	Frequency	Percentage
Age (years) M = 40.46	20–30	41	18.8
	30–40	55	25.2
	40–50	86	39.5
	50–60	36	16.5
Gender	Mail	172	78.9
	Female	46	21.1
Level of education	B.Sc.	30	13.8
	M.Sc.	100	45.8
	Ph.D.	88	40.4
Field of study	Technical engineering	20	9.2
	Basic sciences	22	10.1
	Agricultural engineering	119	5436
	Humanities	41	18.8
	Other	16	7.3
Organizational position	Expert	109	50
	Senior expert	45	20.7
	Manager	40	18.3
	Faculty members	24	11
Work experience (years)	1–5	26	11.9
	5–10	63	28.9
	10–15	73	33.5
	15–20	44	20.2
	20–25	7	3.2
	25–30	5	2.3

4. Measurement Model Test

The model testing process is conducted step by step, beginning with the construction of the PLS model in the software. This step helps to identify the relationships between variables and their corresponding indicators and constructs. In the initial phase of our research, we employed the grandad theory paradigm model. Through face-to-face interviews with key influencers, we extracted essential elements, including causal conditions, background conditions, intervening conditions, strategies, and consequences associated with the extension of slow food. It is crucial to highlight that these identified factors directly align with the variables we are investigating in our study (refer to Figure 1). Based on the known variables in Table 2 and the relationship between them according to the grounded theory model (Figure 1), the model was evaluated. As illustrated in Table 6 and Figure 2, the causal conditions variable demonstrates the most significant causal effect when estimating the variance of slow food (beta = 0.667, t = 3.237, $p < 0.05$). For this factor, people's lifestyle, the tendency of young people and children to eat fast food, and fast food production centers had the highest relationship with casual conditions of slow food. Subsequently, supportive policies exhibit the highest meaningful causal relationship with slow food in next step (beta = 0.349, t = 2.671, $p < 0.05$).

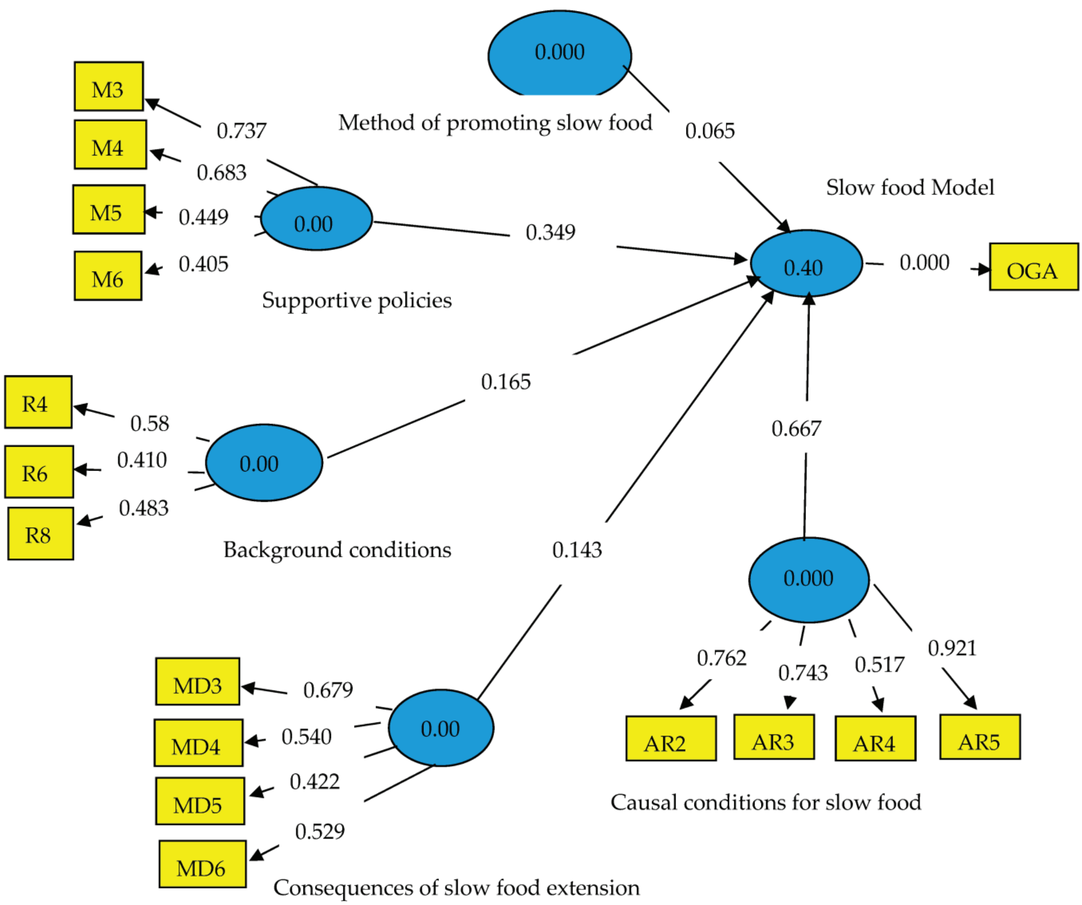

Figure 2. Measurement of the final model and the results of the hypotheses in the standard mode.

Table 6. Values of factor loading under the modified components of the knowledge and information system of smallholder farms.

Factors	Visible Variables	Symbols	Factor Loading	t-Value
Background conditions	Capacity of food tourism	R4	0.584	2.618 *
	Community food culture	R8	0.483	4.319 *
	Slow food NGOs	R6	0.410	3.348 *
Causal conditions	People's lifestyle	AR5	0.921	3.704 *
	The tendency of young people and children to fast food	AR2	0.762	2.381 *
	Fast food production centers	AR3	0.743	2.127 *
	Weakness of general culture	AR4	0.517	2.227 *
Intervening conditions	Revision of the rules	M3	0.737	3.349 *
	Supporting extension and media programs	M4	0.683	3.177 *
	Supporting associations and social groups	M5	0.449	3.012 *
	The support of relevant groups	M6	0.405	2.420 *
Extension variables	Holding festivals and exhibitions	A9	0.812	13.102 **
	Using the capacity of non-governmental organizations	A10	0.765	10.106 **
	Use of mass media	A13	0.723	10.890 **
	Using local and popular capacities and methods	A10	0.651	10.106 *
	Using the capabilities of Internet technologies in education	A11	0.495	4.880 *
Consequence's variables	Prevention of diseases and illnesses	MD3	0.679	3.361 *
	Healthy life	MD4	0.540	2.544 *
	Reducing the cost of living	MD6	0.529	4.059 *
	Environmental protection	MD5	0.422	2.097 *

** $p < 0.01$, * $p < 0.05$.

5. Factor Load Measurement

The reliability of each item is ascertained based on the count of factor loadings linked to each observed variable. This evaluation aids in determining the efficacy of the observed variables in gauging the latent, underlying variables. Typically, a minimum acceptable value of 0.3 is deemed suitable. Factor loadings of 0.4 signify a moderate level of significance, and those exceeding 0.5 denote a substantial level of significance. Table 7 presents the factor loading values corresponding to each of the independent variables.

The high fit of the model indicates that the model is well explained. Esposito et al. [46] suggest that a goodness-of-fit index (GoF) higher than 0.5 indicates a good fit for the model. Davari and Rezazadeh [47] agree with this assessment. The overall GoF for this research model is 0.503, which suggests the model has a good fit (Table 8).

Table 7. General model quality criteria.

Components	Composite Reliability (CR)	Coefficient of Determination (R^2)	Composite Reliability	Cronbach's Alpha	Common Values (Community)	Shared Reliability (AVE)	Redundancy Index Q^2 (= 1 − SSE/SSO)
Extension of food slow	0.817	0.389	0.802	1.00	1.000	1.00	0.298
Method food slow	0.895	0.573	0.931	0.768	0.742	0.823	0.447
Supportive policy food slow	0.912	0.573	0.903	0.839	0.854	0.805	0.176
Background food slow	0.954	0.573	0.851	0.920	0.951	0.782	0.341
consequences food slow	0.861	0.573	0.911	0.832	0.789	0.841	0.177
Causal conditions of slow food	0.924	0.108	0.912	0.736	0.874	0.766	0.188

Table 8. Final model fit.

Index	R^2	Communality
Extension of slow food	0.62	0.56
Extension methods	0.56	0.37
Supportive policies	0.75	0.43
Background conditions	0.88	0.16
Benefits of slow food	0.56	0.38
Causal conditions of slow food	-	1

6. Discussion

The study unveils six crucial elements within the structure of the slow food extension framework. These elements encompass requirements, extension, background conditions, supporting policies, consequences, and causal conditions components. Employing the research background and grounded theory approach, we meticulously crafted a distinctive conceptual model, making a noteworthy contribution to the field. This conceptual model underwent empirical testing within a statistical population comprising experts and extension specialists nationwide. The analysis results affirmed its appropriateness and effectiveness as a suitable framework.

The study indicates that advancing slow food necessitates enhancing human resources, a fundamental aspect of this initiative. Extending slow food further requires dedicated budgetary and financial resources, constituting essential sub-components. This aligns with Allahyari's findings [14], emphasizing the substantial investment required for slow food extension. Efficient organizational structures are crucial in the array of slow food model prerequisites, as supported by various studies [26,53,54]. Allahyari's research [14] reinforces the idea that slow food extension mandates a significant infusion of financial resources and adept budgeting. Collectively, this evidence emphasizes the pivotal role these sub-components play within the slow food model, working in tandem with human resources.

The research supports the use of virtual networks, aligning with Fatemi Amin and Fouladian's findings [53]. Both previous researchers and experts interviewed highlight the importance of people's awareness and knowledge. Slow food aims to foster active engagement, emphasizing that informed consumers understand food production challenges [55]. Building on background research, the study's findings on extensional methods align with MirKarimi et al. [54] and Williams et al. [56]. Other studies by Aşkin Uzel [37], Petrini [35], Slow Food [20], Simonetti [22], and Heitmann et al. [36], also discuss methods for slow food development.

Experts in agricultural policies emphasize endorsing organic agriculture and reducing pesticide use within the slow food movement. Policies on transgenic crops or seed modification, a key concern addressed in this research, are also deemed essential. Peano et al.'s study [55] suggests that establishing slow food committees enhances sustainability, focusing on socioeconomic and cultural aspects while prioritizing environmental and qualitative aspects of food production. Related research by Leitch [33], Slow Food [20], Dumitru et al. [21], and Schneider [34] aligns with this study's findings, emphasizing the importance of advocating for government policies and expanding oversight for the advancement of slow food [20].

The quantitative phase of the research, utilizing partial least squares analysis, affirmed the influence of tourism, traditional food culture, and non-governmental organizations in expanding the slow food model. These results align with various studies, including those by Slow Food [20], Dumitru et al. [21], Simonetti [22], Counihan and Van Esterik [24], Andrews [25], Petrini [26], and Sassatelli and Davolio [27]. Durst and Bayasgalanbat's [57] research further supports these findings, while Abshar [47] and Aini Zeinab and Sobhani [48] demonstrate that traditional and indigenous foods in Iran are more environmentally sustainable than popular Western foods.

The background research aligns with Taghvi [58] and Peano et al. [55], reinforcing and supporting the discussed issue. The prevalence of fast food in societies is partly attributed to employed family members with limited time for food preparation due to work or studies.

The growing interest in healthy eating acknowledges slow food as a health-conscious pattern that prioritizes natural ingredients while avoiding preservatives. This approach is bolstered by strategies, such as promoting organic agriculture and endorsing a diverse diet, which is gaining traction for its health and eco-friendly attributes. By highlighting the use of fresh, raw, and natural ingredients, slow food contributes to preventing heart diseases, diabetes, and cancer; reducing food waste; improving product quality; and fostering sustainable agriculture. The promotion of supportive policies, including financial incentives, stimulating consumer demand, and establishing suitable retail spaces, is essential for its widespread adoption.

To establish a foundation for slow food principles, key elements must be addressed: cultivating technical proficiency among farmers, establishing a favorable market, and enhancing the national food system. Three pivotal factors—food tourism capacity, community food culture, and Non-Governmental Organizations (NGOs) involvement—are suggested. Food tourism capacity involves a region's ability to offer local culinary delights, preserving traditions, promoting sustainable practices, and cultivating local craftsmanship. Food culture, tied to nutrition habits and behaviors, endorses slow food by promoting local and organic fare, encouraging home cooking with fresh ingredients, celebrating food diversity, and enhancing the social experience of consuming food. Leveraging existing food culture fosters a deeper understanding, guiding individuals toward healthier choices and embracing the slow food philosophy.

NGOs play a vital role in promoting local and slow food principles among farmers and producers through activities like training sessions, awareness campaigns, and workshops, utilizing internet resources and collaborative approaches. They also organize classes and workshops to encourage individuals to adopt home-cooked meals, promoting diverse and high-quality foods. Beyond education, these organizations conduct research to raise awareness and advocate for slow and healthy food principles, contributing to the widespread adoption of sustainable eating habits and the preservation of local culinary traditions.

Slow food practices yield several key benefits, including the prevention of nutrition-related diseases, cost reduction in maintaining a healthy lifestyle, and contributions to environmental conservation. These practices effectively combat cardiovascular diseases, diabetes, cancer, and obesity by promoting mindful eating and reducing risks associated with excessive calorie and fat consumption. Embracing slow food translates to healthier living, diminishing the financial burden of disease prevention and treatment, streamlining food-related expenses, and enhancing overall quality of life. Ecologically, the implications are significant; local, fresh ingredients minimize long-haul food transportation, averting environmental harm from preserved and processed goods and playing a crucial role in preserving biodiversity and preventing environmental degradation.

To expand slow food practices, a well-suited organizational framework is crucial. This framework should include culturally aligned nourishment, adept management of slow food extension, adequate human resources, budget allocations, and organizational policies championing healthful cuisine. Key factors for success include robust leadership committed to slow food promotion, a dedicated and proficient team, provision of necessary resources, and collaborative engagement with public and private entities, research centers, and universities.

Cultural compatibility of food is essential for slow food extension, aligning with local tastes and safeguarding indigenous knowledge, values, and traditions. This requires considering prevalent culture, historical context, and local culinary traditions. Culturally compatible foods serve as communication and social catalysts within society, nurturing and reinforcing social bonds.

Efficient management of slow food promotion involves forming an expert working group to devise strategies aligned with audience needs. Educational initiatives, workshops, festivals, and collaboration with organizations are pivotal. Human resources encompass education, awareness, and research, with encouragement and support being crucial. Financial allocation and suitable facilities are pivotal considerations for successful slow food promotion, contributing to the overall well-being of society.

Supportive policies are integral to societal benefit, particularly in the context of slow food promotion. A key policy avenue involves revising laws related to food, nutrition, and health, offering a streamlined means to enhance the reach of the slow food movement. Amendments and updates to these laws facilitate the process of promoting slow food effectively. Extensional programs, encompassing various media outlets, such as the internet, television, and radio, play direct and indirect roles in this promotion. Financial backing and well-organized execution of these programs significantly contribute to the success of the slow food movement. Additionally, associations and social groups contribute by hosting festivals, exhibitions, workshops, and educational webinars focused on slow food.

Causal conditions and factors drive the adoption of slow food, including the proliferation of fast food production centers, the inclination of young individuals and children toward fast food, limited emphasis on slow food in public culture, and shifts in people's lifestyles. Given the health risks associated with fast food, curtailing fast food production centers and promoting slow food becomes crucial for public health. Increasing awareness, fostering slow food production, and enacting laws pertaining to fast food production and slow food promotion are necessary. Addressing the deficiency in public culture involves boosting understanding of the benefits of slow food for overall health. Strategies for extending slow food adoption include training initiatives, incentives for slow food production, menu adjustments, and innovative advertising techniques.

Globally, the slow food movement is recognized as an international force in nutrition and agriculture. Actively supporting sustainable agriculture, high-quality food markets, dietary diversity, and healthy eating habits, this movement contributes to better health, improved quality of life, reduced food waste, environmental preservation, and economic opportunities. Raising awareness and advocating for slow food assumes great importance on a global scale, addressing vital concerns in the domains of nutrition and health for the worldwide community.

7. Conclusions

The extension of the slow food movement holds paramount importance as a developmental imperative in Iran. To bolster its reach, a comprehensive examination of factors is essential, encompassing compatible extension requisites, methods for proliferation, supportive policies, underlying and causal conditions, as well as the ensuing consequences of adopting slow food practices. Given the profound influence of slow food on promoting health-conscious eating habits and enhancing people's overall quality of life, a concerted push to amplify its adoption on a national scale becomes imperative.

The positive consequences of endorsing slow food practices, benefiting societal health and fueling economic growth, underline the need for heightened efforts on a national scale. A collaborative effort among stakeholders—producers, consumers, government bodies, and private institutions—is essential to advance the slow food cause.

To optimize the role of extension institutions, empowering human resources within the Agricultural Extension and Education Institute and the Ministry of Health's Food and Drug Deputy is crucial. This entails formal endorsement, resource allocation, and elevating knowledge in the realm of healthy and slow food.

Media integration is recommended by positioning the "healthy life" theme within the scope of "healthy food" through dedicated programs on mass media platforms. Enhanced monitoring of fast food establishments is warranted to ensure adherence to standards.

Supporting non-governmental entities dedicated to slow food, coupled with strategic planning, resource allocation, and organizational fortification within government institutions, is crucial. Organizing food festivals, collaborating between extension and health systems, and emphasizing organic practices align with agricultural policies.

Embracing these recommendations reinforces the slow food movement, contributing to healthier lifestyles, sustainable agriculture, and improved societal well-being.

8. Recommendations

To bolster the slow food movement and enhance the role of extension institutions, the following recommendations are proposed:

Empowering Extension Institutions:

- Given the pivotal role of the Agricultural Extension and Education Institute and the Ministry of Health's Food and Drug Deputy in the slow food extension framework, formal endorsement and meticulous planning are crucial.
- Resources should be allocated to enhance human resources' knowledge in healthy and slow food practices, positioning human resource empowerment as a linchpin in the broader domain of human resources management.

Media Integration:

- Positioning the "healthy life" theme within the scope of "healthy food" on mass media platforms, including radio and television, is recommended.
- A designated program promoting healthy food and lifestyles should be crafted, approved by the Supervisory Council of the Broadcasting Organization, and prominently featured in national-level strategic documents.

Enhanced Monitoring:

- Rigorous and continuous supervision of fast food production and distribution establishments is necessary to ensure adherence to standards. A comprehensive plan supporting this effort is warranted.

NGO Support:

- Government institutions should actively encourage and endorse the establishment of non-governmental entities dedicated to slow food, supporting extension efforts through careful planning, resource allocation, and organizational fortification.

Healthy Eating Promotion:

- Organizing food festivals through collaboration between extension and health systems, coupled with robust education on healthy nutrition, effectively nurtures wholesome eating habits.
- Aligning the slow food movement with agricultural policies emphasizing organic practices is crucial for promoting sustainable agricultural practices.

Embracing these recommendations will reinforce the slow food movement, contributing to healthier lifestyles, sustainable agriculture, and improved societal well-being.

Author Contributions: Methodology, M.S.S.; Validation, M.N.; Investigation, H.N., M.S.A. and E.D.; Writing—original draft, M.S.A.; Supervision, M.S.S. and M.S.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Written informed consent has been obtained from the patient(s) to publish this paper.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Vu Ngoc, A. Promotion of Food Tourism on Websites of Tourist Offices: Cross-Content Analyses of Helsinki, Copenhagen, and Lyon. Bachelor's Thesis, HAAGA-HELIA, Helsinki, Finland, 2013.
2. Guptill, A.E.; Copelton, D.A.; Lucal, B. *Food & Society: Principles and Paradoxes*; John Wiley & Sons: Hoboken, NJ, USA, 2022; ISBN 1509542256.
3. Stajcic, N. Understanding Culture: Food as a Means of Communication. *Hemispheres* **2013**, *28*, 77–87.
4. Di Giovine, M.A.; Brulotte, R.L. Introduction Food and Foodways as Cultural Heritage. In *Edible Identities: Food as Cultural Heritage*; Routledge: London, UK, 2016; pp. 1–27.
5. Abdollahi, M.; Mohammadi, F.; Houshiar-Rad, A.; HajiFaragi, M.; Esfarjani, F. Shares of Energy and Nutrients Intakes from Subsidized Food Items in Iranian Households in Different Socio-Economic Status. *Iran. J. Nutr. Sci. Food Technol.* **2011**, *6*, 43–56.
6. Payandeh, E.; Allahyari, M.S.; Fontefrancesco, M.F.; Surujlale, J. Good vs. Fair and Clean: An Analysis of Slow Food Principles toward Gastronomy Tourism in Northern Iran. *J. Culin. Sci. Technol.* **2022**, *20*, 51–70. [CrossRef]
7. Jones, P.; Shears, P.; Hillier, D.; Comfort, D.; Lowell, J. Return to Traditional Values? A Case Study of Slow Food. *Br. food J.* **2003**, *105*, 297–304. [CrossRef]
8. Tomková, V. Zpomalení Aneb Slow Movement. Vnímání a Prožívání Času v Environmentálních Perspektivách. Ph.D. Thesis, Masarykova Univerzita, Brno, Czech Republic, 2011.
9. Alshuwaikhat, H.M.; Abubakar, I. An Integrated Approach to Achieving Campus Sustainability: Assessment of the Current Campus Environmental Management Practices. *J. Clean. Prod.* **2008**, *16*, 1777–1785. [CrossRef]
10. Fontefrancesco, M.F.; Corvo, P. Slow Food: History and Activity of a Global Food Movement toward SDG2. In *Zero Hunger. Encyclopedia of the UN Sustainable Development Goals*; Leal Filho, W., Azul, A., Brand., L., Özuyar, P., Wall, T., Eds.; Springer: Cham, Switzerland, 2019.
11. Fox, R. Food and Eating: An Anthropological Perspective. *Soc. Issues Res. Cent.* **2003**, *2003*, 1–21.
12. Atsan, T.; Isik, H.B.; Yavuz, F.; Yurttas, Z. Factors Affecting Agricultural Extension Services in Northeast Anatolia Region. *Afr. J. Agric. Res.* **2009**, *4*, 305–310.
13. Swanson, B.E. Changing Extension Paradigms within a Rapidly Changing Global Economy. In Proceedings of the 19th European Seminar on Extension Education: Theory and Practice of Advisory Work in a Time of Turbulences, Assisi, Italy, 15–19 September 2009; pp. 113–117.
14. Allahyari, M.S. Reorganization of Agricultural Extension toward Green Agriculture. *Am. J. Agric. Biol. Sci.* **2009**, *4*, 105–109. [CrossRef]
15. Mahaliyanaarachchi, R.P.; Bandara, R. Commercialization of Agriculture and Role of Agricultural Extension. *Sabaragamuwa Univ. J.* **2006**, *6*, 13–22. [CrossRef]
16. Sabouri, M.S.; Malekmohammadi, I.; Chizari, M.; Hosseini, S.M. An Analysis of Future Orientations of Extension Role in Agricultural Development: The Viewpoints of Actors in "Agricultural Knowledge and Information System". *Village Dev.* **2012**, *14*, 1–26.
17. Fahad, S.; Nguyen-Thi-Lan, H.; Nguyen-Manh, D.; Tran-Duc, H.; To-The, N. Analyzing the Status of Multidimensional Poverty of Rural Households by Using Sustainable Livelihood Framework: Policy Implications for Economic Growth. *Environ. Sci. Pollut. Res.* **2023**, *30*, 16106–16119. [CrossRef] [PubMed]
18. Izadi, H. Food Tourism: Opportunity for Sustainable Development of Rural Areas in Iran. *Rural Res.* **2015**, *6*, 65–96.
19. McGoldrick, M.; Hardy, K. *V Re-Visioning Family Therapy: Race, Culture, and Gender in Clinical Practice*; Guilford Press: New York, NY, USA, 2008; ISBN 1593854277.
20. Slow Food. *Good, Clean and Fair: The Slow Food Manifesto for Quality*; Slow Food: Bra, Italy, 2015; pp. 1–2.

21. Dumitru, A.; Lema-Blanco, I.; Kunze, I.; García-Mira, R. *Transformative Social Innovation: Slow Food Movement. a Summary of the Case Study Report on the Slow Food Movement*; Slow Food: Bra, Italy, 2013; pp. 1–2.
22. Simonetti, L. The Ideology of Slow Food. *J. Eur. Stud.* **2012**, *42*, 168–189. [CrossRef]
23. Parkins, W.; Craig, G. *Slow Living*; Berg: Oxford, UK, 2006; ISBN 1845201604.
24. Counihan, C.; Van Esterik, P. Why Food? Why Culture? Why Now? Introduction to the Third Edition. In *Food and Culture*; Routledge: London, UK, 2012; pp. 15–30.
25. Andrews, G. *The Slow Food Story: Politics and Pleasure*; Pluto Press: London, UK, 2008.
26. Petrini, C. *Slow Food: The Case for Taste*; Columbia University Press: New York, NY, USA, 2003; ISBN 0231128444.
27. Sassatelli, R.; Davolio, F. Consumption, Pleasure and Politics: Slow Food and the Politico-Aesthetic Problematization of Food. *J. Consum. Cult.* **2010**, *10*, 202–232. [CrossRef]
28. Boyd, S.W. Reflections on Slow Food: From 'movement'to an Emergent Research Field. In *Heritage Cuisines*; Routledge: London, UK, 2015; pp. 166–179.
29. Madison, D. *Slow Food: Collected Thoughts on Taste, Tradition and the Honest Pleasures of Food*; Chelsea Green Publishing: Chelsea, VT, USA, 2001; ISBN 1603581723.
30. Laudan, R. Slow Food: The French Terroir Strategy, and Culinary Modernism: An Essay Review. *Food Cult. Soc.* **2004**, *7*, 133–144. [CrossRef]
31. Bolhuis, D.P.; Forde, C.G.; Cheng, Y.; Xu, H.; Martin, N.; de Graaf, C. Slow Food: Sustained Impact of Harder Foods on the Reduction in Energy Intake over the Course of the Day. *PLoS ONE* **2014**, *9*, e93370. [CrossRef]
32. Alexander, C.; Gregson, N.; Gille, Z. Food Waste. *Handb. Food Res.* **2013**, *1*, 471–483.
33. Leitch, A. Slow Food and the Politics of "Virtuous Globalization". In *Food and Culture*; Routledge: London, UK, 2012; pp. 423–439.
34. Schneider, S. Good, Clean, Fair: The Rhetoric of the Slow Food Movement. *Coll. Engl.* **2008**, *70*, 384–402.
35. Petrini, C. *Slow Food Nation: Why Our Food Should Be Good, Clean, and Fair*; Rizzoli Publications: New York, NY, USA, 2013; ISBN 0847841464.
36. Heitmann, S.; Robinson, P.; Povey, G. Slow Food, Slow Cities and Slow Tourism. In *Research Themes for Tourism*; CABI: Wallingford, UK, 2011; pp. 114–127.
37. Aşkin Uzel, R. Slow Food Movement and Sustainability. *Encycl. Sustain. Manag.* **2020**, 1–13.
38. Bashiri, F.; Ghiasvand, R.; Kian Bakht, S.; Heshmati, J. Effects of Slow Food on Health: A Critical Review. *J. Nutr. Sci. Food Ind.* **2016**, *12*, 1–12.
39. Abbasi, M.H.; Ghasemi, R.; Rezazadeh, A. Slow Food and the New Economy: Examining Its Impact on Sustainable Development. *Sci. Res. J. Econ. Dev. Strateg.* **2018**, *2*, 1–18.
40. Shujaei, R.; Bahreini Esfahani, N.; Mohammadi Nasrabadi, F. The Principles and Methods of Slow Food in Food Preparation and Consumption. *Sci. Res. J. Nutr. Sci. Food Ind.* **2017**, *13*, 1–14.
41. Zerehposh, Z.; Lotfizadeh, M.; Eshraghian, M. Effects of Slow Food on Physical and Mental Health: A Systematic Literature Review. *Sci. Res. J. Nutr. Sci. Food Ind.* **2015**, *11*, 1–12.
42. Hafizi, H.; Bayat, M.; Dehghani, F.; Amin Bidokhti, M.; Hosseini, F. Promoting Slow Food in Society: Challenges and Solutions. *J. Psychol. Health* **2017**, *8*, 1–12.
43. Ghorbani, M. *Slow Food: A Solution for Health and Economic Prosperity*; Mehr News Agency: Tehran, Iran, 2018.
44. Habibi, E.; Mohammadi, M.; Kalantari, M.; Aghababai, H.; Moradi, A. Slow and Slow Food: Challenges and Opportunities. *J. Nutr. Health* **2018**, *3*, 121–130.
45. Masoudi, M.; Bazarafshan, A.; Abolghasemi, N. Slow Food: A Strategy to Improve Community Health. *J. Nutr. Sci. Food Ind. Iran* **2016**, *12*, 1–12.
46. Esposito, M.; Lindenberg, K.; Van den Broeck, C. Entropy production as correlation between system and reservoir. *New J. Phys.* **2010**, *12*, 013013. [CrossRef]
47. Davari, A.; Rezazadeh, A. *Structural Equation Modeling with PLS Software*; Jihad Academic Organization Publications: Tehran, Iran, 2012.
48. Aini Zeinab, H.; Sobhani, S.R. *Sustainable Diets and Traditional-Native Foods of Community Nutrition Group*; Shahid Beheshti University of Medical Sciences: Tehran, Iran, 2016.
49. Amini, A.; Niknami, S.; Bahmani, A. The Effect of Health Education on Nutritional Style Related to Fruit and Vegetable Consumption Pattern in Adolescent Girls of Chabahar City. *Sci. Res. J. Sabzevar Univ. Med. Sci.* **2015**, *25*, 127–133.
50. Hariri, N.; Naseri, E.; Hoshiar Rad, A.; Zabori, F.; Bandarianzadeh, D. Evaluation of the Relationship between Alternative Healthy Nutrition Index and 10-Year Risk of Cardiovascular Diseases in Male Em-Ployees Working in the Public Sector (Tehran, 2011). *J. Nutr. Sci. Food Ind. Iran* **2012**, *8*, 41–50.
51. Hosseini, H.; Haghigian Rudsari, A. *Rethinking the Position of Traditional Foods, Institute of Nutritional Research and Food Industries of Iran*; Shahid Beheshti University of Medical Sciences: Tehran, Iran, 2016; pp. 135–140.
52. Meshkani, R.; Sanei, P.; Ismailzadeh, A.; Hassanzadeh Keshtali, A.; Faizi, A.; Adibi, P. The Relationship between Eating Habits and Obesity in Iranian Adults. *J. Nutr. Sci. Food Ind. Iran* **2015**, *11*, 19–34.
53. Fatemi Amin, Z.; Fouladiyan, M. Educational System and Educational Production: Comparative Study of 70 Countries. *Strategy Cult.* **2009**, *2*, 103–130.

54. Mirkarimi, K.; Bagheri, D.; Honarvar, M.R.; Kabir, M.J.; Ozouni-Davaji, R.B.; Eri, M. Effective Factors on Fast Food Consumption among High-School Students Based on Planned Behavior Theory. *J. Gorgan Univ. Med. Sci.* **2017**, *18*, 88–93.
55. Peano, C.; Migliorini, P.; Sottile, F. A Methodology for the Sustainability Assessment of Agri-Food Systems: An Application to the Slow Food Presidia Project. *Ecol. Soc.* **2014**, *19*, 24. [CrossRef]
56. Williams, L.T.; Germov, J.; Fuller, S.; Freij, M. A Taste of Ethical Consumption at a Slow Food Festival. *Appetite* **2015**, *91*, 321–328. [CrossRef]
57. Durst, P.; Bayasgalanbat, N. Promotion of Underutilized Indigenous Food Resources for Food Security and Nutrition in Asia and the Pacific. In Proceedings of the Regional Symposium on Promotion of Underutilized Indigenous Food Resources for Food Security and Nutrition in Asia and the Pacific, Khon Kaen, Thailand, 31 May–2 June 2012; FAO Regional Office for Asia and the Pacific: Bangkok, Thailand, 2014.
58. Taghvi, M. Fast Foods Are a Threat to Society's Health. *Resalat* **2011**, 7519.

sustainability

Article

The Determinants of Becoming Sustainable Agropreneurs: Evidence from the Bottom 40 Groups in Malaysia

Mastura Jaafar [1,*], Alireza Jalali [2,*], Suhaida Herni Suffarruddin [3] and Nachiamei Ramasamy [4]

1 School of Housing, Building and Planning, University Sains Malaysia, Gelugor 11800, Malaysia
2 Department of Management, College of Economics and Political Science, Sultan Qaboos University, Seeb 123, Oman
3 Faculty of Economics and Muamalat, University Sains Islam Malaysia, Nilai 71800, Malaysia
4 Human Capital Division, Northern Corridor Implementation Authority (NCIA), Simpang Ampat 14100, Malaysia
* Correspondence: masturaj@usm.my (M.J.); arjiaa@yahoo.com (A.J.)

Abstract: Training in the agricultural sector has been set as a continuing government agenda to educate people in rural areas. This study aims to identify several determinants that play a key role in developing sustainable agropreneurs in the Bottom 40 (B40) group in Perak, Malaysia. To this end, data were collected from 200 participants in the Agropreneur Community Training Program (ACTP). A quantitative research method was used for describing and analysing the collected data. The results showed that an internal factor, which was the agropreneurs' attitudes towards behaviour, displayed a significant positive relationship with the expansion of the farm. As for the external factors, the results showed that family support and social networking have a significant positive relationship with increased income. Moreover, the results revealed that subjective norms exhibited a significant negative relationship with increasing income. Accordingly, more representative samples are required to verify the results of the postulated relationships between the internal and external factors of becoming a sustainable agropreneur in rural areas. The agricultural sector has become a pressing global concern, with issues such as natural disasters, wars, and climate change. Thus, the results of this study provide several theoretical and practical insights for government agencies, especially in developing countries, to execute more viable training programs for agropreneurs.

Keywords: sustainable agropreneurs; agropreneur training program; B40 group; Malaysia; attitude; behaviour; social networking; subjective norms; human motivation theory

Citation: Jaafar, M.; Jalali, A.; Suffarruddin, S.H.; Ramasamy, N. The Determinants of Becoming Sustainable Agropreneurs: Evidence from the Bottom 40 Groups in Malaysia. *Sustainability* **2023**, *15*, 8283. https://doi.org/10.3390/su15108283

Academic Editors: Giuseppe Antonio Di Vita, Hamid El Bilali, Tarek Ben Hassen and Carola Strassner

Received: 27 February 2023
Revised: 25 April 2023
Accepted: 8 May 2023
Published: 19 May 2023

1. Introduction

The agricultural sector has received considerable attention worldwide to overcoming the issue of food security, and Malaysia is not an exception. Since the 1990s, the policy of the Malaysian government has emphasised the important agenda of the country's agricultural development. In line with the 5th Malaysia Plan (1986–1990), the government injected the elements of modernisation and commercialisation by encouraging the private sector to revitalise and modernise [1]. In this regard, the National Agrofood Policy (2011–2020) (NAP) was initiated to emphasise product commercialisation, and one of the policy objectives is to increase the income level of agricultural entrepreneurs. Since then, there have been improvements in terms of the involvement of the private sector and the use of new technology to improve productivity. The agenda is strengthened by the existence of National Agrofood Policy 2.0 (2021–2030), which focuses on 'smart agriculture'. However, the effectiveness of these policies is in doubt. According to Malaysia's gross domestic product (GDP), from 2010 to 2020, the percentage of agricultural growth in Malaysia reached a maximum level of 11.45% in 2011 before showing a stagnant growth of 9.79–7.51% (2012–2018) and recorded the lowest growth in 2019 (7.24%) and 2020 (7.40%) [2]. In this regard, Kunasekaran et al. [3,4] asserted that the contribution of the agricultural sector to Malaysia's economy is far too small compared with other Asian countries, including Thailand, Indonesia, and Vietnam.

Many developed and developing countries have associated the escalating number of local entrepreneurs with the current economic boost. Asian countries such as Korea, Japan, and Taiwan have achieved impressive success rates in their growth levels of economic development by developing their local entrepreneurs [5,6]. The similar concept of agropreneurs was derived from the core activities of farmers. This newly derived concept refers to 'a group of people who conduct part-time or full-time activities of farming, cultivating soil, growing crops, and raising livestock as their main source of income' [7]. The emerging concept of 'agropreneurship' combines entrepreneurship and agriculture to generate lucrative profits from various farming activities [8]. In the context of this study, however, agropreneurship refers to a farmer who cultivates crops or plants and nurtures agricultural products as a source of generating income for a living. In Malaysia, numerous agropreneurship training and education programs have already been implemented to support new agricultural policies, which aim to train and educate farmers to become entrepreneurs [1].

Entrepreneurship has been particularly recognised as a feasible solution to many economic, social, and environmental challenges [9–11]. It provides a robust platform for everyone to explore business opportunities using a variety of readily available resources. Schaltegger and Wagner [12] described sustainable entrepreneurship as 'an innovative, market-oriented and personality-driven form of creating economic and societal value'. Sustainable entrepreneurship is about seizing economic opportunities that bring into existence particular future products that provide both economic and non-economic gains to society and individuals [13–17].

Previous scholars [18,19] have stated that entrepreneurial opportunities could be an outcome of 'a self-transformation process, which can be achieved through training and education'. Having the right combination of motivation, skills, and opportunities will empower new entrepreneurs to become productive and successful [18]. In the agricultural sector, rural farmers usually have small plots of land, and they generate low yields from their farms. However, escaping poverty seems impossible to them [20]. Thus, agropreneurship development necessitates more effective strategies and policies to address the social and economic imbalance in less developed areas in the country [21–23]. According to Firdaus et al. [24], there is a trend in Malaysian society that family background, income potentials, the market environment, knowledge, skills, and incentives are among the major drivers of the younger generation to become involved in the agricultural sector.

Primarily, this study takes the initiative to bridge the gap in the literature about agropreneurship. Generally, previous studies [25,26] have investigated the factors contributing to becoming an entrepreneur in different fields, while only a handful of studies have focused on the agricultural sector [27–29]. Second, Alsos et al. [30] maintained that many studies have overlooked the significant role of entrepreneurs in the agricultural sector. Yusoff et al. [31] emphasised that further studies should examine the influential factors of agropreneurs' behaviour in Malaysia. Third, according to De Wolf et al. [32], many studies on entrepreneurship and farmers often question the necessary skills of farmers to compete in a market-driven environment. Providing education on entrepreneurship could help rural farmers in making strategic decisions about their livelihoods. This study mainly aims to encourage Malaysian farmers to become sustainable agropreneurs through a planned training program that is conducted by the Northern Corridor Implementation Authority (NCIA). The mission of the program is to elevate the living standards of the B40 rural community. The B40 community consists of those with a household income of RM 2388 (equivalent to USD 525.36) per month. The program is part of a government initiative under the 11th Malaysia Plan (11 MP) to increase the B40 group's mean income from below RM 3888 to RM 5, 270 by 2020, while simultaneously bridging the income gap within the B40 community. Therefore, to sustain agribusiness, entrepreneurship training is a requirement [1,33,34].

Accordingly, the primary objective of this study is to identify the internal and external factors that determine the agropreneurs' sustainability among the ACTP participants (Bagan Datuk, Perak). In this regard, Ridzwan et al. [35] revealed that only 20% of entrepreneurs have successfully sustained their businesses owing to exceptional personal capabilities. To achieve sustainability, entrepreneurs must identify their strengths, available opportunities, and potential resources. Therefore, they must develop a highly effective network, understand the business ecosystem, and use the existing resources. This paper is organised into five sections, including the literature review, the development of the study framework, the methodology, the results and discussion, and the conclusion. The findings of the study have significantly contributed to the conducted training program for rural agropreneurs in Perak, Malaysia. Therefore, stakeholders are expected to be provided with a better understanding of the role of several key factors in devising training programs for rural communities to train and educate sustainable agropreneurs.

2. Literature Review and Theoretical Framework

2.1. Underpinning Theory

The theory of planned behaviour is a theoretical construct that determines one's motivational factors or determinants of the likelihood to perform the target behaviour. According to Bird and Schjoedt [36], the predictor elements, such as experience, knowledge, skills, abilities, learning, intentions, and motivation, can influence entrepreneurial behaviour. Sustainable agropreneurship refers to farmers who successfully manage to sustain their farming and farming-related business for a longer duration. To sustain themselves in agrobusiness, agropreneurs should particularly consider potential opportunities and future market trends [37]. Based on the human motivation theory, McClelland [38] demonstrated that the motivational level is lower in poor countries or among poor people, which corresponds to the investigation scenario of the B40 group in the context of this study. In the same vein, Acs and Kallas [39] asserted that starting a business is easier than sustaining it in the long run, especially amidst low-income communities.

2.2. Sustainable Agropreneurs

The three key drivers of becoming sustainable agropreneurs are (1) having strong internal or altruistic motivation [37,40], (2) acquiring environmental knowledge [1,29,41], and (3) receiving external support and incentives [1,39,42,43]. According to Smith and Woods [44], despite the assistance provided by agencies and stakeholders, some farmers have failed to earn sufficient income as agropreneurs, and only a few farmers have sustained their agropreneurial activities for longer periods. Fisher et al. [45] suggested that businesses that can 'live' or 'sustain' beyond any involvement and continuous business growth constitute a key measurement tool of a successful entrepreneur.

2.3. Internal and External Factors for Sustainable Agrepreneurs

This study proposes that involvement in agropreneurship or entrepreneurial behaviour can be determined by a number of internal and external factors. The internal factors refer to the agropreneurs' attitudes towards behaviour [46], perceived behavioural control [47], attitudes towards behaviour [48], and knowledge or skills [43,49]. On the other hand, the external factors include family support [46], subjective norms [29], social networking, and government support [43,46,50,51] in conjunction with the community support [50] of the trained agropreneurs. The measurements of sustainable agropreneurs are sustained business duration, financial performance (e.g., increase in income), quality of life, business expansion, and productivity [33,52,53]. Figure 1 illustrates the proposed theoretical framework of the study.

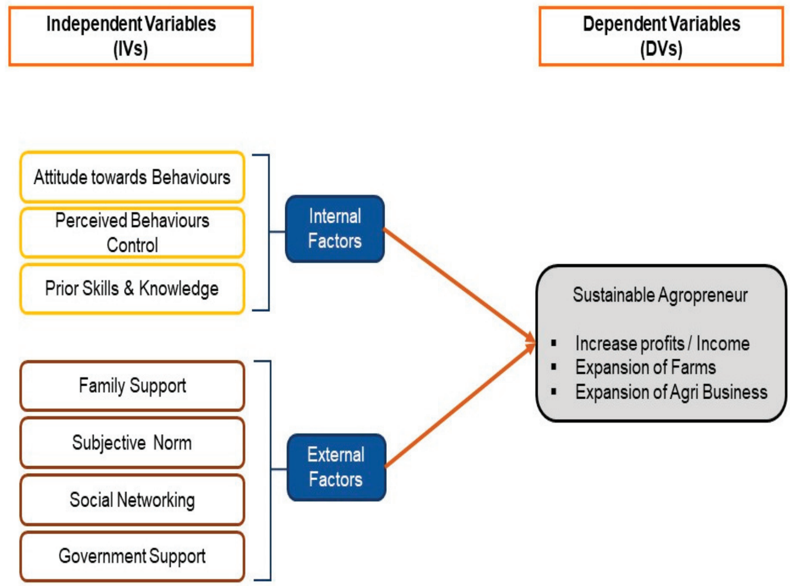

Figure 1. Theoretical framework.

Because of the mixed results in the literature on the relationships among the variables, two main hypotheses and twenty-one sub-hypotheses are proposed in this study. The two main hypotheses are postulated as follows:

Hypothesis 1: *There is a significant positive relationship between internal factors and sustainable agropreneurs.*

Hypothesis 2: *There is a significant positive relationship between external factors and sustainable agropreneurs.*

3. Materials and Methods

Via NCIA, the Malaysian government organised an ACTP covering theoretical knowledge, practical training, and handholding processes at four different locations in Perak State, Malaysia, including Bagan Serai, Manjung, Sg Siput, and Bagan Datuk. The program has hosted 800 local communities and 200 participants at each location. The ACTP was originally developed in response to the government's progressive agenda under the National Agro-food Policy (2011–2020) to create well-equipped rural farmers who utilise effective farming practices, including soil and water management, as well as judicious use of fertilisers and pesticides. The program mainly aims to equip the farmers with the required farming knowledge and agricultural skills to achieve sustainability and eradicate poverty among rural communities. Under this training program, the participants (farmers) have a comprehensive eight-month training program. The objectives of ACTP are illustrated in Figure 2.

The ACTP has followed the approach of introducing the fertigation system (FS) to the participants because this system offers farmers many benefits. The FS is a combined activity with an efficient irrigation system, which can supply the right amount of fertiliser to meet the needs of the crops. Farmers can enjoy various advantages by participating in the fertigation system (FS), which saves time and money and maximises harvest with high-quality products. Moreover, by using the best irrigation system, the FS can effectively supply accurate and standard levels of fertiliser to the plants by using the fertiliser in specific areas. The FS can also provide a consistent supply of soil nutrients. This system saves labour costs, time, and water and produces minimum waste. Therefore, through the ACTP, the farmers are educated through the introduction of modern farming skills and the management of FS. They learn how to prepare and mix the fertiliser, set the irrigation system, and other effective farming practices. By educating the farmers in new farming and irrigation approaches, their yield will increase with the existing land size, thereby increasing their income and uplifting their living standards.

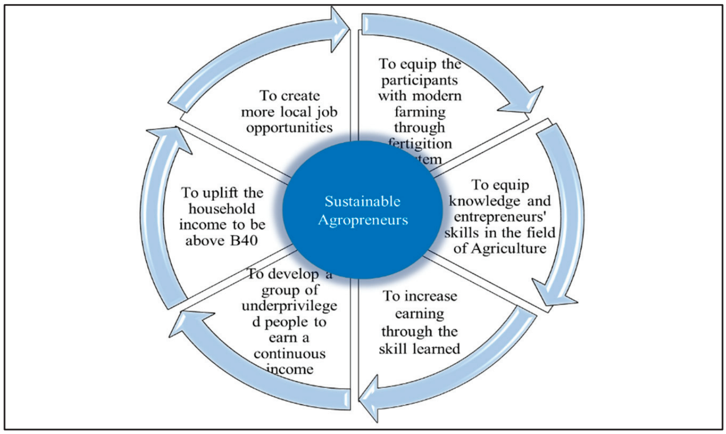

Figure 2. The objectives of the Agropreneur Community Training Program.

For this study, the training program included 200 trained farmers from an earlier ATCP conducted at Bagan Datuk, Perak. This group of trained farmers was selected mainly because they had completed their agropreneurship training program in 2019 and were under a post-monitoring period at the time the survey was conducted. The farmers had undergone four stages or eight months of training, which included 30% theoretical classes and classroom learning, 80% practical training, and six months of post-training, as shown in Table 1.

Table 1. Agropreneur Community Training Program implementation stages (Jaafar et al. [54]).

Stage	Activity	Duration
Stage 1	Recruitment process Selection of participants, including shortlisting them Identify the location for practical training	2 months of pre-training
Stage 2	Execution of training Theory classes and land preparation process	2 months
Stage 3	Theory and practical training Twelve modules to be completed within 600 training hours	6 months
Stage 4	Monitoring	6 months of post-training

In this study, the quantitative research method, SPSS software, descriptive analysis, and multiple regression analysis were used to examine the relationships between the independent and dependent variables. In the questionnaire, the five-point Likert scale was employed to measure the selected variables. The items and constructs of the questionnaire were adapted and modified from previous studies. The examined internal factor items, which designated 'attitudes towards behaviour', were retrieved from previous studies, including Schwarz et al. [55], Liñán and Chen [56], and Yusoff et al. [31], whereas the items that designated 'perceived behavioural control' were obtained from Kolvereid and Iakovleva [57], Yusoff et al. [31], Liñán and Chen [56]. The questionnaire items that designated 'prior knowledge or skills' were taken from Lee and Zhang [58], Liñán and Chen [56].

Moreover, the examined external factors items, which consisted of 'family support or involvement and subjective norm', were retrieved from Autio et al. [59], 'social networking' from Taormina and Lao [60], and 'government support' from Yusoff et al. [31]. In this study, sustainable agropreneurship was focused on increasing income, farm expansion, and agribusiness expansion [45]. It is perhaps worth mentioning that a pilot survey was also conducted using 25 respondents from a different project group. The Cronbach alpha values for all variables exceeded 0.69. The quantitative data of this study were gathered via a face-to-face survey.

4. Results

Profile of Respondents

A total of 200 participants were involved in this study. The results of SPSS descriptive analysis showed that most of them belonged to an age group ranging between 41 and 50 years old (50.5%), followed by 18–40 years old (25.5%), and 51–60 years old (24%). Regarding gender, 67.5% of the participants were males and 32.5% females. As for marital status, 92.5% of them were married, 6.0% single, and 1.5% widows. In terms of race, 73.0% were Malays, 26.5% Indians, and one participant only (0.5%) was Chinese. Regarding the participants' levels of education, most participants (82.0%) completed secondary school education (up to Form 5), while 1.5% of the participants completed primary school, 3.0% held an STPM/Diploma, and 3.5% had higher education qualifications. Regarding family size, 77.0% of the participants had 4–6 family members, 18.0% had fewer than 3 family members, 3.0% had 7–9 family members, and 2.0% had more than 10 family members. Regarding the participants' occupations, 70.0% of them were self-employed, 20.0% were homemakers/housewives, 5.0% had jobs in private-sector factories, 4.5% had jobs in the public sector, and 0.5% were students. Remarkably, after attending the designated training program, a significant improvement was observed in terms of earning additional family income. Therefore, for the income category of less than RM 1000, an 8% reduction was observed (8–20 participants), whereas a 53% reduction (45–96 participants) was recorded for the (RM 1001-2000) income category. As for the (RM 2001-3001) category and above, an increment of 4% and 27% (72–81 and 12–66 participants) was observed, respectively.

This study used SPSS software to analyse the data. Confirmatory factor analysis (CFA) is a multivariate statistical procedure. It is used to test how properly the measured variables represent the number of constructs. As illustrated in Table 2 the value of the Kaiser–Meyer–Olkin Measure (KMO) and Bartlett's test for the desired correlations among the variables was >0.7.

The formula for this test is as follows:

$$MO_j = \frac{\sum_{i \neq j} r_{ij}^2}{\sum_{i \neq j} r_{ij}^2 + \sum_{i \neq j} u} \quad (1)$$

R = $[r_{ij}]$ is the correlation matrix,

U = $[u_{ij}]$ is the partial covariance matrix,

Σ = summation notation ("add up").

The significance of the study was $p < 0.05$. Table 2 tabulates the values of both tests for the selected variables of the study. In addition, multiple regression was used to test the hypotheses of the study.

As for the factor loadings (see Tables 3–5), all the tested items were valid and highly significant (factor values that exceeded 0.50 signified acceptable construct validity). Considering the dependent variables, the factor loadings for sustainable agropreneurs (9 items) indicated that two items scored below 0.4, and, therefore, they were deleted (the second measure of the expansion of agribusiness). Accordingly, all the hypotheses about the expansion of agribusiness were excluded from further analysis. Table 1 tabulates the mean, standard deviation (SD), and alpha values for the study variables.

Table 2. Kaiser–Meyer–Olkin Measure and Bartlett's Test.

Variable	KMO	Bartlett's Test		
		Value	df	Sig. (*p*)
Internal factor	0.837	5126.767	351	0.000
External factor	0.702	1322.060	66	0.000
Sustainable agropreneur	0.765	838.000	36	0.000

Source: The authors.

Table 3. Factor loading, mean, and SD values of the internal factors of the study.

Item	Factor Loading		
	Attitudes toward Behaviour	Perceived Behavioural Control	Prior Knowledge/Skill
I have succeeded in making a living by earning a higher income as an agropreneur.	0.791		
I believe that the agricultural sector can provide a higher return.	0.717		
As an agropreneur, I can generate a lot of money.	0.812		
If I had the opportunity, I would start my own farm-based business.	0.712		
I have the opportunity to succeed if I run a business based on agriculture.	0.789		
It is very easy to start a business based on agriculture.	0.811		
Agropreneurship will give me more advantages.	0.759		
Agropreneur is my top choice career.	0.608		
I will have the maximum self-satisfaction as an agropreneur.	0.732		
Doing my own business in the agricultural sector is easy for me.		0.808	
As an agropreneur, I can easily manage agricultural business activities.		0.678	
If I continue my career as an agropreneur, the chances of failure are low.		0.788	
I am willing to make personal sacrifices to sustain my agricultural business.		0.728	
To be a successful agropreneur, I need to be more efficient.		0.867	
As a farming entrepreneur, I must adapt to any situation to achieve more promising results.		0.835	
It is easy for me as an agropreneur to keep my farming business running smoothly.		0.837	
If I initiate agropreneur activities, I will have broader success prospects.		0.816	
I strongly believe that I will be a successful agropreneur.		0.806	
My family members have extensive experience in farming.			0.842
My family has successfully cultivated my interest in agriculture.			0.699
My family members have skills in agriculture or as agropreneur.			0.690
I have the practical knowledge needed to start a farm-based business.			0.765
I have innovative skills and techniques in agriculture.			0.866
I attended agricultural entrepreneurship training before.			0.857
I'm willing to do anything to become an agropreneur.			0.828
I look forward to establishing a more progressive agriculture-based business in the future.			0.850
I will do my best to run and sustain an agriculture-based business.			0.787
Cronbach's alpha value	0.894	0.723	0.894
Mean and SD	M: 4.23 SD: 0.39	M: 3.99 SD: 0.33	M: 3.83 SD: 0.39

Source: The authors.

Table 4. Factor loading, mean, and SD of the external factors of the study.

Item	Factor Loading			
	Family Support	**Subjective Norm**	**Social Networking**	**Government Support**
If I became an agropreneur, my family would consider it a good career.	0.765			
My family will encourage me to become an agropreneur.	0.748			
My family will motivate me when I face challenges.	0.764			
If I became an agropreneur, my best friends would consider it very good.		0.744		
If I became an agropreneur, people close to me would consider it a success.		0.852		
If I became an agropreneur, villagers and the community would consider it a success.		0.782		
For me, having good relationships with other entrepreneurs is an important factor to succeed as an agropreneur.			0.752	
When I need help, I often refer to other agropreneurs for advice.			0.809	
From my perspective, good relationships, in conjunction with support from stakeholders in agriculture, are crucial to success.			0.673	
Government training and financial assistance programs helped me start my own business as an agropreneur.				0.694
It is very easy for me to access information on government assistance.				0.821
The government has been very supportive in helping new agropreneurs like me.				0.813
Cronbach's alpha value	0.894	0.723	0.723	0.723
Mean and SD	M: 3.75 SD: 0.47	M: 3.90 SD: 0.53	M: 4.02 SD: 0.46	M: 4.06 SD: 0.48

Table 6 presents the results of multiple regression. The coefficient determination of the developed model was 0.29 (R^2 = 0.29). The standard coefficient values (Beta = β) indicated that the variables of 'social networking' emerged as the main indicators of increased profit and agribusiness sustainability based on the highest standard coefficient values ($\beta = 0.273$, $\rho \leq 0.05$), followed by 'family support' ($\beta = 0.210$, $\rho \leq 0.05$). 'Subjective norm' had a significant negative correlation with an increased profit and agribusiness sustainability ($\beta = -0.339$, $\rho \leq 0.05$).

Table 5. Factor loading, mean, and SD related to the intention to be a sustainable agropreneur.

Item	Factor Loading		
	Increased Income	Expansion of Agrobusiness	Expansion of Farm
I am looking forward to increasing my income within 3 years.	0.550		
I will set the expectation of increasing my income within 3 years.	0.669		
I will work hard to achieve the increase in revenue that I have set.	0.728		
I have the desire to stay in the agriculture-based business for a longer time.		0.697	
I am determined to stay in the agriculture-based business because I have good relationships with other agropreneurs.		0.410	
I am determined to stay in the agriculture-based business with the help and support of stakeholders.		0.316	
I have set plans to expand my farm.			0.795
I will use technical facilities to grow my agriculture-based business.			0.705
I will improve the cultivation and harvesting process to develop agrobusiness.			0.835
Cronbach's alpha value	0.838	-	0.859
Mean and SD	M: 4.19 SD: 0.43	-	M: 4.16 SD: 0.42

Source: The authors.

Table 6. Multiple regression.

Model		Standardised Coefficients	t	Sig.	Collinearity Statistics	
		Beta			Tolerance	VIF
1	(Constant)		4.840	0.000		
	Attitude towards Behaviour (ATB)	0.049	0.647	0.519	0.640	1.563
	Perceived Behavioural Control (PBC)	0.047	0.517	0.606	0.454	2.204
	Prior Knowledge/Skill (PKS)	0.163	1.535	0.126	0.329	3.037
	Family Support (FS)	0.210	2.283	0.024	0.437	2.287
	Subjective Norm (SN)	−0.339	−3.919	0.000	0.495	2.022
	Social Networking (SNt)	0.273	3.525	0.001	0.616	1.622
	Government Support (GS)	0.109	1.419	0.157	0.627	1.595

Note: The significant values are $p \leq 0.01$, $p \leq 0.05$, and $p \leq 0.10$. Source: The authors.

Table 7 illustrates the results of the postulated sub-hypotheses in relation to the determinants of the internal and external factors of a sustainable agropreneur.

Table 7. Results of hypothesis testing on two dimensions of a sustainable agropreneur.

	Hypothesis	Finding
	Internal Factor	
H1a1	Attitude towards behaviour has a significant and positive relationship with increased profit/income	Not Supported
H1a3	Attitude towards behaviour has a significant and positive relationship with farm expansion	Supported
H1b1	Perceived behavioural control has a significant and positive relationship with increased profit/income	Not Supported
H1b3	Perceived behavioural control has a significant and positive relationship with farm expansion	Not Supported
H1c1	Prior knowledge/skill has a significant and positive relationship with increased profit/ income	Not Supported
H1c3	Prior knowledge/skill has a significant and positive relationship with farm expansion	Not Supported
	External Factor	
H2a1	Family supports has a significant and positive relationship with increased profit/income	Supported
H2a3	Family supports has a significant and positive relationship with farm expansion	Not Supported
H2b1	Subjective norm has a significant and positive relationship with increased profit/income	Negatively Supported
H2b3	Subjective norm has a positive relationship with farm expansion	Not Supported
H2c1	Social networking has a significant and positive relationship with increased profit/income	Supported
H2c3	Social networking has a significant and positive relationship with farm expansion	Not Supported
H2d1	Government support has a significant and positive relationship with increased profit/income	Not Supported
H2d3	Government support has a significant and positive relationship with farm expansion	Not Supported

Source: The authors.

5. Discussion

Entrepreneurship in rural agriculture often sheds light on issues of how to increase the income level. According to [61], this can be realised by focusing on behaviour. Based on the theory of planned behaviour, this study proposed a framework to examine the key internal and external factors that identified the sustainable agropreneurs among the ACTP training participants in Bagan Datuk, Perak State, Malaysia. To this end, regression analysis was conducted based on using five-point Likert scale variables to test two dependent variables, which were the increase in profit or income and farm expansion.

The results in Table 6 regarding attitudes towards behaviour displayed a significant positive relationship with farm expansion. In this regard, Sadati et al. [62] reported that attitudes emerged as a crucial factor for the acceptance of sustainable agriculture in the business domain. Attitude is a psychological construct that is shaped by cognition (thought), values (beliefs), and affection (emotions) towards a particular object. This may lead to a strong desire to encourage an individual to act accordingly [63]. The trained participants' positive attitudes such as passion and ambition have empowered them to have positive and optimistic perceptions towards agropreneurship. Therefore, they developed the desire to expand their farms to engage in agrobusiness more effectively. However, perceived behavioural control did not influence the intention of the trained participants to become sustainable agropreneurs. This finding was inconsistent with the results reported by Solesvik et al. [64]. In addition, prior knowledge/skill was found to be insignificant regarding the intention to be a sustainable agropreneur. On the contrary, previous studies concluded that upon acquiring adequate knowledge and skills regarding entrepreneurship, farmers were able to apply more efficient agricultural practices in their cultivation of crops [25,65,66]. The majority of participants in the ACTP program (75%) were considered older generation (above 50 years old) and 82% received up to the secondary level of formal education. The background could explain the insignificant result for the internal factors. It can be assumed that: (1) the participants did not possess proper agricultural knowledge and skills; the training program had a minimal impact on their behaviour, (2) they may not have fully engaged themselves in this sector; thus, transferring knowledge to the participants did not bring about a noticeable impact.

Considering the external factors, the three sub-hypotheses displayed a significant positive relationship with being a sustainable agropreneur. First, family support was positively linked with increasing profits and sustaining agribusiness. This finding was consistent with the results of previous studies conducted by Abdullah and Sulaiman, [46], who reported that family support has a significant role in influencing people to become involved in agropreneurship. Moreover, the social network positively influenced the intention to be sustainable agropreneurs by increasing their income. Previous scholars [67,68] found that the network is important in helping entrepreneurs to gather relevant and accurate information about entrepreneurial activities, apart from identifying market opportunities. Personal ties within social networks are considered resources that are important in establishing a business [69,70]. Wang and Qian [71] identified a close and good relationship with stakeholders, wherein other entrepreneurs were willing to aid farmers, especially in terms of resources to increase their profit and sustain agribusiness. Additionally, D'Silva et al. [72] found that adequate support from stakeholders, community, and family is needed to influence the entrepreneur's intention.

More importantly, government support was not significantly linked to the intention to become a sustainable agropreneur. This can be attributed to the fact that the ACTP participants sought government support in terms of funding, training, and other incentives, but not to become sustainable agropreneurs. Similarly, Papzan et al. [73] observed an insignificant correlation between government support and entrepreneurs' success. Hendratmi and Sukmaningrum [74] confirmed that government support is less effective in relation to women entrepreneurs' behaviour in Indonesia because of the lack of coverage and socialisation. This finding, however, contradicted previous findings on the role of government in encouraging the participation of the youth in agropreneurship. Previous studies showed that the role of the government is significant in promoting agropreneurship [46,49,75–79]. However, it is insignificant when it comes to supporting entrepreneurial practices. The role of government agencies should be more effective and focus on their strategy implementation, especially in encouraging sustainable entrepreneurs to support the national policy.

The 'subjective norm' exhibited a significant negative link with the intention related to income increase. According to Yeop Abdullah et al. [80], a subjective norm is belief in the significance of referents and the motivation to act in accordance with those referents. For example, if the respondents have a mentor, they may tend to follow their behaviour. This finding was supported by García-Rodríguez et al. [81], who confirmed the insignificant impact of 'subjective norm' on sustainable entrepreneurship. Additionally, Nguyen et al. [82] verified that 'subjective norm' does not affect the entrepreneurial intention in the context of Vietnam. Nishimura and Tristán [83] found that 'subjective norm' did not significantly influence the people's intentions to engage and sustain themselves in agribusiness. To further illustrate, entrepreneurship represents an innovative business opportunity platform provided for them, and it is not embedded in their normal culture. In the same vein, Zampetakis et al. [84] asserted that 'subjective norm' occasionally influences the shaping of an individual's intention to become an entrepreneur.

6. Contribution

The findings of this study can be employed as a benchmark for upcoming government programs to establish agropreneur entrepreneurship. The attitudes of an individual can be seen as a collection of personal traits, which can be developed by learning through general knowledge, including cognition, emotions, and actions. The findings of this study emphasised that family support exerts a significant positive effect on sustainable agropreneurs. The results highlighted the role of family and social networks in encouraging and supporting sustainable agropreneurs. More importantly, people's mindsets towards agropreneurship, as well as family support, should be considered because they can influence the trained participants. This study provides significant practical implications for the government and policy makers to open new cooperative channels for supporting rural farmers. Government support, which may include financial assistance, training programs, marketing promotion assistance, and consultation service assistance, are all crucial to helping rural farmers raise their living standards. The provided support and information, however, have not benefited these farmers so far. In this regard and as prescribed by Chang et al. [85], the government should encourage entrepreneurial drive and agropreneurial intention by providing adequate policy tools, such as agropreneurial funds and loans, as well as promoting the exchange and sharing of experiences by successful entrepreneurs who possess agropreneurship expertise. The government should ensure that support is effectively delivered for agropreneurship development, particularly for the B40 group in rural areas. The study results are useful for relevant authorities in devising more effective policies or finalising initiatives aiming at creating sustainable B40 agropreneurs. Moreover, the findings of the study mainly contribute to achieving the national agenda of eradicating poverty and enhancing the living standards of rural communities.

This study also contributes to the body of knowledge by providing essential theoretical and practical contributions. Theoretically speaking, this study spotlights the implementation of the theory of planned behaviour as the underpinning theory in assessing the ACTP participants' intentions to sustain their farming activities. Accordingly, this study investigates ACTP-trained participants who become sustainable agropreneurs as an outcome of actual agropreneurship behaviour.

7. Conclusions and Future Research

In general, the findings of the study supported the achievement of the Sustainable Development Goal (SDG) agenda on achieving food security and reducing poverty levels. The agricultural sector has become a global concern, with pressing issues such as natural disasters, wars, and climate change. This has, in turn, necessitated training programs to inject new or modern techniques into the agricultural sector. Therefore, training or supporting new agropreneurs should be a constant effort shouldered by the government with the identification of the right talent. The identification of the right trainee is significant in ensuring effective solutions in the agricultural sector in the future.

Such changes mean that farmers should continually appraise their professional and management skills and develop viable farm strategies in order to be successful. However, a major challenge for the agricultural sector is to enable farmers to develop their entrepreneurial skills through providing support in education and training.

Similar to any other research, this study has some limitations that can be addressed in further studies, such as suggesting improvements based on conditions before the participants joined the training program. For further studies, future training programs should focus on attitudes towards behaviour as a key factor in achieving agribusiness sustainability. The selection of participants should be reconsidered for this kind of training to ensure a higher value for the training program. Conducting more focused programs, such as mentoring and coaching, might be a more effective tactic to gain the necessary knowledge and skills, thereby enhancing the participants' intentions towards becoming sustainable agropreneurs.

The respondents' categories were as follows: only 25.5% of the young population (average age of 18–40 years old) and only 32.5% females. Young people represent the future generation and, therefore, they should be encouraged to become involved in the modern agricultural sector. Furthermore, women should be targeted, as 70% of the world population are women [74]. Moreover, further studies should focus on training programs, particularly for these groups of people, and the results could be different as the new generations are more educated and proactive with technology.

Furthermore, it is worth mentioning that this study examined one rural location only, thus dismissing statistical generalisation. The findings may be influenced by the individual-specific socioeconomic conditions and, therefore, they might not mirror the intentions of the entire group of ACTP-trained participants to become sustainable agropreneurs. Thus, more representative samples are required to verify the results of the hypotheses, which should refer to the relationships between the internal and external factors to become a sustainable agropreneur. Additionally, different research techniques may be deployed to explore other factors that are associated with attitude, owing to the importance of this dimension in determining the actual behaviour of agropreneurs. More specifically, exploring the mediating or moderating role of several viable factors is highly recommended.

Author Contributions: Conceptualisation, M.J. and N.R.; methodology, S.H.S.; software, S.H.S.; validation, M.J., N.R. and A.J.; formal analysis, M.J.; investigation, A.J.; resources, N.R.; data curation, M.J.; writing—original draft preparation, M.J.; writing—review and editing, A.J.; visualisation, S.H.S.; supervision, M.J.; project administration, A.J.; funding acquisition, M.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data can be found by contacting the corresponding author at masturaj@usm.my.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Abdulkadir, H.S. Challenges of implementing internal control systems in Non-Governmental Organizations (NGO) in Kenya: A case of Faith-Based Organizations (FBO) in Coast Region. *J. Bus. Manag.* **2014**, *16*, 57–62.
2. Department of Statistic Malaysia. 2021. Available online: https://www.dosm.gov.my/v1/index.php?r=column/ctwoByCat&parent_id=45&menu_id=Z0VTZGU1UHBUT1VJMFlpaXRRR0xpdz09 (accessed on 12 June 2022).
3. Kunasekaran, P.; Ramachandran, S.; Yacob, M.R.; Shuib, A. Development of farmers' perception scale on agro-tourism in Cameron Highlands, Malaysia. *World Appl. Sci. J.* **2011**, *12*, 10–18.
4. Schlaegel, C.; Koenig, M. Determinants of entrepreneurial intent: A meta-analytic test and integration of competing models. *Entrep. Theory Pract.* **2014**, *38*, 291–332. [CrossRef]
5. Muthomi, E. *Challenges and Opportunities for Youth Engaged in Agribusiness in Kenya*; United States International University-Africa: San Diego, CA, USA, 2017.
6. Naqvi, S.W.H. Critical success and failure factors of entrepreneurial organizations: Study of SMEs in Bahawalpur. *J. Public Adm. Gov.* **2011**, *1*, 17–22.
7. Vesala, K.M.; Peura, J.; McElwee, G. The split entrepreneurial identity of the farmer. *J. Small Bus. Enterp. Dev.* **2007**, *14*, 48–63. [CrossRef]
8. Bairwa, S.L.; Lakra, K.; Kushwaha, S.; Meena, L.K.; Kumar, P. Agripreneurship development as a tool to the upliftment of agriculture. *Int. J. Sci. Res. Publ.* **2014**, *4*, 1–4.
9. Wannamakok, W.; Liang, W.K. Entrepreneurship Education and Entrepreneurial Intention: Perspectives on Institutional Theory. *J. Entrep. Bus. Econ.* **2019**, *7*, 106–129.
10. Jalali, A.; Jaafar, M.; Ramayah, T. Entrepreneurial orientation and performance: The interaction effect of customer capital. *World J. Entrep. Manag. Sustain. Dev.* **2014**, *10*, 48–68. [CrossRef]
11. Jalali, A.; Abhari, S.; Jaafar, M. Indirect effect of extra-industry network and innovativeness on performance through proactiveness. *J. Facil. Manag.* 2022, *ahead-of-print*. [CrossRef]
12. Schaltegger, S.; Wagner, M. Sustainable entrepreneurship and sustainability innovation: Categories and interactions. *Bus. Strategy Env.* **2011**, *20*, 222–227. [CrossRef]
13. Yakubu, B.N.; Salamzadeh, A.; Bouzari, P.; Ebrahimi, P.; Fekete-Farkas, M. Identifying the key factors of sustainable entrepreneurship in the Nigerian food industry: The role of media availability. *Entrep. Bus. Econ. Rev.* **2022**, *10*, 148–162. [CrossRef]
14. Chigozirim, O.N.; Okore, N.P.; Ukeh, O.O.; Mba, A.N. Dynamics of Food Price Volatility and Households' Welfare in Nigeria. *AGRIS On-Line Pap. Econ. Inform.* **2021**, *13*, 49–60. [CrossRef]

15. Bouzari, P.; Salamzadeh, A.; Soleimani, M.; Ebrahimi, P. Online Social Networks and Women's Entrepreneurship: A Comparative Study between Iran and Hungary. *J. Women's Entrep. Educ.* **2021**, *3*, 61–75.
16. Jalali, A. Mediating role of Entrepreneurial orientation between relational capital and firm performance: Evidence from Iranian SMEs. *Int. J. Asian Bus. Inf. Manag.* **2023**, *14*, 1–19. [CrossRef]
17. Jalali, A.; Jaafar, M.; Ramayah, T. Organization-stakeholder relationship and performance of Iranian SMEs: Examining the separate mediating role of innovativeness and risk-taking. *Int. J. Islam. Middle East. Financ. Manag.* **2020**, *13*, 417–436. [CrossRef]
18. Nima, R. Entrepreneurial opportunities for youth engagement and empowerment for a sustainable future Journal of Entrepreneurship. *Bus. Econ.* **2020**, *8*, 175–195.
19. Jalali, A.; Thurasamy, R.; Jaafar, M. The Moderating Effect of Social Capital in Relation to Entrepreneurial Orientation and Firm Performance. In *Handbook of Research on Small and Medium Enterprises in Developing Countries*; IGI Global: Hershey, PA, USA, 2017; pp. 82–115.
20. Manabhanjan, S.; Jitendra, K.S. Sustainability of Indian Agriculture: A "Triple Bottom Line" Approach. *Int. Res. J. Eng. Technol.* **2016**, *3*, 622–628.
21. Razak, M.I.M.; Abas, N.M.; Yaacob, N.J.A.; Rodzi, S.N.A.M.; Yusof, N.M.; Azidin, R.A. An overview of the primary sector in Malaysia. *Int. J. Econ. Commer. Manag.* **2015**, *3*, 1–13.
22. Rueda, S.; Moriano, J.A.; Liñán, F. Validating a Theory of Planned Behavior Questionnaire to Measure Entrepreneurial Intentions. In *Developing, Shaping, and Growing Entrepreneurship*; Edward Elgar Publishing: London, UK, 2015.
23. Siwar, C.; Ahmed, F.; Begum, R.A. Climate change, agriculture, and food security issues: Malaysian perspective. *J. Food Agric. Environ.* **2013**, *11*, 1118–1123.
24. Firdaus, R.B.R.; Ebekozien, A.; Samsurijan, M.S.; Rosli, H. What Drives the Young Malaysian Generation to Become Horticulture Farmers? A Qualitative Approach. *Millenn. Asia* **2022**, 09763996221129900. [CrossRef]
25. Lüthje, C.; Franke, N. Entrepreneurial Intentions of Business Students—A Benchmarking Study. *Int. J. Innov. Technol. Manag.* **2004**, *1*, 269–288.
26. Turker, D.; Selcuk, S.S. Which factors affect the entrepreneurial intention of university students? *J. Eur. Ind. Train.* **2009**, *33*, 142–159. [CrossRef]
27. Montaño, D.E.; Kasprzyk, D. Theory of Reasoned Action, Theory of Planned Behavior, and the Integrated Behavioral Model. In *Health Behavior and Health Education: Theory, Research, and Practice*; Jossey-Bass: San Francisco, CA, USA, 2008; Volume 4, pp. 67–95.
28. Jalali, A.; Jaafar, M.; Hidzir, N.I. Indirect effect of workplace bullying on emotional exhaustion through job insecurity among Malaysian workers: The buffering role of religion. *J. Islam. Account. Bus. Res.* **2020**, *7*, 1325–1342. [CrossRef]
29. Yusoff, A.; Ahmad, N.H.; Halim, H.A. Promoting Agropreneurship among Gen Y: An Integration of Individual, Institutional and Social Level Factors. *Aust. J. Basic Appl. Sci.* **2015**, *9*, 74–86.
30. Alsos, G.A.; Carter, S.; Ljunggren, E. Entrepreneurial Families and Households. In *The Routledge Companion for Entrepreneurship*; Routledge: London, UK, 2014; pp. 165–178.
31. Yusoff, A.; Ahmad, N.H.; Abdul-Halim, H. Agropreneurship among Gen Y in Malaysia: The Role of Academic Institutions. In *Handbook of Research on Small and Medium Enterprises in Developing Countries*; IGI Global: Hershey, PA, USA, 2017.
32. De Wolf, P.; McElwee, G.; Schoorlemmer, H. The European farm entrepreneur: A comparative perspective. *Int. J. Entrep. Small Bus.* **2007**, *4*, 679–692. [CrossRef]
33. Owoade, O.A. Agropreneur Development: A Framework for Sustainable Food Security and Rural Livelihood. *IIARD Int. J. Econ. Bus. Manag.* **2017**, *3*, 24–65.
34. Yusoff, A.; Ahmad, N.H.; Halim, H.A. Entrepreneurial orientation and agropreneurial intention among Malaysian agricultural students: The impact of agropreneurship education. *Adv. Bus. Relat. Sci. Res. J.* **2016**, *7*, 77–92.
35. Ridzwan, R.; Muhammad, N.M.N.; Ab Rahman, A.A. Exploring Model of Entrepreneurship Success: A Summary Review of the Literature. *Saudi J. Bus. Manag. Stud.* **2017**, *2*, 270–277.
36. Bird, B.; Schjoedt, L. Entrepreneurial Behavior: Its Nature, Scope, Recent Research, and Agenda for Future Research. In *Understanding the Entrepreneurial Mind*; Springer: Berlin/Heidelberg, Germany, 2009; pp. 327–358.
37. Ratten, V. Sustainable farming entrepreneurship in the Sunraysia region. *Int. J. Sociol. Soc. Policy* **2018**, *38*, 103–115. [CrossRef]
38. McClelland, D.C. *The Achieving Society*; Van Nostrand: Princeton, NJ, USA, 1961.
39. Acs, Z.J.; Kallas, K. State of Literature on Small to Medium-Size Enterprises and Entrepreneurship in Low-Income Communities. In *Entrepreneurship, Growth and Public Policy*; Edward Elgar Publishing: Cheltenham, UK, 2007; pp. 21–45.
40. Kuckertz, A.; Wagner, M. The influence of sustainability orientation on entrepreneurial intentions—Investigating the role of business experience. *J. Bus. Ventur.* **2010**, *25*, 524–539. [CrossRef]
41. Patzelt, H.; Shepherd, D.A. Recognizing opportunities for sustainable development. *Entrep. Theory Pract.* **2011**, *35*, 631–652. [CrossRef]
42. Hallberg, N.L. Managing value appropriation in buyer-supplier relationships: The role of commercial decision resources. *Eur. Manag. J.* **2018**, *36*, 125–134. [CrossRef]
43. Mupfasoni, B.; Kessler, A.; Lans, T. Sustainable agricultural entrepreneurship in Burundi: Drivers and outcomes. *J. Small Bus. Enterp. Dev.* **2018**, *25*, 64–80. [CrossRef]

44. Smith, L.; Woods, C. Stakeholder engagement in the social entrepreneurship process: Identity, governance, and legitimacy. *J. Soc. Entrep.* **2015**, *6*, 186–217. [CrossRef]
45. Fisher, R.; Maritz, A.; Lobo, A. Evaluating entrepreneurs' perception of success. *Int. J. Entrep. Behav. Res.* **2014**, *20*, 478–492. [CrossRef]
46. Abdullah, A.A.; Sulaiman, N.N. Factors that influence the Interest of youths in agricultural entrepreneurship. *Int. J. Bus. Soc. Sci.* **2013**, *4*, 288–302.
47. Yusoff, A.; Ahmad, N.H.; Abdul Halim, H. Unravelling agropreneurship activities among Malaysian Gen Y. *Int. J. Entrep. Behav. Res.* **2018**, *25*, 457–479. [CrossRef]
48. Ridha, R.N.; Burhanuddin; Wahyu, B.P. Entrepreneurship intention in the agricultural sector of young generation in Indonesia. *Asia Pac. J. Innov. Entrep.* **2017**, *11*, 76–89. [CrossRef]
49. Nor, N.M.; Masdek, N.N.M.; Maidin, M.K.H. Youth inclination towards agricultural entrepreneurship. *Econ. Technol. Manag. Rev.* **2015**, *10*, 47–55.
50. Harniati, H.; Anwarudin, O. The Interest and Action of Young Agricultural Entrepreneur on Agribusiness in Cianjur Regency, West Java. *J. Penyul.* **2018**, *14*, 148–157. [CrossRef]
51. Jalali, A.; Jaafar, M. The role of proactiveness as a mediator between organizational-stakeholders relationship and SMEs performance. *J. Southwest Jiaotong Univ.* **2019**, *54*, 1–11.
52. Martin, B.C.; McNally, J.J.; Kay, M.J. Examining the formation of human capital in entrepreneurship: A meta-analysis of entrepreneurship education outcomes. *J. Bus. Ventur.* **2013**, *28*, 211–224. [CrossRef]
53. Owoade, O.A. Nigerian youths and agropreneur development: Turning challenges into opportunities. *Yaba J. Manag. Stud.* **2014**, *9*, 110–119.
54. Jaafar, M.; Jayabalan, S.; Ramasamy, N.; Suffarruddin, S.H. A Four-level Agropreneurship Training Evaluation Model for Rural Communities. *J. Bus. Soc. Dev.* **2022**, *10*, 41–58. [CrossRef]
55. Schwarz, E.J.; Wdowiak, M.A.; Almer-Jarz, D.A.; Breitenecker, R.J. The effects of attitudes and perceived environment conditions on students' entrepreneurial intent. *Educ. Train.* **2009**, *51*, 272–291. [CrossRef]
56. Liñán, F.; Chen, Y. Development and Cross-Cultural Application of a Specific Instrument to Measure Entrepreneurial Intentions. *Entrep. Theory Pract.* **2009**, *33*, 593–617. [CrossRef]
57. Kolvereid, L.; Iakovleva, T. An integrated model of entrepreneurial intentions. *Int. J. Bus. Glob.* **2009**, *3*, 66–80.
58. Lee, C.; Zhang, B. *SMEs, Competition Law, and Economic Growth. Competition Law, Regulation and SMEs in the Asia-Pacific: In Understanding the Small Business Perspective*; ISEAS-Yusof Ishak Institute: Singapore, 2016; ISBN 9789814695800.
59. Autio, E.H.; Keeley, R.; Klofsten, M.; Parker, G.G.C.; Hay, M. Entrepreneurial intent among students in Scandinavia and the USA. *Enterp. Innov. Manag. Stud.* **2001**, *2*, 145–160. [CrossRef]
60. Taormina, R.J.; Lao, S.K.M. Measuring Chinese entrepreneurial motivation. *Int. J. Entrep. Behav. Res.* **2007**, *13*, 200–221. [CrossRef]
61. Al-Swidi, A.; Huque, S.M.R.; Hafeez, M.H.; Shariff, M.N.M. The role of subjective norms in theory of planned behavior in the context of organic food consumption. *Br. Food J.* **2014**, *116*, 1561–1580. [CrossRef]
62. Sadati, S.A.; Shaabanali Fami, H.; Asadi, A.; Sadati, S.A. Farmer's attitude on sustainable agriculture and its determinants: A case study in Behbahan County of Iran. *Res. J. Appl. Sci. Eng. Technol.* **2010**, *2*, 422–427.
63. Bagozzi, R.P.; Warshaw, P.R. An examination of the etiology of the attitude-behavior relation for goal-directed behaviors. *Multivar. Behav. Res.* **1992**, *27*, 601–634. [CrossRef] [PubMed]
64. Solesvik, M.Z.; Westhead, P.; Kolvereid, L.; Matlay, H. Student intentions to become self-employed: The Ukrainian context. *J. Small Bus. Enterp. Dev.* **2012**, *19*, 441–446. [CrossRef]
65. Azman, A.; D'Silva, J.L.; Samah, B.A.; Man, N.; Shaffril, H.A.M. Relationship between attitude, knowledge, and support towards the acceptance of sustainable agriculture among contract farmers in Malaysia. *Asian Soc. Sci.* **2013**, *9*, 99–105. [CrossRef]
66. Mohamad, N.; Lim, H.-E.; Yusof, N.; Soon, J.-J. Estimating the effect of entrepreneur education on graduates' intention to be entrepreneurs. *Educ. Train.* **2015**, *57*, 874–890. [CrossRef]
67. Fernández-Pérez, V.; Alonso-Galicia, P.E.; del Mar Fuentes-Fuentes, M.; Rodriguez-Ariza, L. Business social networks and academics' entrepreneurial intentions. *Ind. Manag. Data Syst.* **2014**, *114*, 292–320. [CrossRef]
68. Hock-Eam, L.; Ahmad, S.A.; Jan, S.J. The Inferring Predisposed Factors for Graduate Agropreneur in Malaysia: Mismatch? In Proceedings of the 9th Asia-Pacific Business Research Conference, Singapore, 5–6 November 2015; pp. 1–10.
69. Davidsson, P.; Honig, B. The role of social and human capital among nascent entrepreneurs. *J. Bus. Ventur.* **2003**, *18*, 301–331. [CrossRef]
70. Kautonen, T.; Van Gelderen, M.; Tornikoski, E.T. Predicting entrepreneurial behaviour: A test of the theory of planned behaviour. *Appl. Econ.* **2013**, *45*, 697–707. [CrossRef]
71. Wang, H.; Qian, C. Corporate philanthropy and corporate financial performance: The roles of stakeholder response and political access. *Acad. Manag. J.* **2011**, *54*, 1159–1181. [CrossRef]
72. D'Silva, J.L.; Shaffril, H.A.; Uli, J.; Samah, B.A. Socio-demography factors that influence youth attitude towards contract farming. *Am. J. Appl. Sci.* **2010**, *7*, 609–614. [CrossRef]
73. Papzan, A.; Zarafshani, K.; Tavakoli, M.; Papzan, M. Determining factors influencing rural entrepreneurs' success: A case study of Mahidasht township in Kermanshah province of Iran. *Afr. J. Agric. Res.* **2008**, *3*, 597–600.

74. UNDP. *Human Development Report 1995: Gender and Human Development*; Oxford University Press: New York, NY, USA; Oxford, UK, 1995.
75. Austin, O.C.; Baharuddin, A.H. Risk in Malaysian Agriculture: The Need for A Strategic Approach and A Policy Refocus. *Kaji. Malays. J. Malays. Stud.* **2012**, *30*, 21–50.
76. Jalali, A.; Hidzir, N.I.; Jaafar, M.; Dahalan, N. Factors that trigger bullying amongst subcontractors toward intention to quit in the construction projects. *Built Environ. Proj. Asset Manag.* **2019**, *10*, 140–152. [CrossRef]
77. Fatoki, O.; Asah, F. The impact of firm and entrepreneurial characteristics on access to debt finance by SMEs in King Williams' town, South Africa. *Int. J. Bus. Manag.* **2011**, *6*, 170–179. [CrossRef]
78. Hassan, F.; Ramli, A.; Desa, N.M. Rural women entrepreneurs in Malaysia: What drives their success? *Int. J. Bus. Manag.* **2014**, *9*, 10–21. [CrossRef]
79. Ifenkwe, G.E. Cooperative Groups: Potential Roles in Agricultural and Rural Development in Nigeria JU Agbamu. In *Perspectives in Agricultural Extension and Rural Development in Nigeria*; Springfield Publishers Ltd.: Owerri, Nigeria, 2009; pp. 293–308.
80. Hendratmi, A.; Sukmaningrum, P.S. Role of government support and incubator organization to success behaviour of woman entrepreneur: Indonesia Women Entrepreneur Association. *Pol. J. Manag.* **2018**, *17*, 105–116. [CrossRef]
81. García-Rodríguez, F.J.; Gil-Soto, E.; Ruiz-Rosa, I.; Sene, P.M. Entrepreneurial intentions in diverse development contexts: A cross-cultural comparison between Senegal and Spain. *Int. Entrep. Manag. J.* **2015**, *11*, 511–527. [CrossRef]
82. Nguyen, C. The entrepreneurial intention of international business students in Viet Nam: A survey of the country joining the Trans-Pacific Partnership. *J. Innov. Entrep.* **2017**, *6*, 2–13. [CrossRef]
83. Nishimura, J.S.; Tristán, O.M. Using the theory of planned behavior to predict nascent entrepreneurship. *Acad. Rev. Latinoam. Adm.* **2011**, *46*, 55–71.
84. Zampetakis, L.A.; Anagnosti, A.; Rozakis, S. Understanding entrepreneurial intentions of students in agriculture and related sciences. In Proceedings of the Poster Session Presented at the Meeting of the EEAE 2014 Congress "Agri-Food and Rural Innovations for Healthier Societies", Ljubljana, Slovenia, 26–29 August 2014; pp. 1–13.
85. Chang, H.C.; Tsai, K.H.; Peng, C.Y. The Entrepreneurial Process: An Integrated Model. *Int. Entrep. Manag. J.* **2014**, *10*, 727–745.

sustainability

Article

Indigenous Peoples' Psychological Wellbeing Amid Transitions in Shifting Cultivation Landscape: Evidence from the Indian Himalayas

Dileep Kumar Pandey [1], Shantanu Kumar Dubey [2], Ashwani Kumar Verma [3], Lobsang Wangchu [1], Sreenath Dixit [4,*], Chabungbam Victoria Devi [1] and Gajanan Sawargaonkar [4]

1 College of Horticulture & Forestry, Central Agricultural University, Imphal 791102, India
2 ICAR-Agricultural Technology Application Research Institute, Kanpur 208002, India
3 R. B. S. College, Dr B. R. Ambedkar University, Agra 282002, India
4 ICRISAT Development Centre (IDC), International Crops Research Institute for the Semi-Arid Tropics, Hyderabad 502324, India
* Correspondence: d.sreenath@cgiar.org

Abstract: Recent changes in the shifting cultivation landscape (SCL) of the Indian Himalayan region—a global biodiversity hotspot—is of great concern due to their implication to conservation and economic development of the region and their impact on ecosystem services as well as the wellbeing of the region's inhabitants. The present study investigated the changes in land use in the SCL and their impact on the psychological wellbeing of the indigenous people of the region. Longitudinal data for over 15 years on land-use patterns and cross-sectional data from 481 respondents across 52 villages representing six states in India's North East that are part of the Indian Himalayas were utilized for the study. To analyze subjective wellbeing, Cantril's self-anchoring scale was used, followed by focused group discussions to triangulate the self-reported responses. Results reveal that the respondents were aware of the effects of landscape changes on their psychological wellbeing. These changes mostly represented a decline in shifting cultivation (SC), land ownership, food systems, social cohesion, cultural fulfillment, the diversity of cultivated native plants, and the availability of wild edible plants. Although the decline in SCL led to a gain in the area under green cover, it led to a marked decline in the diversity of cultivated and wild edible plants. This, the respondents perceived as adversely impacting their wellbeing. Empirical analysis established positive effect of SC on the psychological wellbeing of the respondents. However, a decline in SC seemed to have had an adverse impact on the perception of their wellbeing and thus increasing the migration. Therefore, optimized and ecosystem-based approaches and frameworks of socio-ecological systems are essential to harmonize the ecosystem services with wellbeing of the people.

Keywords: agro-forest landscape; engagement and life satisfaction; indigenous people; plantation crops; psychological wellbeing; shifting cultivation landscape

Citation: Pandey, D.K.; Dubey, S.K.; Verma, A.K.; Wangchu, L.; Dixit, S.; Devi, C.V.; Sawargaonkar, G. Indigenous Peoples' Psychological Wellbeing Amid Transitions in Shifting Cultivation Landscape: Evidence from the Indian Himalayas. *Sustainability* **2023**, *15*, 6791. https://doi.org/10.3390/su15086791

Academic Editors: Alejandro Javier Rescia Perazzo, Hamid El Bilali, Tarek Ben Hassen and Carola Strassner

Received: 1 February 2023
Revised: 6 April 2023
Accepted: 11 April 2023
Published: 18 April 2023

1. Introduction

The changing global environment and turbulent human initiatives demand strengthening the human and nature relationship, which may be vital for accomplishing the sustainable development goal [1]. The global level environmental dynamics is often governed by local-level land use changes, thus determining the regional ecological security [2,3]. The existing landscape spectrum determines the land-use changes [4,5], may govern the ecosystem structure, services and performances by changing biophysical indicators [6,7]. The natural and agro-ecosystems are the means to achieve the ends of local people, benefits often referred as Ecosystem services (ES) which is delivered under the three broad dimensions of provisioning of food, fiber, firewood, freshwater, ornamental, medicinal resources; regulating the climate water purification, carbon sequestration, pollination, and biodiversity conservation service or habitat service and cultural i.e., hunting, and recreational activities [8,9]. However, the provisioning components of ES are largely being threatened by a range of factors like forest conversion and agricultural intensification; population growth, and climate change [10,11]. Human activities may alter the landscape pattern, impair ecosystem services (Figure 1), and thus affect the wellbeing of locals [12]. The reciprocal proximity of landscape hue, ecosystem services, and human wellbeing being noticed in a casual way, the research on this relationship, therefore becomes imminent [12] which is also the targeted goal of regional sustainable development [13].

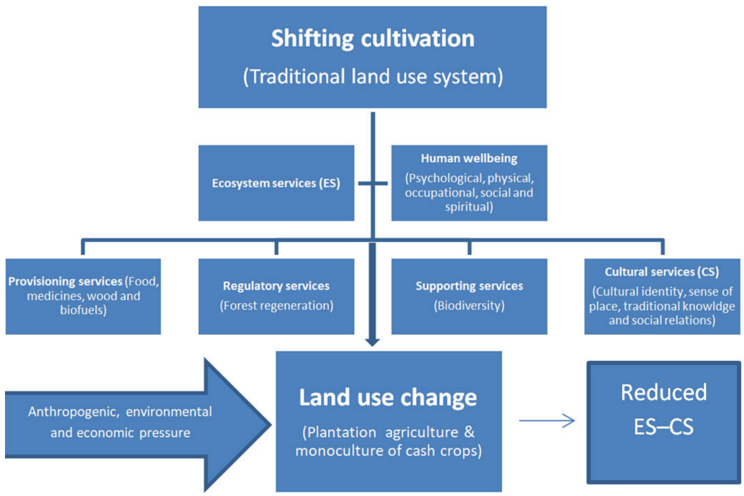

Figure 1. A conceptual framework of land use change in SC landscape and their influence on the ecosystem services.

Landscapes are also the basis for the evolution of social processes. Therefore, any human-led alteration in landscapes may impact the cultural values, conventions, and related social phenomena [14,15]. The social and ecological elements are also identified as integrated and interlinked between nature and culture comprising economic, social, and environmental processes [16–21]. The recent thoughts have designated the landscapes as spatial units wherein several basic processes of social and ecological systems unfold thus conceptualizing the landscapes as social-ecological systems (SESs) in itself which are exhibited as the interacting elements of bio-geophysical determinants and the related social actors [1,22–27]. Thus, the interdependence of the environment and human wellbeing is embedded in particular landscapes [28].

Over space and time, various pathways of land-use changes are identified which are unique as well as region and time period specific. For example, till the early twenty-first century, tropical deforestation was largely attributed to smallholder colonization of forest frontiers. The reality, in contrast, was the production of export-oriented commodities like, palm oil, soy, and beef by "large holders" which increasingly accounted for a large fraction of this deforestation, both directly and indirectly and thus pushing the smallholders into the frontier [29]. This implies examining the complexity of agroforestry landscapes using a socio-ecological lens using different such perspectives [30,31]. Therefore, empirically comprehending these issues becomes more pertinent at the current time of rapid change in population, socio-cultural aspects, land-use system, market, climate, and ecological changes. The myriad impact of land use and land cover change (LUCC) on local and regional climate, and human health induced or mediated by landscape changes also ought to be empirically documented [32].

Shifting cultivation sometimes referred to as "slash-and-burn agriculture", "swidden", and "rotational bush fallow agriculture", is a type of traditional subsistence farming that has been used for a long time by upland farmers in the tropics. In the humid tropics of the world's uplands, it is frequently practiced in Africa, Latin America, Oceania, and South and Southeast Asia and covers around 280 mha area worldwide [33]. More than 200 million people in Asia depend on this forest-based agriculture [34,35]. Because, practice involves periodic clearing of new forest patches for cultivation, shifting cultivators are also labeled as "forest eaters" although, such attribution of forest loss to shifting cultivators has been based on inadequate evidence [36], that has become a basis for the state to regulate or transform the shifting cultivation (SC) into other land uses.

Transitioning the land-use from SC to intensified cropping systems may enhance the household income, albeit compromise with customary practice, socio-economic wellbeing, livelihood options, and staple yields [37]. Intensive land use breeds dysfunctional consequences on ecosystem services (ES) enlarging the inequalities among poorer households who are heavily dependent on ES [38,39]. Thus, land use intensification-related empirical evidences need rigorous synthesis for comprehending the advanced landscape ecology and sustainability science in the changing climatic regime [32]. Further, the advancement of landscape sustainability science demands future research emphasizing the relationships among landscape patterns, ecosystem services, and human wellbeing *vis-a-vis* proactively integrating the complementary approaches across the social and natural sciences [40]. Forest landscapes as socio-ecological systems, demand comprehensive theorization for understanding the landscapes and associated actors' ability to manage them preferably in this century [41,42]. The locally managed landscape also governs the major dimensions of psychological wellbeing (attention restoration, stress reduction, and the evocation of positive emotions), physical wellbeing (promotion of physical activity in daily life as well as leisure time and through workable environments), and social wellbeing (social integration, social engagement and participation, and through social support and security) [43]. Moreover, the stronger emotional component of place identity also enhances the perceived wellbeing if people visit these places [44,45]. These places include personal and collective experiences, traditions, views as well as memories which usually locate our past, present, and future thus raising epistemological queries like how we come to know who and what we are [46]. This fact establishes that the wellbeing of indigenous people has a deep and complex relationship with the land. Besides, in the given context, therefore, the consequences of environmental changes on landscape value warrant careful attention from the local ecosystem's perspective [47] as only the indigenous mass are usually the most vulnerable and susceptible population affected by the environmental alteration [48]. Thus, this study was contemplated to capture the determinants of well-being of the indigenous communities in relation to the rapidly changing land-use systems with specific objectives of examining the land use change in the SCL of Northeast India, as a result of it, measuring the psychological wellbeing of indigenous people dependent on SC and, finally establishing the causality between the land use change and psychological wellbeing.

2. Materials and Methods

2.1. Study Area and the Community

The eight states namely Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, and Tripura constitute the north-eastern region of India which shares 7.98% of the geographical area and nearly 25% of the country's forest cover. This region also hosts two of the world's 36 biodiversity hotspots. Of the total geographical area of the northeastern region, 64.66% is accounted by forests besides sharing 56.1% of the total tribal population of India [49,50]. More than 200 different indigenous communities (60–94% of the total population) are dependent on forest products including non-timber forest products (NTFPs) as food and medicines [51]. Usually, land is owned by the community among the shifting cultivators; however, this system is being gradually replaced by private ownership of land [52].

Shifting cultivation (slash-and-burn farming or swidden) is locally known as *jhum* in Northeast India which is surrounded by forests and other natural landscapes are a source of livelihood (Figure 2). Generally, women carry out the bulk of agricultural labour, whereas men clear and burn the sites and they are the custodian of biodiversity and traditional food system [53,54]. When the produce from the *jhum* is insufficient during external vulnerabilities, produce from the surrounding forests is utilized [55]. Despite low yields from the *jhum* lands, it is continued because it is part of their culture, their way of life, and also because it is less demanding than conventional farming [56]. More than 40 crops, with numerous landraces grown as part of SC by farmers sustain the livelihoods and food security in the region, which constitutes the bedrock of the indigenous food system that ensures food security through culturally accepted food [57,58]. Shifting cultivation is also a landscape in its own right (Figure 1) and is inseparable from land and its associated festivals, rituals, and their sense of bonding with nature [59–62]. The study hypothesized that *jhuming or* shifting cultivation is an integral part of the socioeconomic and cultural life of the indigenous communities, and any changes in the shifting cultivation landscape will affect the economic and cultural milieu of the life and livelihoods these communities.

Figure 2. A shifting cultivation landscape in Saiha, Mizoram, showing a mosaic of cultivated fields, regenerating fallows, and forests.

2.2. Sources of Data

To assess the changes in land use in the study region (Figure 3), we consulted the 2000 and 2019 editions of the *Wastelands Atlas of India* [63]. In India, SC is often considered a wasteland in official documents; the *Wastelands Atlas of India* is the only official source that maps SC. Further, data on forest cover and plantation crops were extracted from the Forest Survey of India, the Indian Institute of Oil Palm Research, the Rubber Board of India, and the Tea Board of India. To examine subjective wellbeing based on primary data, random samples of respondents were obtained from 52 purposively chosen villages representing six states constituting India's Northeastern region (Figure 3). The intensity of SC having the highest density of *jhumia* families was another criterion for selecting one district from each state. Within the selected district, keeping in mind the size of the state, either 50 households (smaller states) or 100 households (larger states) practicing *jhum* were chosen. The final sample comprised 481 respondents from 500 households, 19 households of which were excluded because of circumstances beyond our control. Following a primary survey in 2016/17, focus group discussions (FGDs) were conducted so that the information gathered earlier could be explicated and triangulated for a more comprehensive understanding of ground realities. We conducted six such FGDs at various locations (one FGD in each selected district) and also spoke to the relevant stakeholders (including village heads, who are the traditional leaders and custodians of local opinion and actions) to elicit their views. Each FGD involved 8 to 12 participants. *Krishi Vigyan Kendra* (Agricultural Science Centers), forest department officials, and heads or principals of state-run schools helped in identifying suitable participants for the FGDs. Six FGDs were formulated at each of the six study locations and the first author participated in each FGD. Typically, the FGDs started with members of the research team introducing themselves, and then the participants doing the same. Through a session intended to break the ice, the research team could establish a good rapport with every member of each FGD. Consent to record the discussions was obtained verbally from all the participants.

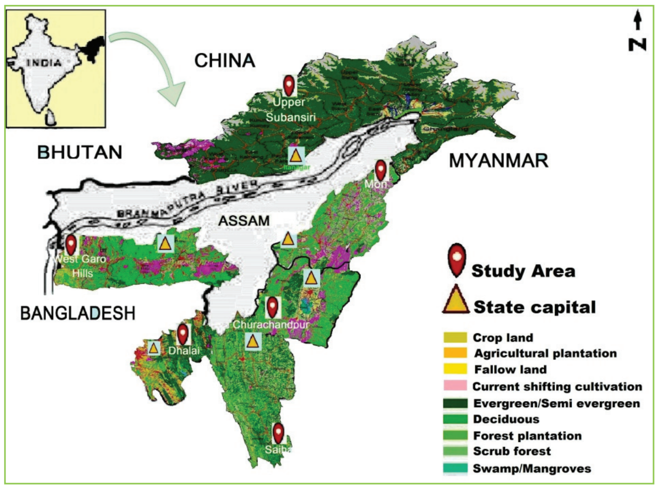

Figure 3. Map of Northeast India showing the study locations along with land use cover.

2.3. Description of Variables

No single standardized approach is available for assessing subjective wellbeing under all situations and for all purposes [64]. We chose Cantril's self-anchoring scale [65] because it is the most enduring, widely used, and reliable single-item measure [66]. A major advantage of the scale is enabling the respondents to anchor themselves based on their perspectives. The respondents were asked to imagine a stepladder with a spoke bearing numbers zero (the lowermost spoke) to 10 (the topmost spoke). It was explained to them that the highest spoke represents the best possible life for you and the bottom, the worst. The respondents were then asked two questions: 'On which spoke of the stepladder do you think you are at present?' and 'On which spoke do you think you will be in about five years from now?' We classified the respondents into three categories based on a system for classifying wellbeing into meaningful groupings [67]. The categories were as follows: thriving, struggling, and suffering; these were applied to each element, based on the rating assigned to each facet of wellbeing. 'Thriving' meant a rating of 7 or more for the present situation and of 8 or more in the future, scores that signaled a strong and consistent sense of wellbeing. 'Struggling' (ratings between 6 and 4) was defined as a moderate and inconsistent sense of wellbeing, and 'suffering' (ratings below 4), as a low and inconsistent sense of wellbeing. In other words, those respondents who viewed their current situation in a positive light and hoped to improve their lot over the next five years were categorized as 'thriving'; those who took a dim view of the present and showed little hope for the future were categorized as 'suffering'; and the rest, who appeared to be merely 'getting by', were categorized as 'struggling'.

A conceptual framework was designed for the subjective enumeration of the factors influencing human wellbeing which were most important to the respondents. The framework comprised basic human needs, economic needs, environmental needs, and subjective happiness [68,69]. After enumerating the constituents of wellbeing related to life satisfaction as experienced by residents in SC landscapes, the groups were asked to rank those items in descending order of significance to their lives. Once the members of the group started listing these items, additional prompts were provided; for example, 'What contributes the most to your happiness?' Based on the observations of the six focus groups, the final list of factors that influence wellbeing was compiled and then structured to ensure that top-ranked statements (those with the most 'likes') were incorporated into the list. This list was then shared among members of the focus groups and also among key representatives of government agencies and communities who had expressed their willingness to offer additional responses. The completeness of the list was ascertained, based on the feedback obtained from these individuals and representatives. The wellbeing components were grouped under five categories: land use, food consumption, social cohesion, decision-making role of gender, and communication access. Land use comprised seven constituents of wellbeing; food consumption comprised five constituents; social cohesion, ten; decision making, six; and communication access, five. Thus, a total of 33 constituents were identified. Based on interactions with members of the FGDs and their perceptions of each component of wellbeing as changing for the better or for worse or not changing at all, a score was assigned to each level of change that represented the number of FGDs expressing their perception of a particular level of change. For example, under the component land use as one of the constituents of wellbeing, the indicator 'access to education' was rated as having changed for the better in FGDs, as having changed for the worse in FGDs, and as not having changed at all in FGDs. Each indicator under different components was similarly quantified in terms of the number of FGDs recording that the indicator had changed for the better or worse or not changed at all.

2.4. Establishing the Causality

The study primarily focused on FGDs for establishing the relations between the psychological wellbeing of jhumias (those practicing SC) and their behavioural attributes with jhum cultivation. However, for triangulating the results and for establishing the empirical association, quantitative analysis was performed—zero order correlation between all the selected variables and stepwise regression analysis (backward elimination method) with a carefully chosen set of independent variables keeping psychological wellbeing as the dependent one. The independent variables were those attributes that were anticipated to have influenced the psychological wellbeing of jhumias. The quantitative operationalization of the selected variables and their measurements are given in Table 1.

Table 1. Description of the selected variables.

Variables	Level of Measurement	Nature of Variable
Gender	Nominal (Male 1, 2 otherwise)	Indep.
Jhum Experience	Ratio (In years)	Indep.
Education	Ratio (Years of formal education)	Indep.
Access to mass media	Nominal (yes 1, 2 otherwise)	Indep.
Beneficiary of watershed development project	Nominal (yes 1, 2 otherwise)	Indep.
Migration	Ratio (In years)	Indep.
Non-Jhum Ownership	Nominal (yes 1, 2 otherwise)	Indep.
Jhum Ownership	Nominal (yes 1, 2 otherwise)	Indep.
Cropping period in Jhum	Ratio (Number of years)	Indep.
Fallow period	Ratio (Number of years)	Indep.
Psychological well being	Interval (Level of aspiration)	Depen.

The model utilized for stepwise regression analysis is depicted below (Draper & Smith, 1981) and this was done using SPSS -v25 and also matched with R programming.

$$b_{j,std} = b_j \frac{s_{x_j}}{s_y}$$

s_y and s_{x_j} denote standard deviations for the dependent variable psychological wellbeing and the corresponding jth independent variable. The percentage change in the square root of mean square error (RMSE), which will occur if the specified variables are added or deleted from the model, was estimated. This value was then used by the Min MSE method. This percentage change in RMSE was calculated using following formula:

$$\text{Percentage change} = \left[\frac{RMSE_{previous} - RMSE_{current}}{RMSE_{current}}\right] \times 100$$

3. Results

Considering the objectives, the results of the present study are presented under three subheads. Land use transition in the SCL narrates the recent changes in land use in different states comprising the study area (Section 3.1). The data collected from the cross-sectional survey is analyzed and presented under Section 3.2 which also includes level of self-reported subjective wellbeing. The final Section 3.3 highlights the changes in constituents of wellbeing and elucidates the perception of the respondents on different constituents of wellbeing. Graphics, data tables, and photographs are also employed suitably to supplement the narration.

3.1. Land Use Transition in the SCL

As mentioned in Section 3.2, land under SC is often recorded as wasteland in official documents; the *Wastelands Atlas of India* is the only official source that maps SC. Therefore, using time series data on land-use changes over last 15 years (2000–2015) from the *Atlas*, we depicted the changes (Figure 4).

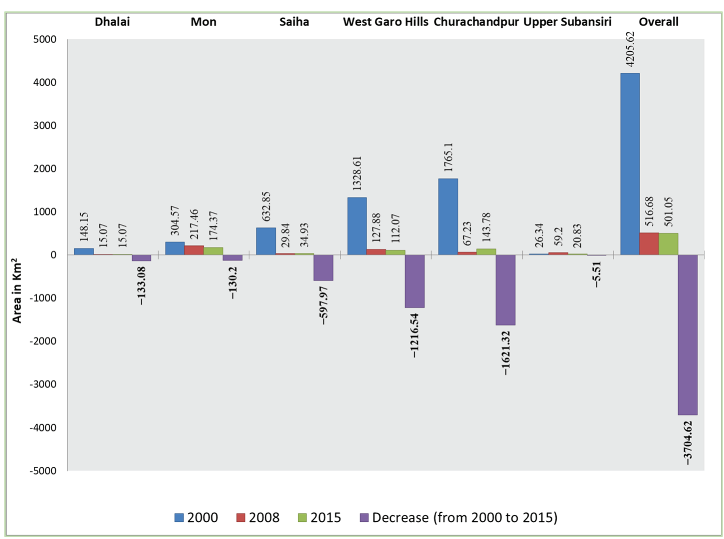

Figure 4. Transition in the area (km^2) under jhumscape in six districts of India's Northeast (2000–2015).

The decline in the area under *jhumscape* (SCL) in the sampled districts of Indian Himalayas during the period 2000–2015 is shown in Figure 3. Marked changes in land use are immediately apparent. In 2000, about 4200 km^2 was under SC; however, within

15 years, it decreased by 3700 km^2 (88.08%). This pattern with about the same intensity was observed in nearly all the six districts. The maximum decline (91.8%) was observed in Churachandpur district of Manipur, followed by Saiha (94.48%) in Mizoram and West Garo Hills (91.56%) in Meghalaya. The maximum decline occurred during 2000–2008 and then it slowed down almost to a halt. This may be because of the enactment of the Forest Rights Act, 2006, of the Government of India (effective from January 2008). The Act recognizes that forest-dwelling communities have three kinds of rights, namely (1) rights to occupation and cultivation (individual rights), (2) rights for grazing, collecting fuel wood, fishing, ownership, and disposal of non-timber forest produce (community rights); and (3) rights to protect, conserve, regenerate, and manage the areas under community forest resources.

Usually, SC is considered the sole factor for forest loss/degradation and thereby it is often discouraged by the state [49]. As a result, the area under SC has drastically declined in the region (Figure 4). However, the forest restoration programmes and legislation helped to regain forest cover slightly (2.94%) between 2000 and 2015. The plantation agriculture particularly the oil palm and natural rubber has partly covered or converted the SC/fallow area in this region (Table 2 and Figure 5).

Table 2. Land cover transition in Northeast India (in Km^2).

Year/Item	2000	2015	Increase (%)
Forest cover	163,799.00	168,607.00	2.94
Natural rubber	468.85	1556.20	231.92
Oil palm	0	273.11	100.00
Tea garden	3909.06	4571.33	16.94

Figure 5. Oil palm plantations in Upper Subansiri and Saiha (**a**,**b**); tea plantations in West Garo Hills, Meghalaya (**c**); rubber plantations in Dhalai, (**d**); cabbage grown in Saiha, Mizoram (**e**); pineapple grown in West Garo Hills, Manipur (**f**), Northeast India.

3.2. Level of Self-Reported Subjective Wellbeing

The cross-sectional survey data of 481 respondents from across 52 villages of six states in Northeast India, were analyzed for self-reported subjective wellbeing. As mentioned above, the respondents were grouped into three mutually exclusive categories suggested by Gallup [67], namely thriving, struggling, and suffering, based on how they rated each given facet of wellbeing (Figure 6).

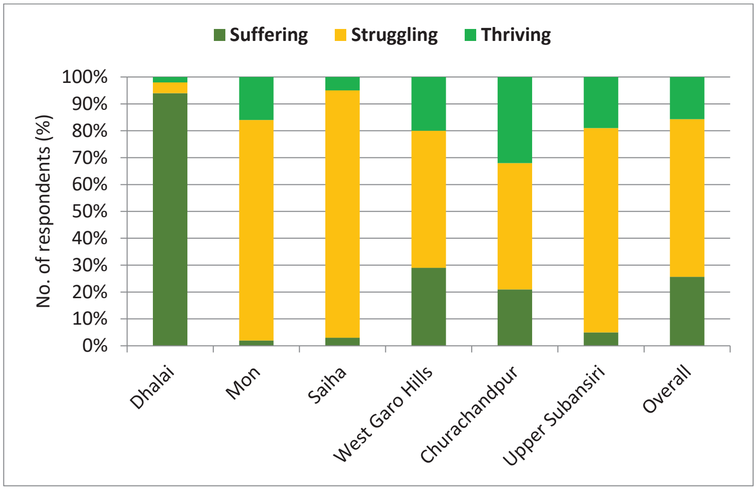

Figure 6. Level of self-reported subjective wellbeing of respondents, by district.

A majority (approximately 58%) of the respondents reported moderate or inconsistent levels of psychological wellbeing (Figure 6). At the time of the survey, they were either struggling or foresaw greater struggles in the near future. In Dhalai district in Tripura, 90% of the respondents belonged to the 'suffering' category. In West Garo Hills in Meghalaya, only about 30% in 'suffering' category, more than half in the 'struggling' category, and 20% in the 'thriving' category. In all the remaining five districts, the proportion of respondents in the struggling category exceeded that in the other two categories. About a quarter (26%) of the respondents perceived that their wellbeing was at high risk. They reported that they had inadequate access to the basic necessities of life, namely food, shelter, and clothing and rated their current life situation below 4 on a scale of 0 to 10. They believed that their lot was unlikely to be better in the next five years. Approximately 16% of the respondents expressed their level of wellbeing as strong, consistent, and progressive and assigned higher scores to both current and future levels of their wellbeing.

3.3. Changes in Constituents of Wellbeing

The agroforestry landscape is considered an integral part of the socio-cultural and economic dimensions of livelihood of the local community. Therefore, any decline in the area under SC is bound to affect the five constituents (Table 3) of wellbeing examined in the present study, namely land use, food consumption, social cohesion, the role of gender in decision making, and communication.

Table 3. Change, if any, and its direction in the constituents of wellbeing as reported by respondents.

	Constituents of Wellbeing	No. of Focus Discussion Groups		
		Positive Change	No Change	Negative Change
	Land use			
1	Nature of land ownership	-	-	3
2	Having sufficient food (local nutritious food)	2	-	4
3	Access to education	4	1	1
4	Level of income	4	-	1
5	Cultivating cash crops	3	-	-
6	Cultivating rice	1	-	1
7	Having livestock	-	-	2
	Food consumption			
1	Being adequately healthy	2	-	4
2	Food security	-	-	3
3	Indigenous food	1	-	4
4	Dietary diversity	1		5
5	Having a long life	-	-	2
	Social cohesion			
1	Healthful environment	2	-	3
2	Freedom of expression	3	-	1
3	Good governance	1	1	2
4	Cordial social relations among villagers (social cohesion)	1	-	1
5	Ability to practice religion	3	-	1
6	Mutual assistance and solidarity	-	-	2
7	Healthy relationships between couples	-	-	2
8	Ability to manage personal time	1	-	-
9	Congenial relationship in the family and household	-	-	2
10	Social equality	1		5
	Decision making: role of gender			
1	Self-planning about life	2	-	1
2	Making one's own decisions	2	-	-
3	Rejoicing and recreation	1	-	-
4	Being admired	-	1	3
5	Actively engaged in village-level participatory decision making	-	-	1
6	Income control by women	-	-	6
	Communication			
1	Access to means of communication	4	-	2
2	Rejoicing and recreation	2		4
3	Interpersonal communication	1		4
4	Personal wellbeing	4		2
5	Socio-cultural and emotional development	1		5

The changing geo-ecological perspective of SC has manifold implications for the satisfaction of the constituents of wellbeing of the indigenous people. In the case of land use, both 'access to education' and 'level of income' changed positively whereas 'having sufficient food' changed negatively, pointing to a decline in food diversity. These changes are reflected in some constituents under food consumption, namely 'dietary diversity', 'being adequately healthy', and 'indigenous foods'. Some constituents of social cohesion, namely 'freedom of expression' and 'ability to practice religion', changed positively whereas 'social equality' and 'healthful environment' changed negatively. Under decision-making, 'income control by women' was the most negatively affected constituent, followed by 'being admired'. Thus, the traditional women-dominated family system is being challenged due to changes in land use. As to communication, 'access to means of communication' and 'personal wellbeing' changed positively whereas 'socio-cultural and emotional development', 'rejoicing and recreation', and 'interpersonal communication' changed negatively. Access to means of communication is particularly important because, for a society, social and psychological support services are as important as income-based wellbeing.

3.4. Stepwise Regression Modelling

A set of 10 independent variables that are likely to exert influence on psychological wellbeing were subjected to establish the association and causal relationship. The descriptive statistics (Table 4) indicated that respondents had about 25 years of association with *jhuming*. The related variables like the cropping period in *jhuming* were almost 2 years, and the fallow period was more than 5 years. With the increased mass media exposure (mean value 5.10) and encouraging a policy of government institutions towards settled and specialized agriculture in this fragile region, the jhum ownership *vis-à-vis* non-jhum ownership was comparable resulting into alarming migration (mean value 1.85). Albeit the psychological wellbeing of *jhumias* was found to be high (6.07) which indicates their level of contentedness with *jhuming* system.

Table 4. Descriptive statistics of the selected variables (n = 481).

Variables	Mean	Std. Deviation
Gender	1.05	0.214
Jhum experience	24.61	12.582
Education	5.10	5.113
Access to mass media	2.07	1.377
Beneficiary of watershed development project	1.93	0.255
Migration	1.85	0.353
Non-*Jhum* Ownership	1.43	0.495
Jhum Ownership	1.06	0.234
Cropping period in Jhum	1.6475	0.79139
Fallow period	5.68	3.429
Psychological well being	6.07	1.986

When the selected variables were subjected to zero-order correlation with psychological wellbeing, *jhuming* experiences and access to mass media exhibited significant positive association ($p < 0.01$) while non-*jhuming* experiences exhibited a negative and significant association ($p < 0.01$). Thus, it clearly establishes the importance of *jhuming* system of land management in their wellbeing status (Table 5).

Table 5. Correlation and stepwise regression model of *Jhumias*' psychological wellbeing.

Model	Correlation Coefficient	b Value	R Square	F Value	*p* Value
Non-*Jhum* ownership	−0.40517 **	−0.280	0.164	97.81 (at 479 and 1 df)	0.001
Jhuming experiences	0.34680 **	0.193	0.240	78.64 (at 478 and 2 df)	0.001
Access to mass media	0.36515 **	0.358	0.279	63.83 (at 477 and 3 df)	0.001
Beneficiary of watershed development project	0.02998	0.282	0.344	64.99 (at 476 and 4 df)	0.001
Migration	−0.15558 *	−0.142	0.370	57.99 (at 475 and 5 df)	0.001
Fallow period	0.17765 (NS)	0.126	0.385	51.48 (at 474 and 6 df)	0.001
Education	0.28485 *	0.112	0.396	46.08 (at 473 and 7 df)	0.001

* $p < 0.01$; ** $p < 0.1$; NS: Non- significant.

In stepwise regression analysis, seven variables were retained in the final model. Causation analysis established that *jhuming* experiences had a positive influence on psychological wellbeing, and on the hand, the non-*jhuming* exposure results in increased migration and thereby having a negative effect on the wellbeing of the *Jhumias.* Similarly, enhanced educational opportunities and increased access to mass media had a positive and significant influence on the psychological wellbeing of *jhumias*.

4. Discussion

The present study documented the distinct changes in the SC landscape within the period of fifteen years (2000–2015) (Figure 4 and Table 2), mainly as a result of external interventions aimed at reducing forest loss and checking environmental degradation, the two being always assumed to be the adverse outcomes of SC. The sharp decline in the extent of SC during 2000–2008 (Figure 4) is mainly attributed to such policies and programmes aimed at replacing SC, emphasizing afforestation, raising plantation crops, and converting SC lands to settled agriculture. Such conversion of SC lands to other land uses reduced the net area available for SC and thus contributed to the reduction of fallow periods [70].

Amid such large-scale transformation, the respondents' self-reported and subjective levels of wellbeing reveal that most (nearly 85%) of those engaged in SC were either in the struggling category (nearly 60%) or in the suffering category (a little over 25%) (Figure 6). However, the differences in the level of wellbeing between the sampled districts may be attributed to situational factors that affect an individual's perception of her or his wellbeing [64] besides the socio-economic condition, level of dependence on SC, adaptive capacity, and cultural diversity among ethnic groups across the region. This preliminary study provides stronger causal evidence between the rate of decline of SC (land use change) and the self-reported subjective level of wellbeing (Table 4). Analysis of the FGDs reveals some of the drivers of wellbeing as reported by the respondents (Table 3). In the case of land use, the constituents that showed a positive change were access to education and the level of income—probably the result of growing cash crops –whereas land ownership turned out to be a negative constituent, as the ownership moved from individuals to large companies or to other more resourceful people. Sufficient food as a constituent of wellbeing also proved to be negative because of the increasing dependency on market-based foods, as did food consumption as a result of reduced diversity in diet and falling consumption of indigenous foods—which also had an adverse impact on yet another constituent, namely being adequately healthy. Indeed, the monoculture of cash crops (Figure 5a–f) is a serious threat to biodiversity and to food security [57], health, and wellbeing of the indigenous population in Northeast India [71]. Social cohesion was another category that was positively influenced by such constituents as freedom of expression and the ability to practice religion; however, the healthful environment is affected by changed cultivation practices (the traditional practices fostered togetherness), which also have a negative influence on healthy relationships between couples and congenial relationship among members of a household. In fact, having strong marital and family relationships and connections to the community may play an important role in supporting subjective wellbeing [72]. Above all, the most affected constituent of wellbeing was social equality. In the case of decision-making, women's control over their income is being eroded: in the past, their source of income was locally gathered produce; now, it is what is sold in the market, which is pocketed by men. This is a noteworthy social shift. The impact of the decline in SC and subsequent promotion of oil palm had serious implications for women's wellbeing in Mizoram because their role in settled cultivation of oil palm (Figure 5) is far more subservient than that in SC [73]. When we consider the preoccupations *(Jhuming)* of the indigenous people in Northeast India in the recent past, the most important was asserting and reclaiming where required their inalienable traditional rights to use, manage and control their ancestral land and land-based resources (flora and fauna, water body, and so on) in their own geo-ecologies; preserving their way of life; and resisting being absorbed into the mainstream and its emphasis on materialism and individualism [74]. Although the desire for material goods does play a crucial role, it is the emotional struggle to preserve group identity and its core values that form a major part of the struggle [59,75]. For the *Jhumias*, SC emerged as the source of many other benefits rather than merely a system of food production. Our analysis has clearly established that *jhuming* experience positively impacted wellbeing on SC farmers while non-*jhuming* experience led to wellbeing that can be termed as struggling (Table 5). Thus, the concept of well-being includes not only positive feelings of happiness and satisfaction, but also feelings such as interest, commitment, trust and love [76]. Indeed, shifting cultivation is a way of life for the cultivators rather than just a farming technique [36]. Furthermore, cultivated and wild biodiversity in the SCL contributed to many traditional ethnic, culinary, and ethno-medicinal preparations; for example, *jhum* rice is the main substrate for many traditionally prepared alcoholic beverages. The by-products of jhum, particularly maize, the pseudostem of banana, and tuber crops are used to feed poultry and pigs. In fact, the *jhum* system gives locals access to culturally appropriate foods while also retaining their traditional eating practises, which have a significant chance of enhancing food security [58].

This empirical finding has been also reflected in the outcome of the FGDs (Table 3). Therefore, the perceptual mismatch between the local people and policy makers regarding the usage and benefits of SC land—demands close attention and reappraisal [70]. The urgent need, therefore, is for coherent policies aimed at transforming SC while reducing the negative impacts of this divergence in perceptions.

4.1. Policy Implications

The present study offers some key insights into (1) the extent of change in land use and of the decline in the area under SC in the Indian Himalayas, (2) the impact of those changes in the perception of psychological wellbeing by indigenous people of the region and, (3) dynamic changes in broad categories of the constituents of wellbeing in terms of the extent to which they contribute to the sense of wellbeing. These insights will help in devising ethical approaches to sustainable and inclusive development that values the needs of indigenous peoples. Later on, the findings will also prove useful to managers and policymakers in eliciting active participation of indigenous people in development. More specifically, in the context of Indian Himalayas, these findings would go a long way by taking advantage of the transition and ensure optimized trade-offs between safeguarding the wellbeing and livelihoods of vulnerable communities of the region and making inevitable changes in land use that may have adverse impacts on SC landscapes.

4.2. Limitations and Future Research

The panoramic view of psychological wellbeing presented here will be useful in monitoring the overall reaction of people and in forecasting the socio-psychological impact of changes in land use. However, any such assessment of psychological wellbeing is subject to somewhat random, contextual, and situational perceptions of individual respondents—perceptions that influence the responses to any questionnaire [64]. The assessment is also influenced by sources of information; future research should therefore undertake cross-cultural assessments of psychological wellbeing, which are likely to be more stable. Secondly, any analysis can only reveal associations among various factors, associations that may be causal but may also be due to some other factors.

5. Conclusions

Our study found that the shifting-cultivation landscape (SCL) of the Indian Himalayas is experiencing rapid changes in land use, mostly in favour of monoculture of plantations crops or cash crops owing to market pressure. Such changes in the SCL have manifold implications for the wellbeing of indigenous people of the region. Changes in land use have led to greater access to education and higher levels of income but, at the same time, have also led to a decline in food diversity, which means the indigenous people may not always have sufficient food. These changes clearly point to an unsustainable transition in the SCL—a multifunctional and biocultural landscape—given that a majority of the respondents reported moderate or inconsistent levels of psychological wellbeing and believed that their circumstances represented a continued struggle now and a greater struggle in the near future. The study thus emphasizes the importance of the *jhum* system of land management to the wellbeing of indigenous people dependent on this agroforestry system for their livelihood as well as for fulfilment of their cultural needs. A more integrative conceptual approach that takes into account the perceptions of the indigenous people would help considerably in sustaining the SCL, which is highly fragmented at present, thereby aggravating the problem of managing such agricultural systems sustainably on different geographical scales. An integrated approach to landscape management may make the various subsystems within the SCL more sustainable and strengthen their multi-functionality, ultimately resulting in multiple favourable outcomes.

Author Contributions: D.K.P. and S.K.D.: Conceptualization, Methodology, Software A.K.V.: Data curation, Writing—Original draft preparation. D.K.P.: Funding acquisition, Visualization, Investigation. S.K.D.: Supervision: A.K.V.: Software, Validation: S.D., L.W., C.V.D. and G.S.: Writing—Reviewing and Editing. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Division of Agricultural Extension, Indian Council of Agricultural Research (ICAR), New Delhi, India (Grant Reference: A.Extn.26/10/2015-AE-I/01).

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board (or Ethics Committee) of the Directorate of Research, Central Agricultural University, Manipur (approval no. CAU/DoR-2015/EFP/67-05).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: All data generated or analyzed during this study are included in this article.

Acknowledgments: The research team would like to express sincere thanks to the indigenous people (respondents) for their consent and active participation in the study. The cooperation extended by the heads and senior scientists at the district Agricultural Science Centers (KVK) and district forest officers, who helped in conducting focus group discussions is duly acknowledged.

Conflicts of Interest: The authors declare that they have no conflict of interest.

References

1. Ostrom, E. A general framework for analyzing sustainability of social-ecological systems. *Science* **2009**, *325*, 419–422. [CrossRef] [PubMed]
2. Turner, B.L.; Lambin, E.F.; Reenberg, A. The emergence of land change science for global environmental change and sustainability. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 20666–20671. [CrossRef] [PubMed]
3. Zhang, J.; Qu, M.; Wang, C.; Zhao, J.; Cao, Y. Quantifying landscape pattern and ecosystem service value changes: A case study at the county level in the Chinese Loess Plateau. *Glob. Ecol. Conserv.* **2020**, *23*, e01110. [CrossRef]
4. da Silva, A.M.; Huang, C.H.; Francesconi, W.; Saintil, T.; Villegas, J. Using landscape metrics to analyze micro-scale soil erosion processes. *Ecol. Indic.* **2015**, *56*, 184–193. [CrossRef]
5. Yushanjiang, A.; Zhang, F.; Yu, H. Quantifying the spatial correlations between landscape pattern and ecosystem service value: A case study in Ebinur Lake Basin, Xinjiang, China. *Ecol. Eng.* **2018**, *113*, 94–104. [CrossRef]
6. Cao, Q.; Yu, D.; Georgescu, M.; Han, Z.; Wu, J. Impacts of land use and land cover change on regional climate: A case study in the agro-pastoral transitional zone of China. *Environ. Res. Lett.* **2015**, *10*, 124025. [CrossRef]
7. Kindu, M.; Schneider, T.; Teketay, D.; Knoke, T. Changes of ecosystem service values in response to land use/land cover dynamics in Munessa–Shashemene landscape of the Ethiopian highlands. *Sci. Total Environ.* **2016**, *547*, 137–147. [CrossRef]
8. IPBES, W. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Summary for Policy Makers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES Secretariat, Bonn, Germany. 2019. Available online: https://www.ipbes.net/system/tdf/spm_asia-pacific_2018_digital.pdf?file=1&type=node&id=28394 (accessed on 13 June 2022).
9. United Nations Environment Protection, Sustainable Development, Convention on Biodiversity, Statistical Commission (2018) System of Environmental-Economic Accounting—Experimental Ecosystem Accounting (SEEA EEA) Technical Recommendation. Available online: https://seea.un.org/sites/seea.un.org/files/Presentations/Training_China_2017/seea_eea_tech_rec_final_v3.2_16oct2017.pdf (accessed on 27 June 2022).
10. Christie, M.; Fazey, I.; Cooper, R.; Hyde, T.; Kenter, J.O. An evaluation of monetary and non-monetary techniques for assessing the importance of biodiversity and ecosystem services to people in countries with developing economies. *Ecol. Econ.* **2012**, *83*. [CrossRef]
11. Jackson, L.E.; Pascual, U.; Hodgkin, T. Utilizing and conserving agrobiodiversity in agricultural landscapes. *Agric. Ecosyst. Environ.* **2007**, *121*, 196–210. [CrossRef]

12. Wang, X.; Dong, X.; Liu, H.; Wei, H.; Fan, W.; Lu, N.; Xu, Z.; Ren, J.; Xing, K. Linking land use change, ecosystem services and human wellbeing: A case study of the Manas River Basin of Xinjiang, China. *Ecosyst. Serv.* **2017**, *27*, 113–123. [CrossRef]
13. Fan, M.; Xiao, Y.T. Impacts of the grain for Green Program on the spatial pattern of land uses and ecosystem services in mountainous settlements in southwest China. *Glob. Ecol. Conserv.* **2020**, *21*, e00806. [CrossRef]
14. Nassauer, J.I. Culture and changing landscape structure. *Landsc. Ecol.* **1995**, *10*, 229–237. [CrossRef]
15. Sauer, C.O. *The Morphology of Landscape. Foundation Papers in Landscape Ecology*; Columbia University Press: New York, NY, USA, 1925; pp. 36–70.
16. Antrop, M. The concept of traditional landscapes as a base for landscape evaluation and planning. The example of Flanders Region. *Landsc. Urban Plan.* **1997**, *38*, 105–117. [CrossRef]
17. Brunckhorst, D.; Coop, P.; Reeve, I. Eco-civic'optimisation: A nested framework for planning and managing landscapes. *Landsc. Urban Plan.* **2006**, *75*, 265–281. [CrossRef]
18. Jacobs, P. DeIn {form} ing Landscape Re. *Landsc. J.* **1991**, *10*, 48–56. [CrossRef]
19. Nassauer, J.I. Landscape as medium and method for synthesis in urban ecological design. *Landsc. Urban Plan.* **2012**, *106*, 221–229. [CrossRef]
20. Pinto-Correia, T.; Kristensen, L. Linking research to practice: The landscape as the basis for integrating social and ecological perspectives of the rural. *Landsc. Urban Plan.* **2013**, *120*, 248–256. [CrossRef]
21. Tress, B.; Tress, G. Capitalising on multiplicity: A transdisciplinary systems approach to landscape research. *Landsc. Urban Plan.* **2001**, *57*, 143–157. [CrossRef]
22. Angelstam, P.; Grodzynskyi, M.; Andersson, K.; Axelsson, R.; Elbakidze, M.; Khoroshev, A.; Kruhlov, I.; Naumov, V. Measurement, collaborative learning and research for sustainable use of ecosystem services: Landscape concepts and Europe as laboratory. *Ambio* **2013**, *42*, 129–145. [CrossRef]
23. De, A.I.; Schmitz, M.F.; Aguilera, P.; Pineda, F.D. Modelling of landscape changes derived from the dynamics of socio-ecological systems: A case of study in a semiarid Mediterranean landscape. *Ecol. Indic.* **2008**, *8*, 672–685.
24. Gobster, P.H.; Xiang, W.N. What do we mean by "landscape"? *Landsc. Urban Plan.* **2012**, *106*, 219–220. [CrossRef]
25. Matthews, R.; Selman, P. Landscape as a focus for integrating human and environmental processes. *J. Agric. Econ.* **2006**, *57*, 199–212. [CrossRef]
26. Spies, T.A.; White, E.M.; Kline, J.D.; Fischer, A.P.; Ager, A.; Bailey, J.; Bolte, J.; Koch, J.; Platt, E.; Olsen, C.S.; et al. Examining fire-prone forest landscapes as coupled human and natural systems. *Ecol. Soc.* **2014**, *19*, 1–14. [CrossRef]
27. Liu, J.; Dietz, T.; Carpenter, S.R.; Alberti, M.; Folke, C.; Moran, E.; Pell, A.N.; Deadman, P.; Kratz, T.; Lubchenco, J.; et al. Complexity of coupled human and natural systems. *Science* **2007**, *317*, 1513–1516. [CrossRef]
28. Yuill, C.; Mueller-Hirth, N.; Song Tung, N.; Thi Kim Dung, N.; Tram, P.T.; Mabon, L. Landscape and wellbeing: A conceptual framework and an example. *Health* **2019**, *23*, 122–138. [CrossRef] [PubMed]
29. Turner, B.L.; Lambin, E.F.; Verburg, P.H. From land-use/land-cover to land system science. *Ambio* **2021**, *50*, 1291–1294. [CrossRef]
30. Plieninger, T.; Huntsinger, L. Complex rangeland systems: Integrated social-ecological approaches to silvopastoralism. *Rangel. Ecol. Manag.* **2018**, *71*, 519–525. [CrossRef]
31. Lescourret, F.; Magda, D.; Richard, G.; Adam-Blondon, A.F.; Bardy, M.; Baudry, J.; Doussan, I.; Dumont, B.; Lefèvre, F.; Litrico, I.; et al. A social–ecological approach to managing multiple agro-ecosystem services. *Curr. Opin. Environ. Sustain.* **2015**, *14*, 68–75. [CrossRef]
32. Cao, Q.; Liu, Y.; Georgescu, M.; Wu, J. Impacts of landscape changes on local and regional climate: A systematic review. *Landsc. Ecol.* **2020**, *35*, 1269–1290. [CrossRef]
33. Heinimann, A.; Mertz, O.; Frolking, S.; Egelund, C.A.; Hurni, K.; Sedano, F.; Hurtt, G. A global view of shifting cultivation: Recent, current, and future extent. *PLoS ONE* **2017**, *12*, e0184479. [CrossRef]
34. Cairns, M. *Shifting Cultivation Policies: Balancing Environmental and Social Sustainability*; CABI: Wallingford, UK, 2017.
35. Karki, M.B. Policies that transform shifting cultivation practices: Linking multi-stakeholder and participatory processes with knowledge and innovations. In *Shifting Cultivation Policies: Balancing Environmental and Social Sustainability*; CABI: Wallingford, UK, 2017; pp. 889–916.
36. Nath, A.J.; Reang, D.; Sileshi, G.W. The shifting cultivation juggernaut: An attribution problem. *Global Chall.* **2022**, *6*, 2200051. [CrossRef] [PubMed]
37. Dressler, W.H.; Wilson, D.; Clendenning, J.; Cramb, R.; Keenan, R.; Mahanty, S.; Bruun, T.B.; Mertz, O.; Lasco, R.D. The impact of swidden decline on livelihoods and ecosystem services in Southeast Asia: A review of the evidence from 1990 to 2015. *Ambio* **2017**, *46*, 291–310. [CrossRef] [PubMed]
38. Pandey, D.K.; Adhiguru, P.; De, H.K.; Upadhyay, A.D.; Radhakrishnan, K. Income inequality among indigenous people dependent on traditional agroforestry system in Indian Himalayas. *Indian J. Agric. Sci.* **2021**, *91*, 847–851. [CrossRef]
39. Smith, H.E.; Ryan, C.M.; Vollmer, F.; Woollen, E.; Keane, A.; Fisher, J.A.; Baumert, S.; Grundy, I.M.; Carvalho, M.; Lisboa, S.N.; et al. Impacts of land use intensification on human wellbeing: Evidence from rural Mozambique. *Glob. Environ. Chang.* **2019**, *59*, 101976. [CrossRef]
40. Wu, J. Landscape sustainability science (II): Core questions and key approaches. *Landsc. Ecol.* **2021**, *36*, 2453–2485. [CrossRef]
41. Fischer, A.P. Forest landscapes as social-ecological systems and implications for management. *Landsc. Urban Plan.* **2018**, *177*, 138–147. [CrossRef]

42. Jiang, N.; Li, P.; Feng, Z. Remote sensing of swidden agriculture in the tropics: A review. *Int. J. Appl. Earth Obs. Geoinf.* **2022**, *112*, 102876. [CrossRef]
43. Abraham, A.; Sommerhalder, K.; Abel, T. Landscape and wellbeing: A scoping study on the health-promoting impact of outdoor environments. *Int. J. Public Health* **2010**, *55*, 59–69. [CrossRef]
44. Brehm, J.M.; Eisenhauer, B.W.; Stedman, R.C. Environmental concern: Examining the role of place meaning and place attachment. *Soc. Nat. Resour.* **2013**, *26*, 522–538. [CrossRef]
45. Knez, I.; Eliasson, I. Relationships between personal and collective place identity and wellbeing in mountain communities. *Front. Psychol.* **2017**, *8*, 79. [CrossRef]
46. Knez, I. Place and the self: An autobiographical memory synthesis. *Philos. Psychol.* **2014**, *27*, 164–192. [CrossRef]
47. Bélisle, A.C.; Wapachee, A.; Asselin, H. From landscape practices to ecosystem services: Landscape valuation in Indigenous contexts. *Ecol. Econ.* **2021**, *179*, 106858. [CrossRef]
48. Ford, J.D.; King, N.; Galappaththi, E.K.; Pearce, T.; McDowell, G.; Harper, S.L. The resilience of indigenous peoples to environmental change. *One Earth* **2020**, *2*, 532–543. [CrossRef]
49. FSI. *India State of Forest Report*; Forest Survey of India (Ministry of Environment, Forests & Climate Change): Dehradun, India, 2021.
50. Chandramouli, C.; General, R. *Census of India 2011. Provisional Population Totals*; Government of India: New Delhi, India, 2011; pp. 409–413.
51. Dattagupta, S.; Gupta, A. Non-timber Forest Product (NTFP) in Northeast India: An Overview of Availability, Utilization, and Conservation. In *Bioprospecting of Indigenous Bioresources of North-East India*; Purkayastha, J., Ed.; Springer: Singapore, 2016.
52. Maithani, B.P. *Shifting Cultivation in North-East India: Policy Issues and Options*; Mittal Publications: New Delhi, India, 2005.
53. Dey, S.; Laila, R. Reconstruction of Women's Role in Jhum Cultivation and Shift in the Gendered Division of Labor among the Garos. In *Gendered Lives, Livelihood and Transformation*; University Press Limited: Dhaka, Bangladesh, 2017; pp. 8–39.
54. Ellena, R.; Nongkynrih, K.A. Changing gender roles and relations in food provisioning among matrilineal Khasi and patrilineal Chakhesang Indigenous rural People of North-East India. *Matern. Child Nutr.* **2018**, *13*, e12560. [CrossRef]
55. Bhuyan, R. Review Note on Shifting Cultivation in Northeast India amidst Changing Perceptions. *Dhaulagiri J. Social Anthropol.* **2019**, *13*, 90–95. [CrossRef]
56. Sati, V.P. Shifting cultivation in Mizoram, India: An empirical study of its economic implications. *J. Mt. Sci.* **2019**, *16*, 2136–2149. [CrossRef]
57. Pandey, D.K.; Dobhal, S.; De, H.K.; Adhiguru, P.; Devi, S.V.; Mehra, T.S. Agrobiodiversity in changing shifting cultivation landscapes of the Indian Himalayas: An empirical assessment. *Landsc. Urban Plan.* **2022**, *220*, 104333. [CrossRef]
58. Pandey, D.K.; Momin, K.C.; Dubey, S.K.; Adhiguru, P. Biodiversity in agricultural and food systems of jhum landscape in the West Garo Hills, North-eastern India. *Food Secur.* **2022**, *14*, 791–804. [CrossRef]
59. Pandey, D.K.; De, H.K.; Dubey, S.K.; Kumar, B.; Dobhal, S.; Adhiguru, P. Indigenous people's attachment to shifting cultivation in the Eastern Himalayas, India: Across-sectional evidence. *For. Policy Econ.* **2020**, *111*, 102046. [CrossRef]
60. Sitlhou, H. The shifting 'stages' of performance: A study of 'ChavangKut'festival in Manipur. *Asian Ethn.* **2018**, *19*, 468–488. [CrossRef]
61. Falassi, A. *Time out of Time: Essays on the Festival*; University of New Mexico Press: Albuquerque, NM, USA, 1987.
62. Waterman, S. Carnivals for elites? The cultural politics of arts festivals. *Prog. Hum. Geogr.* **1998**, *22*, 54–74. [CrossRef]
63. NRCS. Wasteland Atlas of India. 2019. Available online: https://dolr.gov.in/documents/wasteland-atlas-of-india (accessed on 17 June 2019).
64. Pavot, W.; Diener, E.; Oishi, S.; Tay, L. The cornerstone of research on subjective wellbeing: Valid assessment methodology. Handbook of wellbeing. In *Noba Scholar Handbook Series: Subjective Wellbeing*; DEF Publishers: Salt Lake City, UT, USA, 2018.
65. Cantril, H. *Pattern of Human Concerns*; Rutgers University Press: Brunswick, NJ, USA, 1965.
66. Cheung, F.; Lucas, R.E. Assessing the validity of single-item life satisfaction measures: Results from three large samples. *Qual. Life Res.* **2014**, *23*, 2809–2818. [CrossRef] [PubMed]
67. Gallup, I. Understanding How Gallup Uses the Cantril Scale: Development of the 'Thriving, Struggling, Suffering' Categories. 2013. Available online: https://news.gallup.com/poll/122453/understanding-gallup-uses-cantril-scale.aspx (accessed on 13 May 2016).
68. Costanza, R.; Fisher, B.; Ali, S.; Beer, C.; Bond, L.; Boumans, R.; Danigelis, N.L.; Dickinson, J.; Elliott, C.; Farley, J.; et al. Quality of life: An approach integrating opportunities, human needs, and subjective wellbeing. *Ecol. Econ.* **2007**, *61*, 267–276. [CrossRef]
69. Summers, J.K.; Smith, L.M.; Case, J.L.; Linthurst, R.A. A review of the elements of human wellbeing with an emphasis on the contribution of ecosystem services. *Ambio* **2012**, *41*, 327–340. [CrossRef]
70. Pant, R.M.; Tiwari, B.K.; Choudhury, D. *Report of Working Group III, Shifting Cultivation: Towards a Transformational Approach*; NITI Aayog: New Delhi, India, 2018.
71. Chyne, D.A.; Meshram, I.I.; Rajendran, A.; Kodali, V.; Getti, N.; Roy, P.; Kuhnlein, H.V.; Longvah, T. Nutritional status, food insecurity and biodiversity among the Khasi in Meghalaya, North-East India. *Matern. Child. Nutr.* **2017**, *13*, 12557. [CrossRef] [PubMed]
72. Camfield, L.; Guillen-Royo, M.; Velazco, J. Does Needs Satisfaction Matter for Psychological and Subjective Wellbeing in Developing Countries: A Mixed-Methods Illustration from Bangladesh and Thailand. *J. Happiness Stud.* **2010**, *11*, 497–516. [CrossRef]

73. Bose, P. Oil palm plantations vs. shifting cultivation for indigenous peoples: Analyzing Mizoram's New Land Use Policy. *Land Use Policy* **2019**, *8*, 115–123. [CrossRef]
74. Pathy, J. Contemporary Struggles of the Tribal Peoples of India. *Indian J. Soc. Work* **1998**, *59*, 208–229.
75. Saikia, P. *Ethnic Mobilisation and Violence in Northeast India*; Taylor & Francis: Abingdon, UK, 2020.
76. Huppert, F.A. Psychological well-being: Evidence regarding its causes and consequences. *Appl. Psychol. Health Well-Being* **2009**, *1*, 137–164. [CrossRef]

sustainability

MDPI

Article

An Assessment of Sustainability of Dual-Purpose, Dairy and Beef Cattle Production Systems in the Cundinamarca Department (Colombia) Using the MESMIS Framework

Fabián Cruz [1], Dolly Pardo [1], Alberto Horcada [2] and Yolanda Mena [2,*]

[1] Animal Production Department, Veterinary Faculty, Antonio Nariño University, Cra 3 este # 47ª 15., Sede Circunvalar, Bogota 110231, Colombia; jaime.cruz@uan.edu.co (F.C.); dopardo@uan.edu.co (D.P.)

[2] Agronomy Department, School of Agricultural Engineering, University of Seville, Ctra, Utrera km 1, 41013 Seville, Spain; albertohi@us.es

* Correspondence: yomena@us.es; Tel.: +34-95-4486-449

Abstract: The Cundinamarca Department is located in the Colombian Andean region, and features a variety of bovine production systems dedicated to milk, beef or dual-purpose production in cold, warm and temperate climate areas, respectively. This paper analyses the sustainability of a sample of 35 farms (12 dual-purpose, 13 milk production and 10 beef production) located in some of its municipal areas using MESMIS methodology, which evaluated indicators related to social, environmental and economic factors of the systems during 1 year, grouping them by their productivity, adaptability, equity, self-management and resilience. For productivity, adaptability and equity, the dairy systems scored higher than dual-purpose and beef systems, whereas for the indicators of self-management, stability and resilience, the dairy systems scored lowest, while dual-purpose systems were the best. The indicators of economic sustainability increased in proportion to the intensification of the production system, availability of agricultural machinery and added value, resulting in the best scores being obtained by the dairy system and the worst by the beef system. For social sustainability indicators, the best score was obtained by dual-purpose systems, with dairy systems scoring the lowest, while dairy systems scored highest for environmental indicators. The results could be used to endorse public policies to promote the generation of sustainable agricultural systems.

Keywords: productivity; stability; adaptability; equity; self-reliance; SWOT

Citation: Cruz, F.; Pardo, D.; Horcada, A.; Mena, Y. An Assessment of Sustainability of Dual-Purpose, Dairy and Beef Cattle Production Systems in the Cundinamarca Department (Colombia) Using the MESMIS Framework. *Sustainability* **2024**, *16*, 7054. https://doi.org/10.3390/su16167054

Academic Editors: Tarek Ben Hassen, Hamid El Bilali and Carola Strassner

Received: 28 June 2024
Revised: 3 August 2024
Accepted: 12 August 2024
Published: 16 August 2024

1. Introduction

Livestock represents around 1.4% of the national Gross Domestic Product (GDP) of the Colombian economy [1]. The Cundinamarca Department has 5.2% of the cattle national inventory and is characterized by a variety of productive systems for livestock farming with beef and dairy and for the provision of food to meet the growing national demand [2,3]. Their diversity of climates produces a wide range of agro-ecological conditions for livestock or agriculture production.

In a previous study, Cruz et al. [4] conducted an analysis of agricultural information from 116 municipal areas in Cundinamarca, which enabled them to characterize and classify the bovine production systems into three categories: dual-purpose, dairy and beef production. In order to assess the sustainability of these three categories of bovine production systems, a detailed analysis is required.

At the farm level, an agricultural system is sustainable if it yields positive economic and social results while preserving the natural resources in the ecosystem [5,6]. Zandstra [7] included environmental sustainability values as a function of chemical input levels, considering that excessive input levels degrade natural resources through accumulation, while inadequate levels degrade resources through exhaustion. This concept is in sharp contrast to the decreasing relationship between chemical input levels and sustainability proposed by Stinner and House [8]. Moreover, social values such as equity, tradition, self-sufficiency, conservation of agrarian culture and preference for small privately run farms have also been incorporated into definitions of sustainability [9].

Until now, the concept of sustainability has yet to be put into practice in many agricultural contexts. To achieve sustainable systems of agriculture, it is imperative to carry out a comprehensive assessment that encompasses broader ecological, economic and social dimensions [5]. To measure the sustainability performance of farms, a large number of sustainability assessment tools have been developed [10], which generally integrate a wide range of themes and indicators to obtain a holistic view and are used for different purposes, such as monitoring, certification, consumer information, farm advice and research [11].

Several frameworks which use indicators to assess sustainability have been described in the literature [12]. Sustainability indicators are tools that can be used by farmers at the farm or field level to assess the effects of managerial changes [13]. Nevertheless, any of these are purely theoretical and cannot be used directly by farmers to make decisions. In fact, complex tools that require large data inputs and expert knowledge to provide estimates are generally not suitable for use at the farm level.

Different techniques are available to build sustainability indicators [6,10,12], which give some guidance regarding the selection and construction of composite indicators, involving strict quality criteria and accurate data gathering to calculate empirical values. However, indicators should be used with caution in all cases because they must be regarded as only partial representations of the complex reality [14]. In order to build and develop indicators for the sustainability evaluation of production systems, researchers agree that one key element is that farmers should participate and be consulted [15].

Given the complexity of the concept of sustainability, as well as the diversity of production systems, the information generated based on indicators must be analyzed in an integrated way. To achieve this, a range of different methodologies is available to facilitate our analysis and understanding of the data. Of these, Response-Inducing Sustainability Evaluation (RISE) is an indicator-based sustainability assessment tool developed at the Bern University of Applied Sciences (School of Agricultural, Forest and Food Sciences, HAFL) [16], while the IDEA (Indicateurs de Durabilité des Exploitations Agricoles or 'Farm Sustainability Indicators') method is tool which is used widely in Europe. IDEA assesses whole-farm sustainability using agro-ecological (18 indicators), socio-territorial (18 indicators) and economic (six indicators) scales [17]. Van Cauwenbergh et al. [6] proposed a method known as SAFE (Sustainability Assessment of Farming and the Environment Framework), which recommended a hierarchical framework based on the goods and services provided by agricultural ecosystems, with the primary level of the hierarchy being the "principles" that correlate with the three dimensions of sustainability: economic, social and environmental.

A methodology frequently used in Latin America to analyze sustainability in agricultural systems is MESMIS (for its acronym in Spanish—Marco para la evaluación de sistemas de manejo de recursos naturales incorporando indicadores de sustentabilidad). It has an operative structure featuring a six-step cycle, including the description of the systems, the identification of critical points and the selection of specific indicators for the environmental, social and economic dimensions of sustainability. The data obtained by means of the indicators is integrated to obtain a value judgment about the resource management systems and to provide suggestions and insights aimed at improving their socio-environmental profile [12].

The aim of this work was to evaluate the sustainability of farms representative of the range of cattle production systems for dual-purpose, milk production and beef production in Cundinamarca Department (Colombia), using the MESMIS method. Understanding and improving the sustainability of these livestock production systems could contribute to achieving sustainable development goals (SDG), specifically Goal 1 (no poverty), Goal 2 (zero hunger), Goal 12 (responsible consumption and production), Goal 13 (climate action) and Goal 15 (life on land). The results of this research could help to provide strategies for future decision-making in productive, environmental, social or political spheres to improve livestock activity on the region, country and surroundings at large.

2. Materials and Methods

2.1. Area Study and Sample Selection

This study was carried out on farms employing livestock systems in the Department of Cundinamarca (Colombia), covering an area of 24,210 km^2, with approximately 3.2 million registered inhabitants living in 116 municipalities distributed over 15 provinces, of whom 8.43% are agricultural producers. The main agricultural products are potatoes (25.4%), sugar cane (19.1%), coffee (15.2%) and other vegetables (39,7%). Notably, this department also provides 10.4% of the national inventory of laying hens, 8.1% of broilers, 6% of cattle and 7% of pigs [2,3].

The present research was based on previous studies reported by Cruz et al. [4]. Thus, with respect to cattle production, the three cattle livestock systems in this area were described as dual-purpose, dairy and beef production (Figure 1). The 'dual-purpose' group included 48 municipal areas, in which 64.6% of the farms employed dual-purpose production and assigned 57.5% of the total registered bovines. The average farm size was 5.2 ha, with 14.7 cattle per farm, a carrying capacity (livestock unit of 500 kg per hectare: LSU/ha) of 1.2 LSU/ha and a milk production per cow of dual-purpose cows of 5.9 kg/d. The 'dairy production' group includes 36 municipal areas, where 65.9% of the farms and 61.9% of their bovines are involved with dairy production. The farms have on average 3.8 ha, with 31.8 cattle per farm, a carrying capacity of 2.3 LSU/ha and a milk production per cow of 19.9 kg/d in specialized systems and 11 kg/d in traditional systems. Moreover, 66.6% of the farms in the 32 municipal areas located in warm climate are dedicated to beef production, with approximately 20% of their area used for agriculture and 63.6% of bovines for beef production. The farms for cattle breeding have an average size of 8.5 ha, with 22.3 cattle/farm and a carrying capacity of 1.2 LSU/ha. In relation to other non-bovine activity, in the department, there is considerable technical poultry and pig activity, and marginal sheep, goat and horse production. More information can be obtained in Cruz et al. [4].

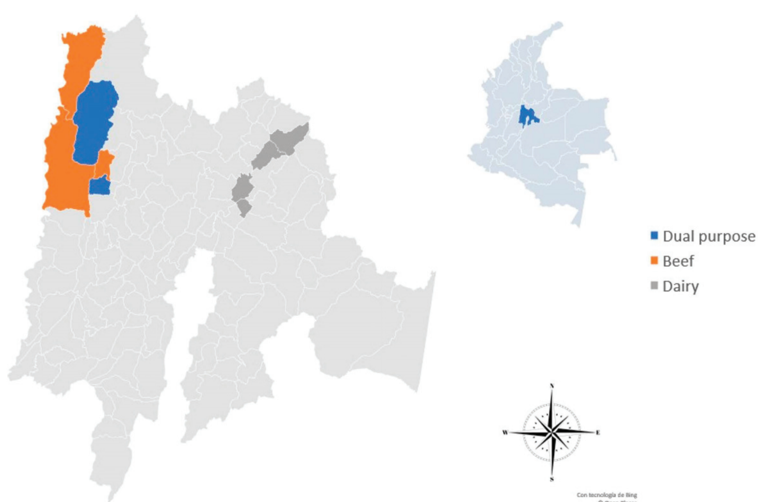

Figure 1. Location of farms sampled in Department of Cundinamarca (Colombia), according to production system.

Description of farm studies: To conduct key case studies, 35 representative farms were selected: 12 for dual-purpose, 13 for dairy and 10 for beef. Farms were selected according to their main productive characteristics, previous experience of the field staff and the researchers' knowledge of the respective geographical areas. The main characteristics of the farms selected in this study are shown in Table 1.

Table 1. Cattle production systems characteristics.

Description	Dual-Purpose	Dairy	Beef
Number of farms	12	13	10
Average land area (ha) *	30.23	19.9	51.83
Carrying capacity (LSU/ha/year) *	1.35	1.91	1.57
Altitude (m.a.s.l) *	1050	2680	520
Main species	Crossed *B. indicus–B. taurus*	*B. taurus*	*B. indicus*
Main products	Raw milk Males for rearing and fattening	Raw milk	Fattening males

* LSU: Livestock unit (500 kg); ha: hectare; m.a.s.l.: meter above sea level.

2.2. MESMIS Framework for Assessing Sustainability

The MESMIS framework enables us to measure and monitor sustainability indicators as part of a systemic, participatory, interdisciplinary and flexible evaluation process. This methodology is well adapted to small farmers, who usually run diversified, small-scale farms, employ family labor and produce both subsistence and commercial goods as crops, livestock or forest products [12].

A complete description of MESMIS is given by López-Ridaura et al. [12] and Masera et al. [18]. Moreover, some of its applications and experiences have been discussed by Speelman et al. [19] and Ripoll-Bosch et al. [20]. The MESMIS program sets five strategic and interrelated goals: (1) to integrate the theory of complex systems into sustainability assessments which are context-based and constrained to a specific spatial and time scale; (2) to develop and update a comprehensive, coherent sustainability assessment framework that can allow stakeholders to make short- and long-term multicriteria comparisons of alternative Natural Resource Management (NRM) strategies; (3) to facilitate the learning processes by which stakeholders can understand, use and give feedback on the concepts, tools and outcomes of such assessments; (4) to validate the framework by promoting a number of case studies; and (5) to promote and facilitate the participation of all stakeholders in the assessment process. In our study, the framework was developed by critically integrating key concepts regarding sustainable development, sustainability, systemic approaches, natural resource management, sustainability evaluation and sustainability indicators [12].

The sustainability analysis of NRM combined with MESMIS methodology is based on the evaluation of seven general systemic attributes: productivity (capacity to generate goods and services), stability (ability to maintain a constant level of productivity under normal conditions), reliability (maintaining productivity at levels close to equilibrium under normal environmental shocks), resilience (a return to equilibrium or productivity levels similar to the initial level after serious disturbance), adaptability or flexibility (ability to find new levels of balance or to continue helping to provide beneficial, long-term changes in the environment), equity (a system's ability to distribute both intra-and inter-generational benefits and costs fairly) and self-reliance (a system's ability to regulate and control interactions with the outside world). Of these, stability, reliability and resilience attributes can be grouped as attributes of "stability" to express the ability of the system to cope with change [12]. The selection of indicators to be included in each attribute, and of the specific weight of each of the indicators, requires a participatory process conducted by an interdisciplinary evaluation team. In this context, the Delphi technique, a procedure that organizes and structures debates among various groups of experts, is recognized as a systematic method to analyze and discuss complex issues, helping channel diverse views and opinions into one or more communal notion through an iterative feedback process [21].

2.3. Data Collected and Information Treatment

Following the MESMIS methodology summarized in Section 2.2, the five-stage evaluating process was conducted as follows:

Stage 1: Definition and identification of critical points of the systems evaluated using in-depth interviews with different stakeholders (farmers and technical advisers) to elaborate a SWOT analysis (strengths, weaknesses, opportunities, and threats) [22]. Characteristics taken into account include satisfaction of labor, time taken to travel to markets, availability of basic public services, rest days per year, participation of women in technical decisions or family's involvement in the farm activities in the medium term (15 years).

Stage 2: Selection of the indicators. A group of experts composed of technical advisers and researchers, using the previous SWOT analysis, selected the indicators, and their correspondence was used to establish system sustainability attributes and sustainability pillars.

Stage 3: Monitoring of 35 farms and collection of the data needed to calculate the indicators. In this study, data were collected during a 12-month period between 2022 and 2023.

Stage 4: Data obtained in the field were entered into a matrix, which included the average of each indicator for each of the three types of cattle production (dual-purpose, dairy and beef). Likewise, the optimal reference value for each indicator was included. To obtain this, optimal values were defined by 8 experts (veterinarians, animal scientists and ranchers) consulting references in the literature referring to each region. Finally, the degree of approximation of each system to this optimal value was calculated and expressed through an index of approximation to sustainability, which could range between 0% (furthest from the value considered sustainable) and 100% (maximum value of sustainability for that indicator). The approximation indices for each indicator and each farming type were obtained through the following formula: (indicator's value/optimal value) $\times$ 100. In the case of complementary finances, it worked in the opposite way, that is, the best indices were those with the lowest value. In these cases, the formula applied was (optimal value/indicator's value) $\times$ 100. Whatever the case, an index value closer to 100% is better in terms of sustainability.

Stage 5: Conclusions and recommendations for improving sustainability of the animal production systems studied were presented.

3. Results

3.1. SWOT Analysis

The ideas summarizing the main points from the interviews with the stakeholders are set out in Table 2. The main strengths of cattle production lay in the grazing-based production, the breeds used for tropical conditions and the highly diverse surroundings. The key opportunities were related to the development of traditional local products with the designation of origin, functional attributes or the production system. A number of different weaknesses were noted, including little generational relief, few transformation processes on farms and poor use of technology. The most important threats from the general context are the poor socioeconomic development in rural areas and the lack of state socio-economic incentives for production.

Table 2. Production system SWOT analysis.

Cattle Production System	Strengths	Weaknesses
Dual-purpose	• Grazing-based production. • Income from the sale of milk and fattened animals. • Use of *Bos taurus* × *Bos indicus* crossings adapted to climate. • Agro-ecological diversity of producing municipal areas.	• Distance to consumption centers (>3 h). • Aging of producers. • Few transformation processes on farms. • Poor productivity of systems. • Poor use of technology.
Dairy	• Grazing-based production. • Use of *taurus* breeds specialized in milk production. • Proximity to consumption centers (<3 h). • Specialized systems with good technological support.	• Heterogenicity in the hygienic quality of milk obtained. • Peasant systems with low level of technological development. • Few transformation processes on farms. • Aging of producers.
Beef	• Grazing-based production. • Use of *indicus* breeds adapted to tropical conditions. • High biodiversity in the environment. • Specialized systems in growth and fattening.	• Distance to consumption centers (>5 h). • Little generational relief. • Few transformation processes (meat preparation) on farms. • Poor productivity of systems. • Poor use of technology.
	Opportunities	**Threats**
Dual-purpose	• National federation and health institutions that develop programs for producers. • Meat exports. • Development of traditional local products with designation of origin, functional attributes or production system.	• Deficient road infrastructure. • Lack of state socio-economic incentives for production. • Import of dairy products. • Little socioeconomic development in rural areas.
Dairy	• National federation and health institutions that develop programs for producers. • Good infrastructure of roads. • Proximity to milk industry. • Development of traditional local products with designation of origin, functional attributes or production system.	• Lack of state socio-economic incentives for production. • Import of dairy products. • Increase in land value due to urbanization processes and proximity to large consumption centers.
Beef	• National federation and health institutions that develop programs for producers. • Opportunities for exporting meat. • Development of traditional local products with designation of origin, functional attributes or production system.	• Deficient road infrastructure. • Lack of state socio-economic incentives for production. • Poor socio-economic development in rural areas.

3.2. Analysis of Sustainability by Attributes, Pillars and Indicators

With the participation of the group of experts and taking account the SWOT results, 39 indicators were selected, which were grouped into five attributes as follows: productivity (n = 8), adaptability (n = 9), equity (n = 7), self-management (n = 5) and resilience (n = 10) (see Tables 3 and 4). The average weighted scores obtained by each farm for any sustainability indicator are only given in the aggregate information. For this reason, an analysis of individual indicators is needed to describe the farming systems in detail.

Table 3. Production system productivity and adaptability indicators compared to optimal values.

Attribute	Indicator	SP	Unit	Weight	Optimal	Dual-Purpose		Dairy		Beef	
Productivity (n = 8)	Meat produced per animal/year	Ec	Kg/year	5%	≥182	217.5	(100.0%)	141.5	(77.7%)	216.8	(100.0%)
	Meat produced per hectare/year	Ec	Kg/ha/year	5%	≥273	293.8	(100.0%)	271.2	(99.3%)	332.4	(100.0%)
	Milk produced per animal/year	Ec	kg average/year	5%	≥3000	1418	(47.3%)	5986	(100.0%)	-	(-%)
	Milk produced per hectare/year	Ec	Kg/ha/year	5%	≥4500	1158	(25.7%)	6866	(100.0%)	-	(-%)
	Average Carrying capacity	Ec	LSU/ha/year	20%	≥1.5	1.35	(90.0%)	1.91	(100.0%)	1.57	(100.0%)
	Net margin per kg milk produced/year	Ec	€/kg/year	15%	≥0.16	0.09	(56.3%)	0.09	(56.3%)	-	(-%)
	Net margin per kg meat produced/year	Ec	€/kg/year	15%	≥0.72	0.53	(73.6%)	0,38	(52.8%)	0.77	(100.0%)
	Net margin per hectare/year	Ec	€/ha/year	30%	≥1500	267.0	(17.8%)	736.5	(49.1%)	255.5	(17.0%)
Adaptability (n = 9)	Use information management systems	S	% Farmers using management systems	5%	100%	38.4	(38.4%)	50.0	(50.0%)	58.3	(58.3%)
	Education level of farmers	S	Scale [a]	10%	2	1	(50.0%)	1.1	(55.0%)	1	(50.0%)
	Time taken to travel to markets <1 h (cities with over 10,000 inhabitants)	S	% farms with time taken to travel to markets < 1 h	15%	100%	100	(100.0%)	100	(100.0%)	91.6	(91.6%)
	Time taken to travel to slaughterhouses	S	% farms with time taken to travel to markets <1 h	5%	100%	53.8	(53.8%)	100	(100.0%)	66.6	(66.6%)
	Diversification of production	En	Scale [b]	15%	≥3	2.7	(90.0%)	1.8	(60.0%)	1.9	(63.3%)
	Use of creole breeds	Ec	Farms using local breeds	10%	>15%	7.7	(51.3%)	0	(0.0%)	0	(0.0%)
	Renewable energy sources	En	Farms using Renewable energy sources	10%	>25%	7.7	(30.8%)	30.0	(100.0%)	16.6	(66.4%)
	Availability of agricultural machinery	Ec	% farmers	15%	100%	30.7	(30.7%)	100.0	(100.0%)	25.0	(25.0%)
	Use of irrigation systems	En	% Farms with irrigation	15%	100%	15.4	(15.4%)	100.0	(100.0%)	0.0	(0.0%)

SP: Sustainability pillar; Ec (economic), En (environmental) and S (social). [a] Min: 0 = No education, but agricultural experience; 1 = Basic or intermediate education and agricultural experience; Max: 2 = Higher education and agricultural experience. [b] Minimum: 1 product; 2 products; Maximum: ≥3 products.

Table 4. Production system equity, self-management and stability indicators compared to optimal values.

Attribute	Indicator	SP	Unit	Weight	Optimal	Dual-Purpose		Dairy		Beef	
Equity (n = 7)	Satisfaction with labor	S	Scale [a]	15%	>4	3.8	(95.0%)	4.0	(100.0%)	4.6	(100.0%)
	Public basic services	S	Scale [b]	15%	3	2.9	(96.7%)	3.0	(100.0%)	2.9	(96.7%)
	Rest day per year	S	Days/year	15%	≥20	4.8	(24.0%)	9.8	(49.0%)	5.8	(29.0%)
	Female workers	S	% female workers	13%	≥50%	44.2	(88.4%)	40.8	(81.6%)	34.2	(68.4%)
	Women's participation in technical decisions	S	% Farms with women as decision-makers	12%	≥50%	84.6	(100.0%)	70.0	(100.0%)	91.6	(100.0%)
	Marketing process	Ec	Scale [c]	15%	2	1	(50.0%)	1.4	(70.0%)	1	(50.0%)
	Labor profitability	S	Net margin/WUY	15%	≥3600 €	5355	(100.0%)	3674	(100.0%)	4871	(100.0%)
Self-management (n = 5)	Family labor	S	% WUY familiar	17%	≥25%	75.1	(100.0%)	17.5	(70.0%)	64.2	(100.0%)
	Fodder self-sufficiency	En	% fodder produced	17%	100%	95.4	(95.4%)	85.5	(85.5%)	97.1	(97.1%)
	Autonomy in decisions on production and marketing	S	% producers with autonomy	16%	100%	84.6	(84.6%)	70.0	(70.0%)	91.6	(91.6%)
	Own farm area	S	% own farm	16%	100%	96.1	(96.1%)	81.5	(81.5%)	93.3	(93.3%)
	Added value	Ec	% farms with product transformation	17%	100%	15.4	(15.4%)	20.0	(20.0%)	0.0	(0.0%)
Stability, resilience (n = 10)	Farm continuity in the next 15 years	S	% producers continuing for next 15 years	15%	100%	84.6	(84.6%)	30.0	(30.0%)	75.0	(75.0%)
	Technical assistance	S	% producers with technical assistance	10%	100%	100.0	(100.0%)	90.0	(90.0%)	83.3	(83.3%)
	Facilities	Ec	Nominal [d]	10%	3	1	(33.3%)	1.7	(56.7%)	1	(33.3%)
	Self-supplying crops	S	% farms with self-supplied crops	10%	100%	84.6	(84.6%)	20.0	(20.0%)	16.6	(16.6%)
	Animal species produced	En	Scale [e]	10%	3	1.9	(63.3%)	1.2	(40.0%)	1.7	(56.7%)
	Use of silvopastoral systems	En	Nominal [f]	10%	3	1	(33.3%)	1	(33.3%)	1	(33.3%)
	Forage species produced	En	Scale [e]	10%	3	3	(100.0%)	2.8	(93.3%)	3	(100.0%)
	Complementary finances	S	% Non-agricultural incomes	5%	≤15%	20.0	(75.0%)	24.5	(61.2%)	27.1	(55.4%)
	Water availability for agricultural use	Ec	Scale [g]	10%	≥1	2.2	(100.0%)	2	(100.0%)	1.7	(100.0%)
	Bio-conservation	En	% area in forest conservation	10%	≥10%	13.8	(100.0%)	4.9	(49.0%)	15.1	(100.0%)

SP: Sustainability pillar; Ec (economic), En (environmental) and S (social). WUY: Working unit year. [a] Minimum: 1 = Very dissatisfied; 2 = Dissatisfied; 3 = Neutral; 4 = Satisfied; Max: 5 = Very satisfied. [b] Minimum: 1 = None; 2= Electricity or rural aqueduct; Max: 3 = Electricity and rural aqueduct. [c] Minimum: 1 = Individual; Max: 2 = Association. [d] 0 = None; 1 = Only for animal management; 2 = Only for store and transformation; 3 = For animal management, store and transformation. [e] 1 = 1 species; 2 = 2 species; 3 = 3 or more species. [f] 0 = None; 1 = less than 25% area; 2 = between 25 and 50%; 3 = more than 50%. [g] 1 = scarce; 2 = sufficient; 3 = abundant.

For the classification of sustainability into three pillars, the experts assigned 14 of indicators to the economic pillar (35.0% of total indicators selected), 18 to the social pillar (45.0%) and 8 to the environmental pillar (20.0%). The optimal value for each indicator, evaluated according to local conditions with the participation of professional advisors, is also shown in Tables 3 and 4.

Positive or negative differences were found between systems for several sustainability indicators, such as net margin per hectare per year (in productivity attribute), availability of agricultural machinery, use of irrigation systems (adaptability attribute), rest days per year, labor profitability (equity), family labor (self-management) and farm continuity in the next 15 years (stability). For self-supplying crops (stability), considerable differences were found in the dual-purpose category.

Tables 3 and 4 present the percentages obtained for each attribute in each production system. The most notable feature of the attribute of 'productivity' was that we found a greater difference in the dairy system compared to the others for the net margin per hectare year indicator. In the same way, for 'adaptability', the dairy system was found to be superior for the attributes of 'renewable energy sources', 'availability of agricultural machinery' and 'use of irrigation systems'. However, for the attribute of self-management, the dual-purpose system scored best, as well as for stability and resilience, where it was found that dairy systems were inferior to the others, especially for the indicator of 'continuity in the next 15 years'.

Figure 2 represents graphically the score obtained by the three systems (dual-purpose, dairy and beef), for the sustainability attributes, as defined in Tables 3 and 4. For productivity, adaptability and equity, the dairy systems scored higher than dual-purpose and beef systems, while for self-management, stability and resilience indicators, the dairy systems obtained the lowest score, with the dual-purpose system the highest.

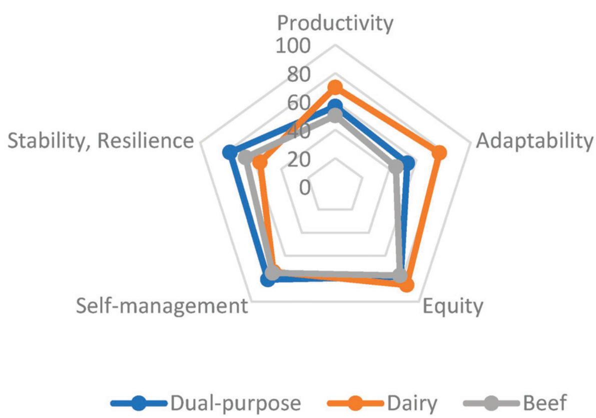

Figure 2. Livestock system sustainability attribute scores.

With respect to the pillars of sustainability, differences among production systems were also considerable. As Figure 3 shows, the economic sustainability indicators increased in line with the intensification of the production system, availability of agricultural machinery and added value, which means that the best score was obtained by the dairy system and the worst by the beef system. For social sustainability indicators, the best score was obtained by dual-purpose systems, due to their family labor and labor profitability, while dairy system scored the lowest. Environmental indicators also showed that the dairy system scored best, probably due to the farms using renewable energy sources.

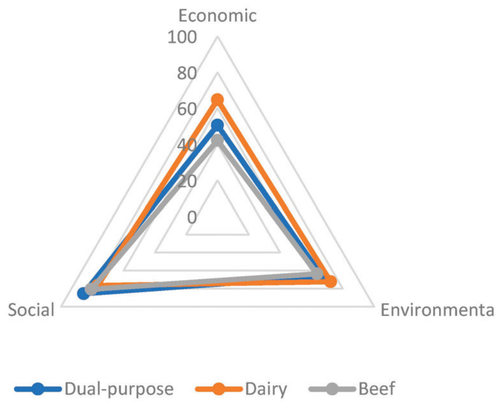

Figure 3. Livestock system sustainability pillar scores.

4. Discussion

4.1. General Approach to the Sustainability of Livestock Systems

The literature on the sustainability assessment of agricultural systems covers the use of integrated and participatory approaches involving various disciplines [23]. These approaches diverge in the different spatial/temporal scales used and the different views taken by the actors in their definition of sustainability [24]. In this context, Bezlepkina et al. [23] and Darnhofer et al. [24] affirmed that policies focusing only on reducing the environmental impact of production systems do not ensure the economic and social reproducibility of farms, and measures taken to improve environmental sustainability need to be implemented at the farm level, with farmers playing a crucial role. On the other hand, at the local level (farmers, technical advisers), greater importance is sometimes given to economic and social issues than to environmental sustainability, and some indicators are perceived as beneficial by some stakeholders and detrimental by others [25].

While the aim of the present research was to compare different livestock systems using representative case studies of farms, the farms following a certain system can be just as heterogeneous as the different systems. It follows, therefore, that it is a challenging task to compare sustainability with multiple indicators across cattle systems, because the critical points of sustainability (and their reference values) can vary across spatial/temporal scales, and therefore, the relevance of certain indicators will not be the same for different systems, agro-ecological regions or socio-economic context, or at different times [26]. Nevertheless, during the participatory process, there is little consensus over reducing the number of indicators and how to distribute individual indicators into particular attributes. In fact, our results and reported by Ripoll-Bosch et al. [20] show how incomes could be assigned to stability or adaptability, or even self-reliance.

Similar average scores for sustainability attributes can also cover up sizeable differences within individual indicators. This means that two systems could have similar scores in one attribute, such as stability, equity or adaptability [20], while the individual indicators of these two systems, such as renewable energy sources or use of irrigation, can vary widely. Binder et al. [27] mentioned that the attributes as defined by MESMIS can also be affected by uncertainty and dynamic aspects of sustainability evaluation, the socio-economic contexts can differ, and there can be trade-offs between attributes and indicators.

4.2. Sustainability Evaluation of Different Types of Cattle Systems in the Department of Cundinamarca by Attributes and Indicators

Productivity attribute: This research found, in beef systems, a meat production of 332.4 kg/ha/year, which is a higher level of productivity than the Colombian average, according to FEDEGAN (Federation of Colombian cattle producers), of 110 kg/year in breeding and fattening systems, and 193 kg/year for the same systems in some improved farms [1].

In regard to the milk produced per animal in the dairy farms evaluated, this research found an average of 5986 kg/year (16.4 kg/day), which is lower in comparison to the 19 kg/day reported in another study by Cruz et al. [4] in specialized dairy and higher than the 11 kg/day reported by the same authors in a peasant dairy. In 2014, the URPA (Regional Unit for Agricultural Planning of Cundinamarca reported an average milk production of 10.25 kg/animal/day for specialized dairy and 7.23 kg/animal/day for traditional dairy [28], while Carulla and Ortega reported an average production in this system of 12 to 14 kg/animal/day [29].

With respect to carrying capacity, between 1.35 LSU/ha/year was found for dual-purpose and 1.91 LSU/ha/year for dairy. Values near 1.2 LSU/ha are considered normal for small and medium livestock producers in Colombia, according to those referenced by González et al. [30]. A higher value in carrying capacity (LSU/ha) is associated with better technological level in the productive systems, which denotes semi-intensive production, characterized by the use of high-yield pastures with electric fences, periodic irrigation and fertilization associated with the food supplementation program systems proposed for Colombia by the CEGA [31]. Carulla and Ortega [29] mentioned that specialized dairy systems in Colombia had an average between 1 and 2 LSU/ha, which is close to the values found in our study. The carrying capacity in beef was 1.2 LSU/ha, which is in line with the complete cycle of breeding and fattening referenced by Mahecha et al. [32] in Colombia.

Adaptability attribute: In Colombia, data on irrigated land is scarce because most irrigation is not registered officially [33]. All the dairy farms evaluated in this research had irrigation systems, probably due to the implementation of improved pastures with a greater demand for water resources, while, in contrast, only 15.4% of dual-purpose farms had them, with none in beef systems, due to its lower technological level and intensification.

In regard to the use of agricultural machinery, all production systems face great challenges in seeking increased efficiency to meet the demands of globalization processes. In fact, specialized dairy systems have sought to optimize processes through the introduction of new technology in milking equipment, the storage and conservation of cold milk and the adoption of programs of good livestock practices in response to the pressure of the dairy industry and to comply with the current regulations [34]. These arguments account for the findings of the present work, with an availability of agricultural machinery in 100% of the dairy systems evaluated. This same variable barely reached 30.7% in dual-purpose systems and 25% in beef livestock, which tends to include areas where it is difficult to use machinery and there is less investment capacity.

The Colombian agricultural sector relies heavily on fossil fuels and suffers from inadequate infrastructure in rural areas, limiting access to energy resources. In fact, the electric power generation capacity in areas not connected to the national grid is supported by diesel in 85.4% of cases, with 14.6% using renewable energy [35]. In many rural areas of Colombia, small milk producers have difficulty accessing electricity networks, or suffer low reliability in their supply. This means that they must generate their own electricity with fuel electric plants in order to keep the temperature of the milk low before to be collected for industrialization and sale in cities. However, solar photovoltaic systems have become a viable option to guarantee a clean, constant supply of energy, taking advantage of the optimum solar radiation conditions that exist in most of the country [36]. Approximately 30% of the dairy producers monitored in this study used some type of alternative energy in their systems, such as for electrifying livestock fences, since in the areas where livestock are kept, there is generally no access to electricity. Solar panels provide the best solution, which are competitively priced and easy to obtain in the market. Another alternative source of energy, although less common in this sector, is to use methane gas from animal manure using anaerobic reactor digestion systems [36]. In our study, we found no farms using biodigesters for energy production, although solar panels for electric fences were found in dual-purpose (7.7% of the farms evaluated) and beef (16.6% of the farms evaluated) systems.

Equity attribute: With respect to the indicator of satisfaction with labor, Beltrán and Tellez [37] reported in technical dairy farming companies in a province in Boyacá (Colombia) that 91.1% of producers were satisfied with living and working in the countryside. The remaining farmers were considering moving to the city due to the difficulties of road access and to improve the educational opportunities for their children. In the present study, the three systems evaluated all scored over 95%, probably due to their tradition as laborers, but those who scored lowest in this variable were those in dual-purpose systems, because the farms evaluated in this category are located far from cities, with fewer opportunities for education and employment for the families.

For the indicator of public basic services, in 2012, in the rural area of the Department of Cundinamarca, about 4% of homes (10,282 houses) did not have electricity and about 1500 had difficulties connecting to the grid due to their remote location, while only 1.4% of rural homes had natural gas [38]. Another study, conducted in 2016 on basic public services [39], reported that the water supply coverage for rural homes was 42.6%, while the sewage coverage was 6.3%. Despite this, the monitoring results observed on farms in 2022 in our study for the three systems analyzed (punctuation over 95%) showed important improvements in public services (electricity and water supply), which has been able to help to improve technological development in local livestock activity.

In general, there are very few studies and little information about gender differences in the livestock sector in Colombia and the rest of Latin America. On the farms evaluated in the present research, producers reported that 44.2% of their workers were women in the dual-purpose system, which was the highest value, while lowest values (40.8 and 34.2%) were found for the dairy and beef systems production, respectively. DANE-ENA [40] reported lower values for the active participation of women in rearing farm animals in Colombia (around 30%). Although it was not confirmed whether they obtained financial remuneration, women were shown to be involved in making decisions on 70% and 91.6% of the farms for dairy and beef, respectively. Arora et al. [41] stated that women in the Department of Cauca participated more actively in the processing and sales of dairy products, while also playing a major role in different livestock and pasture management activities. In the work carried out by Gumucio et al. [42] for Colombian and Costa Rican livestock farms, despite the limited information, it was found that the majority of women worked on their husbands' farms; however, their work in many cases was not renumerated since it was considered "helping at home". In the present research, the farmers stated that over 70% of women were involved in taking technical decisions in the three systems evaluated. Finally, regarding the marketing process, in the three systems evaluated, the milk and beef market is usually promoted individually from the place of production to local or regional markets.

Self-management attribute: In the present research, it was found that for dual-purpose and beef systems, family labor is an important factor (75.1% and 64.2% of the total labor in farm, respectively), compared with dairy systems (17.5%). The producers, most of whom were also owners of the land (>81.5% in the three systems evaluated), stated that they generally had autonomy in making production and marketing decisions (>70%). A similar situation was found in a study carried out in the province of Sumapaz in Cundinamarca (Colombia), where it was found that 17% of the properties were managed at the family level [43]. Fonseca-Carreño et al. [44], in an evaluation carried out with MESMIS methodology in the same region, found that between 75% and 100% of the workforce were members of the family, with 80% of those evaluated owners of the land, 60% stating that they made production and marketing decisions as a family and 40% stating that they made them with their partner.

The added value of products is a key indicator of farm self-management. According to DANE-ENA [40], it is estimated that 8.3% of the milk produced daily at the Colombian level is processed in situ, generally for the production of cheese, which is almost entirely sold through informal channels (through intermediaries, informal cheese shops and in market squares). In some cases, on-farm cheese production solves the marketing problem for milk, which is not collected through formal channels, given the large distances from collection centers and difficult access routes. The remaining 31.7% of the milk is sold to intermediaries belonging to the informal channel, with actors of various sizes participating, while 52.6% of the total milk is sold to the industry. In Colombia, around 400 industries collect raw milk from primary producers, in compliance with Colombian government regulations. However, 52% of the formal milk collection [45] is in the hands of only five of these. Meanwhile, beef produced in Colombia is distributed through formal and informal channels. From its production in breeding and fattening, following the complete cycle or on dual-purpose farms, to its arrival at the end consumer, the generic product (meat) can pass through many hands. Firstly, there is the commercialization of live cattle, which can begin its process through collectors, who sell the cattle (lean or pre-fattened) at livestock auctions or fairs for marketing, or directly take them to informal slaughterhouses or plants for slaughtering and, later, marketing the carcass in butcher's shops and market places. The actors that carry out the transformation in the beef value chain are the animal processing plants or slaughterhouses and the industry dedicated to the production of derivatives. These produce a range of fresh, dried, salted or smoked meat, as well as derivatives such as sausages, black pudding, ham, edible animal offal (innards and giblets) and inedible by-products (skins, tallow and others) [46]. In this study, while the producers of Cundinamarca state that between 15.4 and 20% of milk production is transformed into cheese, in the farms of beef, no transformation process of meat was reported.

Resilience: Regarding continuity on the farm in the next 15 years, in the present work it was found that, in the dual-purpose and beef systems, more than 75% of the farmers wanted to continue their activity, while in the milk production systems, the projected figure barely reaches 30%, probably due to the tough working conditions and the systems having low levels of mechanization and facilities. Beltrán and Téllez [37] reported that 8.9% of dairy producers in a province in Boyacá (Colombia) considered migrating to the city due to the difficult access to roads and the lack of educational opportunities for their children. Regarding the indicator of facilities, the same authors mention that the livestock management activities necessarily take place in the open air, since the animals are kept in grazing systems. For example, milking is carried out at dawn, which exposes the worker to adverse environmental conditions. In dairy systems, the farm worker must remain attentive and available for any eventuality that may happen on the farm, even during their free time, so they cannot mentally disconnect from their work, since the working conditions require it. Consequently, permanent physical and mental fatigue due to the working conditions is a source of dissatisfaction and increases the risk of work accidents [37]. In addition, the farms of small and medium producers only have basic resources for animal management, and it is sometimes non-existent. This was confirmed by Gonzalez-Quintero et al. [47,48] in the study conducted on cattle fattening and breeding in dual-purpose systems in Colombia. Meanwhile, milk production systems usually have better infrastructure and machinery due to the demands that the dairy industry places on product quality [34]. This coincides with the findings in this study, where farms in dairy systems had better infrastructure than dual-purpose and beef systems, mainly for animal management, the storage of raw materials and the processing of products.

The farms of the three systems monitored had technical assistance, with the lowest being those that belonged to the beef systems, with 83.3% stating they received it. In relation to agricultural technical assistance, the Colombian State is responsible for guaranteeing these processes for small- and medium-sized producers, with the secretariats of agriculture in the municipalities charged with carrying out its monitoring and evaluation [49]. Despite several administrative offices running in the Department of Cundinamarca, the provision of services to farmers is reduced [50], and it could be improved by increasing the number of professionals dedicated to technical and administrative advice to farmers.

The changes in economic models has led many underdeveloped nations to reorient their agricultural production processes towards raw material export models [51]. In fact, in these countries, domestic food production has ceased to be a priority, leading to the impoverishment of smallholder farmers with low technological levels and insignificant government aid. This observation has also arisen in Colombia, where the abandonment of primary production is observed in the area to allocating land for export crops and abandoning support for the national food production, leading to a weakening of food sovereignty that also involves a weakening of national food security [52]. This situation is also observed in the specialized beef and milk systems in the Department of Cundinamarca, with under 20% of producers rearing cattle for their own consumption.

For the farms in the three systems evaluated, the extension of silvopasture did not exceed 25% of the total agricultural surface. Despite abundant research favoring and promoting silvopasture systems (SPS), their adoption and use remains at very low levels in Colombia. In fact, UPRA [53] has verified that around 4×10^6 ha has potential for agroforestry, whereas only 216×10^3 ha are currently put to this use, which accounts for only 5% of the potential. This marginal adoption of SPS constitutes a problem not only for Colombia, but also for other Latin American countries, because of its detrimental environmental consequences [54]. Long-term investment, which is required to obtain economic and production benefits, and its high perceived complexity, are still the main barriers hindering the potential adoption of SPS [55], whereby farmers usually adopt several practices, such as the installation of living fences, dispersed trees in paddocks and windbreakers, but few farmers have implemented a fodder bank for animal feed use.

Deforestation is a serious environmental issue in Colombia. In fact, between 2015 and 2016, around 44% more land was deforested [56], with the expansion of agricultural frontiers by extensive cattle farming being the main driver, accounting for 60% of deforested area in Colombia [57]. Livestock farming used 38 million ha, and over 70% is extensively managed with low density tropical cattle farming [53], which has serious environmental consequences, not just in terms of environmental degradation, but also in the low efficiency and profitability of individual farms [58]. On average, less than 15.1% of the three systems monitored in this research practiced forest conservation, with the least conservation corresponding to dairy farming. These figures provide a clear example of the changes to the environment caused by the livestock systems in Cundinamarca, with very few trees included in the systems in this geographical area.

Farmers from Colombia traditionally have several sources of income, with those derived from agricultural activities constituting the majority of the total household income. Colombian national statistics, based on the Household Survey, indicate that agricultural activity is the main source of income and generator of employment in the rural sector of the country for small and medium producers, with only 10% of income coming from remittances, subsidies, pensions or non-agricultural income, such as jobs in nearby towns [59]. This observation contrasts with the situation found in the present work, where between 20 and 27.1% of the producers' total income in the three systems evaluated came from non-agricultural activities such as nearby jobs, remittances and others.

The majority of the Colombian population lives in the Andean region, one of the most vulnerable regions to the effects of climate change. An evaluation of the impacts of climate change on Colombian agriculture shows that if no adaptation measures are taken, 80% of crops could be impacted in over 60% of the current areas of cultivation [60]. Currently, the regions of three systems evaluated in this research have sufficient water supply for livestock activity and agricultural use, as shown in Table 4 (Resilience attribute). However, in the mid-term, this situation could change. Eitzinger et al. [61] proposed that changes in precipitation patterns caused by climate change would affect soil water availability, possibly reducing yields and quality, and thereby lowering farmers' incomes. The shift in climate suitability might also force farmers to shift their crops and livestock to higher elevations, the home of the few remaining forests and the alpine tundra system known as 'páramos'. The effects of this change will be even greater deforestation, which in turn will increase the frequency and intensity of flooding, soil erosion and crop losses due to the changes in the precipitation forecast for the region, together with increased temperatures. As a consequence of the farming systems migrating to higher altitudes (including dairy farms), the ecosystems that provide the population with essential environmental services, like water for rivers and streams, will become threatened.

Traditionally, bovine farming in Colombia is a productive mosaic, not only due to the various forms of production, but also due to the different geographic regions and altitudes in which it is carried out. These frequently include a range of species, which give a mixed character to their farms, combining livestock production of bovines with other bovines (such as buffaloes) and other animals (horses, goats or sheep, poultry or fish) together with agricultural or forestry production. In this process, various forms of pasture management are carried out, using native forage and trees, along with other improved species. Thus, livestock activity has influenced the formation of landscapes made up of grasslands and wild areas [62]. This observation is in line with what was found in the farms in the three systems production we studied (Table 4), where a combination of various species of forage is using for feeding the various species of farm animals.

5. Conclusions

The sustainability evaluation using the MESMIS methodology allowed us to identify that the best attributes of the dual-purpose production systems in Cundinamarca (Colombia) are autonomy and resilience, while for dairy production systems, the best attributes are productivity, adaptability and equity, with beef production systems obtaining high scores for autonomy and equity. With respect to the pillars of sustainability, it was evident how the social dimension is the most important of these systems, and that the economic dimension is the most difficult at the time of the evaluation. The process showed how those systems with better productivity and that carry out agribusiness processes and transformation of their primary products are more sustainable, due to their direct impact on the financial and social aspects.

As recommendations for government and producers to improve sustainability, political measures need to be taken to improve the economic aspects of the dual-purpose and beef systems, through the transformation and industrialization of their products to increase their added value and increase the net margin per hectare. Furthermore, for the environmental pillar, more areas should be dedicated to silvopasture systems, mainly in dairy systems, so that their biodiversity will also improve. The inclusion of renewable energies and improving product diversification, mainly in beef and dual-purpose systems, would certainly contribute to this pillar. As for the social pillar, strategies need to be established that aim at improving the education of producers in the three livestock systems, as well as at establishing systems for the management of their productive and financial information. Productivity is one of the key attributes that must be improved in dual-purpose and beef systems. Here, zootechnical assistance processes are important, so that producers can rear fewer animals with greater productive efficiency and thus increase their net margin per hectare. To improve the attribute of adaptability, access to technological resources and machinery should be encouraged and facilitated, mainly in dual-purpose and beef systems. Finally, aspects like productive and environmental diversity, the most important characteristics of the dual-purpose systems evaluated, must form the backbone of the strategies used to maintain for livestock production in the Department of Cundinamarca, as well as in Colombia in general. Expanding studies to other regions of Colombia is necessary to evaluate the sustainability of their cattle farming systems and generate proposals for their development.

Author Contributions: Conceptualization, analysis, writing—review and editing: F.C., D.P., Y.M. and A.H.; methodology, F.C., Y.M. and A.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data and code used or analyzed in this study are available from the corresponding author upon reasonable request.

Acknowledgments: We would like to thank the farmers who collaborated with their time to provide information for this study.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. FEDEGAN. Cifras de Referencia del Sector Ganadero Colombiano. Informe Técnico Fedegan, 2017. 55p. Available online: www.fedegan.org.co (accessed on 19 April 2022).
2. DANE. Encuesta Nacional Agropecuaria. Departamento Nacional de Estadística, Bogotá. 2019. Available online: https://microdatos.dane.gov.co/index.php/catalog/749#metadata-data_access (accessed on 15 June 2024).
3. Cundimamarca. Mapas y Estadísticas. Gobernación de Cundinamarca. 2022 Cifras. Available online: https://mapas.cundinamarca.gov.co/ (accessed on 28 November 2022).
4. Cruz, F.; Horcada, A.; Castel, J.M.; Mena, Y. Characterization of the Cattle Production Systems in the Department of Cundinamarca (Colombia), Proposals for Sustainability. *Sustainability* **2023**, *15*, 16093. [CrossRef]
5. Antonson, H. Bridging the gap between research and planning practice concerning landscape in Swedish infrastructural planning. *Land Use Policy* **2009**, *26*, 169–177. [CrossRef]
6. Van Cauwenbergh, N.; Biala, K.; Bielders, C.; Brouckaert, V.; Franchois, L.; Cidad, V.; Hermy, M.; Mathijs, E.; Muys, B.; Reijnders, J.; et al. SAFE—A hierarchical framework for assessing the sustainability of agricultural systems. *Agric. Ecosyst. Environ.* **2007**, *120*, 229–242. [CrossRef]
7. Zandstra, H. Sustainability and productivity growth: Issues, objectives and knowledge needs—Guidelines for working groups. In *Reconciling Sustainability with Productivity Growth*; Report of a workshop; University of Florida and Cornell University: Gainesville, FL, USA, 1994.
8. Stinner, B.; House, G. Role of ecology in lower-input, sustainable agriculture: An introduction. *Am. J. Altern. Agric.* **1987**, *2*, 146–147. [CrossRef]
9. Francis, C.; Youngberg, G. Sustainable agriculture—An overview. In *Sustainable Agriculture in Temperate Zones*; Francis, C.A., Flora, C.B., King, L.D., Eds.; John Wiley & Sons: New York, NY, USA, 1990; pp. 1–23.
10. De Olde, E.; Oudshoorn, F.; Sørensen, C.; Bokkers, E.; de Boer, I.J.M. Assessing sustainability at farm-level: Lessons learned from a comparison of tools in practice. *Ecol. Indic.* **2016**, *66*, 391–404. [CrossRef]
11. Schader, C.; Grenz, J.; Meier, M.; Stolze, M. Scope and precision of sustainability assessment approaches to food systems. *Ecol. Soc.* **2014**, *19*, 42. [CrossRef]
12. López-Ridaura, S.; Masera, O.; Astier, M. Evaluating the sustainability of complex socio-environmental systems. the MESMIS framework. *Ecol. Indic.* **2002**, *2*, 135–148. [CrossRef]
13. Pannell, D.; Glenn, N. A framework for the economic evaluation and selection of sustainability indicators in agriculture. *Ecol. Econ.* **2000**, *33*, 135–149. [CrossRef]
14. Gómez-Limón, J.; Sanchez-Fernandez, G. Empirical evaluation of agricultural sustainability using composite indicators. *Ecol. Econ.* **2010**, *69*, 1062–1075. [CrossRef]
15. Rigby, D.; Woodhouse, P.; Young, T.; Burton, M. Constructing a farm level indicator of sustainable agricultural practice. *Ecol. Econ.* **2001**, *39*, 463–478. [CrossRef]
16. Häni, F.; Braga, F.; Stämpfli, A.; Keller, T.; Fischer, M.; Porsche, H. RISE, a tool for holistic sustainability assessment at the farm level. *Int. Food Agribus. Manag. Rev.* **2003**, *6*, 78–90.
17. Vilain, L. *La Méthode IDEA, Indicateurs de Durabilité des Exploitations Agricoles, Guide d'Utilisation*, 3rd ed.; Educagri Éditions: Dijon, France, 2008; ISBN 978-2-84444-669-5.
18. Masera, O.; López-Ridaura, S. (Eds.) *Sustentabilidad y Sistemas Campesinos: Cinco Experiencias de Evaluación en el México Rural*; Grupo Interdisciplinario de Tecnología Rural Apropiada (GIRA A. C.), Programa de las Naciones Unidas para el Medio Ambiente (PNUMA), and Instituto de Ecología (IE-UNAM); MundiPrensa: Mexico City, Mexico, 2000.
19. Speelman, E.; López-Ridaura, S.; Colomer, N.; Astier, M.; Masera, O. Ten years of sustainability evaluation using the MESMIS framework: Lessons learned from its application in 28 Latin American case studies. *Int. J. Sustain. Dev. World Ecol.* **2007**, *14*, 345–361. [CrossRef]
20. Ripoll-Bosch, R.; Díez-Unquera, B.; Ruiz, R.; Villalba, D.; Molina, E.; Joy, M.; Olaizola, A.; Bernués, A. An integrated sustainability assessment of mediterranean sheep farms with different degrees of intensification. *Agric. Syst.* **2012**, *105*, 46–56. [CrossRef]
21. Benitez-Capistros, F.; Huge, J.; Koedam, N. Environmental impacts on the Galapagos Islands: Identification of interactions, perceptions and steps ahead. *Ecol. Indic.* **2014**, *38*, 113–123. [CrossRef]
22. Duarte, A.; Espinosa, J.; Bolívar, J.; Yanes, A. Livestock Sustainability: A Perception Analysis and SWOT Application in Colombian Municipalities. *J. Posit. Sch. Psychol.* **2022**, *6*, 8455–8466.

23. Bezlepkina, I.; Reidsma, P.; Sieber, S.; Helming, K. Integrated assessment of sustainability of agricultural systems and land use: Methods, tools and applications. *Agric. Syst.* **2011**, *104*, 105–109. [CrossRef]
24. Darnhofer, I.; Fairweather, J.; Moller, H. Assessing a farm's sustainability: Insights from resilience thinking. *Int. J. Agric. Sustain.* **2010**, *8*, 186–198. [CrossRef]
25. Fonderflick, J.; Caplat, P.; Lovaty, F.; Thévenot, M.; Prodon, R. Avifauna trends following changes in a Mediterranean upland pastoral system. *Agric. Ecosyst. Environ.* **2010**, *137*, 337–347. [CrossRef]
26. Fernandes, L.A.D.; Woodhouse, P.J. Family farm sustainability in southern Brazil: An application of agri-environmental indicators. *Ecol. Econ.* **2008**, *66*, 243–257. [CrossRef]
27. Binder, C.R.; Feola, G.; Steinberger, J.K. Considering the normative, systemic and procedural dimensions in indicator-based sustainability assessments in agriculture. *Environ. Impact Assess. Rev.* **2010**, *30*, 71–81. [CrossRef]
28. URPA. *Estadisticas de Cundinamarca 2011–2013*; Gobernación de Cundinamarca: Bogotá, Colombia, 2014.
29. Carulla, J.; Ortega, E. Sistemas de producción lechera en Colombia: Retos y Oportunidades. *Arch. Latinoam. Prod. Anim.* **2016**, *24*, 83–87.
30. González-Quintero, R.; Sánchez-Pinzón, M.S.; Bolívar-Vergara, D.M.; Chirinda, N.; Arango, J.; Pantévez, H.A.; Correa-Londoño, G.; Barahona-Rosales, R. Caracterización técnica y ambiental de fincas de cría pertenecientes a muy pequeños, pequeños, medianos y grandes productores. *Rev. Mex. Cienc. Pecu.* **2020**, *11*, 183–204. [CrossRef]
31. CEGA. Actividad económica general de la ganadería en Colombia. *Rev. Coyunt. Colomb.* **2000**, *65*, 95–111.
32. Mahecha, L.; Gallego, L.; Peláez, F. Situación actual de la ganadería de carne en Colombia y alternativas para impulsar su competitividad y sostenibilidad. *Future Food J. Food Agric. Soc.* **2002**, *15*, 213–225. [CrossRef]
33. Gutiérrez-Malaxechebarría, A.M. Informal Irrigation in the Colombian Andes: Local Practices, National Agendas, and Options for Innovation. *Mt. Res. Dev.* **2013**, *333*, 260–268. [CrossRef]
34. Múnera-Bedoya, O.D.; Cassoli, L.D.; Olivera-Ángel, M.; Cerón-Muñoz, M. Caracterización de sistemas de producción lechera de Antioquia con sistemas de ordeño mecánico. *Livest. Res. Rural Dev.* **2018**, *30*, 86.
35. Villegas, S.; Rocha-Meneses, L.; Luna-delRisco, M.; Arroyave, C.; Arrieta, C.; Arredondo, C. Bioenergy transition as a strategic mechanism to diversify energy sources in rural areas in Colombia. *Agron. Res.* **2023**, *21*, 1398–1418. [CrossRef]
36. IICA—Instituto Interamericano de Cooperación para la Agricultura. Diagnóstico Sobre la Utilización de las Energías Renovables en las Cadenas Productivas Agropecuarias en Colombia. Published by: IICA, Fondo de Acceso Sostenible a Energías Renovables Térmicas (Fasert) y Programa Energising Development (EnDev). 2019. 76p. Available online: https://repositorio.iica.int/handle/11324/20918 (accessed on 24 November 2023).
37. Beltrán, D.; Téllez, G. Estudio de percepción del clima organizacional de las empresas tecnificadas de ganadería de leche de la provincia del Tundama, Boyacá (Colombia). *Rev. Med. Vet. Zoot.* **2018**, *65*, 48–74. [CrossRef]
38. Secretaría de Salud de Cundinamarca. *Indicadores de agua y saneamiento básico en los 116 Municipios de Cundinamarca: 2015–2016*; Estadísticas; Report; Gobernación de Cundinamarca: Bogotá, Colombia, 2020; 48p.
39. Superintendencia de Servicios Públicos Domiciliarios (SSPD) y Sistema Único de Información (SUI). Indicadores Política Pública, Cundinamarca: Indicadores agua y saneamiento básico. 2016. Dirección Sistemas de Información Geográfico, Análisis y Estadística. Gobernación Departamento de Cundinamarca—Colombia. Base de datos del SISBEN y SIVICAP. Available online: https://mapasyestadisticas-cundinamarca-map.opendata.arcgis.com/pages/datos-abiertos (accessed on 29 March 2024).
40. DANE-ENA. Encuesta Nacional Agropecuaria (ENA). 2017. [Base de datos]. Available online: https://microdatos.dane.gov.co/index.php/catalog/670 (accessed on 14 June 2024).
41. Arora, D.; Arango, J.; Burkart, S.; Chirinda, N.; Twyman, J. Gender [Im]Balance in Productive and Reproductive Labor among Livestock Producers in Colombia: Implications for Climate Change Responses. In *CCAFS Info Note*; Climate Change, Agriculture and Food Security (CCAFS) and CGIAR: Copenhagen, Denmark, 2017; p. 4. Available online: https://www.ilri.org/knowledge/publications/gender-imbalance-productive-and-reproductive-labor-among-livestock-producers (accessed on 10 May 2023).
42. Gumucio, T.; Mora, M.A.; Twyman, J.; Hernán-dez, M.C. Género en la Ganadería. Consideraciones Iniciales para la Incorporación de una Perspectiva de Género en la Investigación de la Ganadería en Colombia y Costa Rica. 2016. Documentos de Trabajo CCAFS No. 159. Programa de Investigación de CGIAR en Cambio Climático, Agricultura y Seguridad Alimentaria (CCAFS). Conpenhague, Dinamarca. Available online: https://cgspace.cgiar.org/handle/10568/73258 (accessed on 3 August 2023).
43. Bermúdez, C.E.; Arenas, N.E.; Moreno Melo, V. Caracterización socio-económica y ambiental en pequeños y medianos predios ganaderos en la región del Sumapáz, Colombia. *Rev. U.D.C.A Actual. Divulg. Científica* **2017**, *20*, 199–208.
44. Fonseca-Carreño, N.E.; Narvaez-Benavidez, C.A. Aplicación de la metodología MESMIS para la evaluación de sustentabilidad en sistemas de producción campesina en Sumapaz, Cundinamarca. *Rev. Cienc. Agropecu.* **2020**, *6*, 31–47. [CrossRef]
45. USP-Minagricultura. Unidad de Seguimiento de Precios de Leche. 2020. [Base de Datos]. Available online: http://uspleche.minagricultura.gov.co/ (accessed on 18 March 2024).
46. Víctor, N.; Ramírez, N. *Cadena Productiva de Carnes y Productos Cárnicos. Estructura, Comercio Internacional y Protección*; Archivos de Economía; Departamento Nacional de Planeación (DNP): Bogotá, Colombia, 2018; Volume 471, pp. 1–40.
47. González-Quintero, R.; Barahona-Rosales, R.; Bolívar-Vergara, D.M.; Chirinda, N.; Arango, J.; Pantévez, H.A.; Correa-Londoño, G.; Sánchez-Pinzón, M.S. Technical and environmental characterization of dual-purpose cattle farms and ways of improving production: A case study in Colombia. *Pastoralism* **2020**, *10*, 19. [CrossRef]

48. González-Quintero, R.; Sánchez-Pinzón, M.; Bolívar-Vergara, D.; Chirinda, N.; Arango, J.; Pantévez, H.; Correa-Londoño, G.; Barahona-Rosales, R. Technical and environmental characterization of Colombian beef cattle-fattening farms, with a focus on farm size and ways of improving production. *Outlook Agric.* **2020**, *49*, 153–162. [CrossRef]
49. Ley, No. 1876 de 2017. República de Colombia. Congreso de Colombia, Bogotá, Colombia. Diario oficial 29 de diciembre de 2017.
50. Gobernación de Antioquia. *Informe de Seguimiento y Evaluación al Servicio de Asistencia Técnica Directa Rural, año 2013, en el Departamento de Antioquia*; Secretaria de Agricultura y Desarrollo Rural de Antioquia; Universidad de Antioquia: Medellín, Colombia, 2014.
51. FAO. World Agriculture: Towards 2015/2030. 2003. Available online: https://www.fao.org/publications/card/es/c/b092211c-ddc9-53e3-ab89-fb1e9a3db8d4/ (accessed on 27 June 2023).
52. Morett-Sánchez, J.C.; Cosío Ruiz, C. Pérdida de soberanía alimentaria: Una faceta actual de los países subdesarrollados. *Agric. Soc. Desarro.* **2023**, *20*, 178–205. [CrossRef]
53. UPRA—Unidad de Planificación Rural Agropecuaria. Informe de Gestión: Plan de Acción 2015 Segundo Semestre. Colombia. 2015. Available online: https://www.upra.gov.co/documents/10184/40597/Informe+de+Gesti%C3%B3n+2015+versi%C3%B3n+publicaci%C3%B3n.pdf/c204814a-a98c-4eb9-81af-20ceef307a46 (accessed on 3 April 2024).
54. Braun, A.; Dijk, S.V.; Grulke, M. Upscaling Silvopastoral Systems in South America. Inter-American Development Bank (IDB)—Interamerican Investment Corporation (ICC) Publication. 2016. 42p. Available online: https://publications.iadb.org/en/publications/english/viewer/Upscaling-Silvopastoral-Systems-in-South-America.pdf (accessed on 13 November 2023).
55. Seonhwa, L.; Bonatti, M.; Löhr, K.; Palacios, V.; Lana, M.; Sieber, S. Adoption potentials and barriers of silvopastoral system in Colombia: Case of Cundinamarca region. *Cogent Environ. Sci.* **2020**, *6*, 1. [CrossRef]
56. IDEAM—Minambiente. *Estrategia Integral de Control a la Deforestación y Gestión de los Bosques. Bosques-Territorios de Vida*; IDEAM—Minambiente: Bogotá, Colombia, 2018; 174p.
57. Morales, L. *Peace and Environmental Protection in Colombia*; Proposals for Sustainable Rural Development; Inter-American Dialogue: Washington, DC, USA, 2017; 32p.
58. López-Vigoa, O.; Sánchez-Santana, T.; Iglesias-Gómez, J.M.; Lamela-López, L.; Soca-Pérez, M.; Arece-García, J.; Milera-Rodríguez, M.d.l.C. Los sistemas silvopastoriles como alternativa para la producción animal sostenible en el contexto actual de la ganadería tropical. *Pastos Forrajes* **2017**, *40*, 83–95.
59. DNP. Departamento Nacional de Planeación. *Misión para la Transformación del Campo: Diagnóstico de las Condiciones Sociales del Campo Colombiano*; DNP: Bogotá, Colombia, 2015; 53p.
60. Ramirez-Villegas, J.; Salazar, M.; Jarvis, A.; Navarro-Racines, C.E. A way forward on adaptation to climate change in Colombian agriculture: Perspectives towards 2050. *Clim. Chang.* **2012**, *115*, 611–628. [CrossRef]
61. Eitzinger, A.; Läderach, P.; Bunn, C.; Quiroga, A.; Benedikter, A.; Pantoja, A.; Gordon, J.; Bruni, M. Implications of a changing climate on food security and smallholders' livelihoods in Bogotá, Colombia. *Mitig. Adapt. Strat. Glob. Change* **2012**, *19*, 161–176. [CrossRef]
62. Bustamante-Zamudio, C.; Rojas-Salazar, L. Reflexiones sobre transiciones ganaderas bovinas en Colombia, desafíos y oportunidades. *Biodivers. Práct.* **2018**, *3*, 1–29.

sustainability

MDPI

Article

Accelerating Transition to a Low-Carbon Economy: A Coupling Analysis of Agricultural Products and Resource Environment

Xueqiu Liang [1,2] and Jingbo Xu [3,*]

1 College of Economics and Management, Northeast Agricultural University, Harbin 150030, China; b220801001@neau.edu.cn
2 Institute of Jewish Studies, Heilongjiang Academy of Social Sciences, Harbin 150080, China
3 School of Marxism, Northeast Agricultural University, Harbin 150030, China
* Correspondence: ceciliaduxue@163.com

Abstract: This study examines the low-carbon economy, agricultural products, and the resource environment as three interconnected subsystems, establishing an evaluation framework for their coordinated growth across eight regions of China. The results highlight significant regional imbalances, particularly in North China, Northwest China, and Northeast China. Principal component analysis (PCA) shows that the agricultural product system captures 99.502% of its information, while the resource-environment system accounts for 84.823%, demonstrating robust explanatory power. The national Economic–Agricultural–Resource–Environment (EARE) system progressed from sub-coordinated growth (2010–2014) to coordinated growth (2019–2020), moving from mild imbalance to high-quality growth. Initially, resource growth lagged behind economic development (2010–2015), which then shifted to economic growth lagging behind resource and environmental growth (2015–2020). This study underscores the need for targeted policies to enhance regional sustainability and balanced development.

Keywords: low-carbon economy; agricultural products; resource–environment coupling; coordinated growth; regional analysis

Citation: Liang, X.; Xu, J. Accelerating Transition to a Low-Carbon Economy: A Coupling Analysis of Agricultural Products and Resource Environment. *Sustainability* **2024**, *16*, 6315. https://doi.org/10.3390/su16156315

Academic Editors: Hamid El Bilali, Tarek Ben Hassen and Carola Strassner

Received: 9 May 2024
Revised: 12 July 2024
Accepted: 20 July 2024
Published: 24 July 2024

1. Introduction

This study explores the human low-carbon economy [1], a model of green economic growth characterized by low energy consumption, low emissions, low pollution, and high efficiency. It emphasizes the development of clean energy and the pursuit of green GDP. At the 2009 Copenhagen World Climate Conference, nations universally agreed to curb greenhouse gas emissions, actively promoting energy conservation and emission reduction [2] and advocating for a low-carbon economy. With "low carbon" now a leading trend in global economic growth, the agricultural product industry has emerged as a vital sector in sustainable management [3]. The essence of fostering a low-carbon economy involves transforming human development and survival strategies to guide low-carbon lifestyles and green consumption towards achieving sustainable development [4]. However, the interplay between economic and social growth systems—which include economic performance, social progress, population dynamics, and urbanization levels—and the resource environment system, comprising resource endowment, pollution output, and ecological conditions, is complex. These systems are coupled through mutual influence and constraints.

Currently, the challenges of resource shortages and environmental degradation in the agricultural sector are becoming increasingly critical. The industry, now the largest non-point source polluter, faces ecological limits due to the excessive use of chemicals and waste in production, severely impacting water, soil, and air quality. Resource environments are essential for human survival and socio-economic development. Yet, the rapid advancements of human civilization often overlook the finite and non-renewable nature of these resources, leading to their unchecked exploitation and the reckless discharge of pollutants [5]. This has resulted in significant resource depletion and ecological damage, manifesting in water scarcity, reduced forest areas, land subsidence, and severe air pollution, which not only impede socio-economic growth but also pose severe threats to human survival. Addressing these issues requires rethinking the growth models to emphasize resource and environmental factors within the low-carbon framework. Achieving sustainable growth in a low-carbon economy means harmonizing productivity growth with increasing human needs, fostering social sustainability through fairness and justice, and enhancing resource utilization alongside environmental quality. Coordinated growth [6]—balancing social justice with economic growth within the limits of environmental and resource capacities—is pivotal for achieving regional sustainability. This research will investigate the coupling of agricultural products with resources and the environment in a low-carbon context, aiming to enhance environmental protection in agriculture and improve governance transformation in line with modernization goals during the "13th Five-Year Plan." It provides crucial technical support and theoretical references for local and regional planning, fundamentally impacting practical approaches to agricultural and environmental policy.

This study addresses the significant impact of resource endowment and environmental conditions on socio-economic growth within a low-carbon economy framework [7]. Resource endowment is fundamental to economic and social development, population growth, and urbanization. However, excessive pollutant discharges that surpass environmental self-purification capacities can disrupt ecosystems and degrade the quality of the ecological environment, imposing a serious constraint on economic and social progress due to diminishing resource availability and reduced environmental capacity [8]. Therefore, the interaction between agricultural products and the resources and environment system is crucial, as it enables the rational allocation of economic resources and the harmonious coexistence between humanity and nature through the application of natural laws and ecological civilization principles [9].

The concept of coupling, originating in physics, describes the phenomenon where multiple systems exhibit interconnectedness, interaction, and interdependence, significantly influencing each other's outputs through energy transmission [10]. This paper employs the coupling coordination degree model, derived from capacity coupling theory, which quantitatively assesses the level of harmony and consistency between subsystems [11]. Notable research in this field includes proposals by Wang et al. [12], who suggest environmental impact reduction through limits on population growth, material consumption, and enhancements in technology. Meanwhile, Li et al. [13] argue for the effective management of resource utilization conflicts through coordinated approaches, suggesting that alternative resources will eventually replace non-renewable ones. Zhan et al. [14] discuss a coordinated growth theory that adapts economic processes to environmental changes, promoting symbiosis between ecological and social systems. Further, Li et al. [15] emphasize that resource utilization efficiency hinges on technological advancements, which can mitigate resource waste and address environmental challenges inherent to socio-economic development. This approach has been supported by prior studies (e.g., Higgins, 2017) [16]. Moreover, the adoption of an input–output model by Singh et al. [17] introduces resource and environmental considerations into economic studies, demonstrating a new pathway for studying the interrelations between economic behavior and environmental impacts. Similar methodologies have been applied in regional sustainable strategies (Fu and Lin, 2010) [18]. Meng et al. [19] provide a comprehensive analysis of regional coordination. Urban and rural development evaluations have also used these criteria (Zhu, 2013) [20]. Lastly, Hao et al. [21] utilize RS technology to assess urbanization and its ecological impacts in the Lake Aibi basin, employing the coupling coordination model to forecast future growth trends and develop strategic recommendations. This body of research collectively underscores the critical role of coordinated growth in achieving sustainable regional development.

This paper utilizes RS technology to explore the relationship between agricultural product growth and environmental resources within a low-carbon economy, providing quantitative analysis and algorithmic support. Innovatively, this study discusses the coupling coordination evaluation model, which is applied nationwide and divided into eight regions, predominantly using mathematical models with RS technology. This paper is structured into five chapters, starting with an introduction that sets the research background and objectives, followed by a literature review, a detailed methodology section, an experimental analysis, and concluding with a summary of findings and future research directions. This approach highlights the study's contributions to sustainable agricultural practices and regional growth coordination.

2. Methodology

In this study, the low-carbon economy, agricultural products, resources, and environment are treated as three complex yet inseparable subsystems within the broader framework of regional growth. These systems are interconnected, each exerting both promotional and restrictive influences on the others. The interactions among them significantly impact the overall regional growth system. If a problem arises in one subsystem, it can adversely affect the others, potentially leading to disorder and significant changes in the overall system, which may disrupt the coordinated growth of the region. An interesting imbalance index of economic factors affecting agricultural products, resources, and the environment (I) is also introduced to measure the degree of difference between these factors and their regional distribution.

2.1. RS Technology

Remote sensing (RS) technology, a cutting-edge high-tech tool, utilizes spacecraft to collect electromagnetic radiation information from ground objects, providing critical insights into the Earth's environment and resources. The fundamental principle behind RS technology is its ability to discern and identify terrestrial objects based on the differential electromagnetic reflection characteristics exhibited by various materials. This capability makes RS technology invaluable for a wide range of applications, including resource surveys, vegetation classification, land use planning, environmental planning, and pollution monitoring. Its broad sensing range, advanced technological capabilities, rapid information acquisition, frequent update cycles, and the facility for dynamic and real-time monitoring amplify its utility across these domains.

In the context of coupled and coordinated evaluation, RS technology plays a pivotal role by offering a vital data source for land resource assessment. The remote sensing data undergo several preprocessing and classification steps to prepare it for analysis. Preprocessing involves data acquisition, band data fusion, geometric correction, and image registration. The classification process typically includes supervised classification and visual correction. These steps culminate in the accurate classification of land use, which establishes a solid foundation for subsequent land resource evaluations. The data processing workflow, depicted in Figure 1, illustrates these sequential steps, showcasing how remote sensing data are transformed into actionable environmental intelligence. The values and repositories used in this workflow include datasets from Landsat and Sentinel satellites, with specific bands such as Band 1 (Coastal/Aerosol), Band 2 (Blue), Band 3 (Green), Band 4 (Red), Band 5 (Near Infrared—NIR), Band 6 (Shortwave Infrared—SWIR 1), Band 7 (Shortwave Infrared—SWIR 2), Band 10 (Thermal Infrared—TIRS 1), and Band 11 (Thermal Infrared—TIRS 2). These datasets are publicly available and provide consistent and reliable data for our analysis.

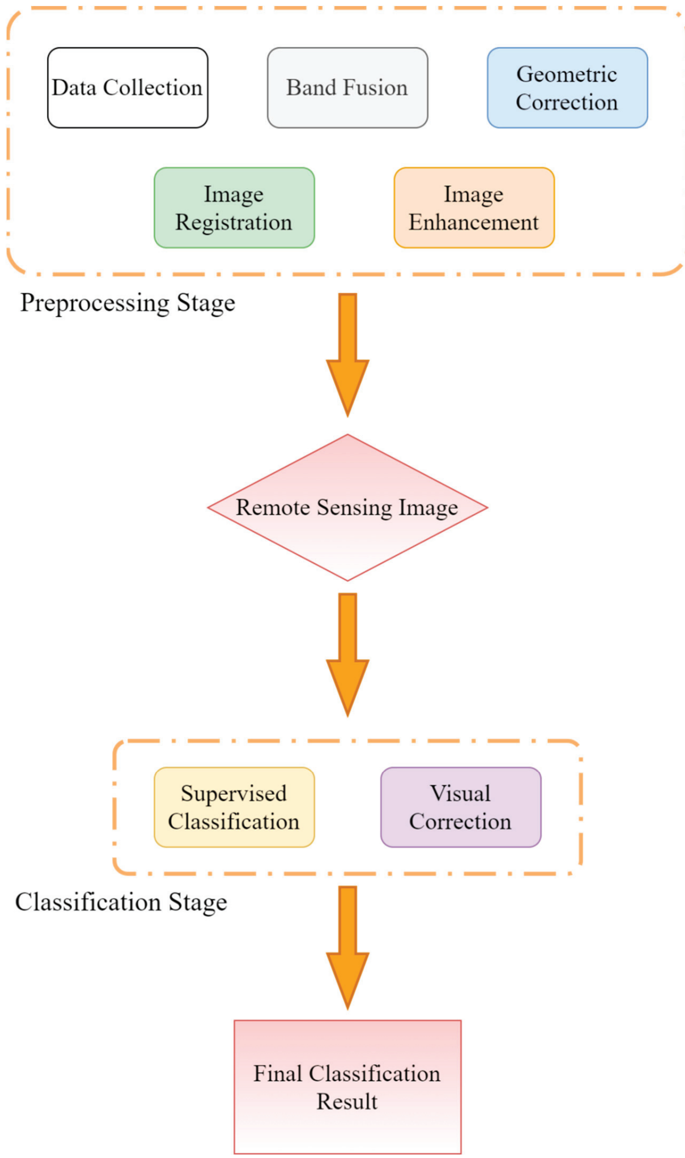

Figure 1. Data processing flow chart.

2.2. Coupling Mechanisms of Agricultural Products, Resources, and Environment

The regional dynamics of the low-carbon economy, agricultural products, resources, and environment are intricately interconnected, shaping the trajectory of social and economic growth. In the early stages, when economic activities are minimal, the ecological environment experiences little disturbance, and resource exploitation is low. However, as development progresses, the demand for resource utilization intensifies, leading to significant environmental degradation and more robust interactions among these systems. This initiates a cycle that can oscillate between phases of primary coordination, high-quality coordination, and low-level coordination, reflecting the evolving nature of mutual coupling and coordination within the region.

On the one hand, the advancement of society and technology enhances resource utilization by increasing the efficiency of material and energy flows, which supports human survival and growth. On the other hand, factors such as population growth, economic expansion, and intensified human activities place considerable pressure on regional resources and the environment. This dual-natured interaction results in ecological degradation and resource depletion that severely impair the quality of life and hinder social and economic progress. Consequently, the relationship between regional growth and its resources and environment is characterized by both mutual promotion and restriction.

To address these challenges, a coordinated approach is necessary. The growth of the social economy can lead to increased investments in environmental protection and improved utilization rates of ecological resources, thereby reducing environmental damage. Enhancing man-made purification processes and adopting practices such as energy conservation, emission reductions, and the implementation of new technologies help alleviate resource pressures and reduce the environmental impact of socio-economic activities. Additionally, improving the ecological environment and promoting sustainable resource use not only enhances the environmental competitiveness of the region but also attracts foreign investments, boosting economic strength and promoting sustainable regional development. This research establishes an evaluation index system that integrates indicators from the subsystems of the low-carbon economy, agricultural products, resources, and environment, creating a comprehensive framework for studying their coupling and coordination (Figure 2).

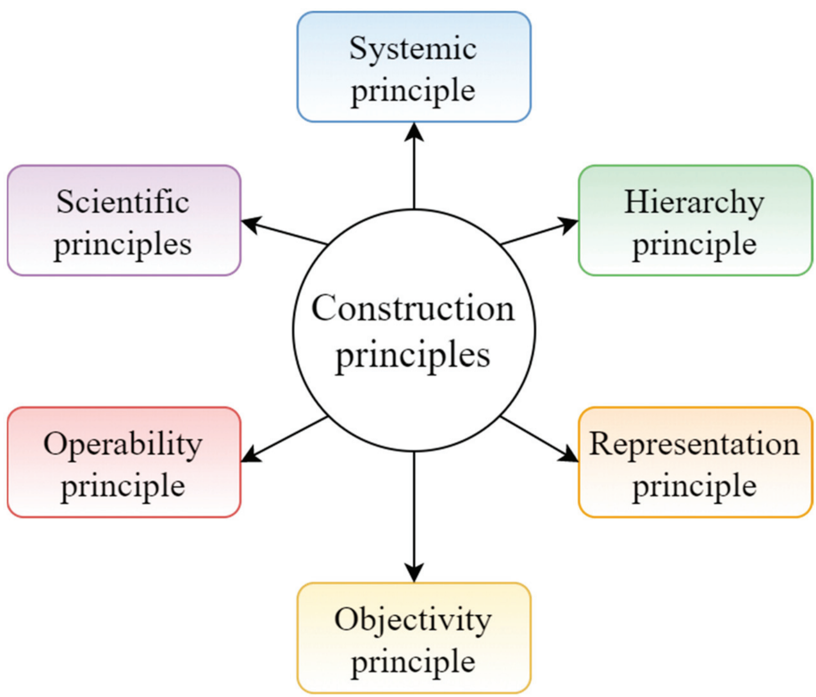

Figure 2. Construction principles of the indicator system.

2.3. Coupling Coordination Evaluation Index System

Under the framework of a low-carbon economy, both the agricultural product system and the resource and environment system are complex entities, exhibiting various stages, dynamics, and levels of complexity in their growth. The term 'low-carbon economy' in this paper encompasses broader economic activities aimed at reducing carbon emissions, including but not limited to the agricultural sector. The evaluation of growth levels within these systems transcends simple index parameters, necessitating a comprehensive assessment that integrates multiple indicators such as GDP per capita, energy consumption per unit of GDP, carbon emissions per unit of GDP, agricultural productivity, and resource use efficiency. These specific indicators were used to establish the regional coupling coordination evaluation index system, as illustrated in Figure 3.

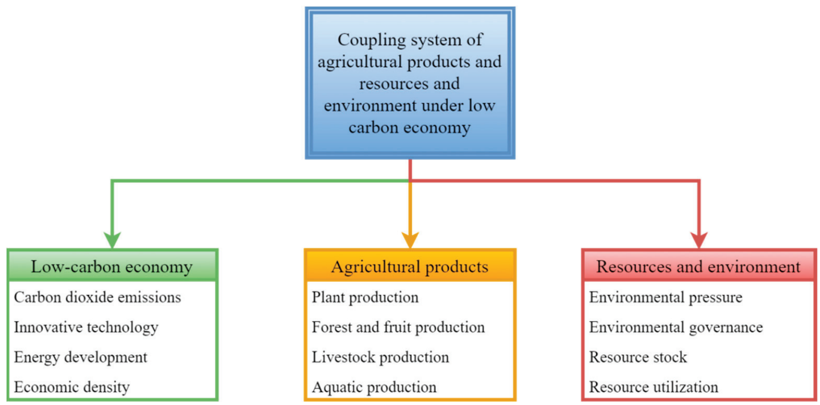

Figure 3. The established regional coupling coordination evaluation index system.

2.3.1. Data Collection and Preparation

The data for this study were collected from various authoritative sources, including national statistical yearbooks, environmental reports, and agricultural databases covering the period from 2010 to 2020. These datasets include economic indicators, environmental metrics, and agricultural production statistics for the eight regions of China.

2.3.2. Software and Tools

The statistical analysis was conducted using SPSS version 17.0. Remote sensing (RS) technology was employed to collect and preprocess environmental data, including land use and resource distribution. The data preprocessing steps included acquisition, band data fusion, geometric correction, and image registration, followed by supervised classification and visual correction.

2.3.3. Statistical Analysis

We utilized the coupling coordination degree model to evaluate the interaction and growth levels of the three subsystems—the low-carbon economy, agricultural products, and resources environment. Principal component analysis (PCA) was performed using SPSS to reduce dimensionality and extract the most significant components representing the data. The coupling degree and coordination degree models were then applied to quantify the interactions and coordination among the subsystems.

The imbalance index (I) was calculated to measure the disparity between agricultural products, resources, and economic factors across the regions. The standardized data were analyzed using a linear scale transformation to ensure comparability across different indicators.

By providing these additional details, we aim to clarify the methodology and enhance the transparency of our experimental and statistical analysis processes.

The imbalance index (I) is introduced to quantify the degree of imbalance between agricultural products, resources, and economic factors in different regions. The calculation formula for the imbalance index is as follows:

$$I = \sum_{i=1}^{n} |x_i - y_i| \tag{1}$$

where x_i and y_i represent the proportions of agricultural products and various resources, environmental, and economic factors in region *i*, respectively. A smaller difference between x_i and y_i indicates a more balanced distribution, while a larger difference indicates greater imbalance.

To address this issue, this study establishes a regional coupling coordination evaluation index system, as illustrated in Figure 3. The weighting of these indices is determined through methods such as data standardization and the coupling coordination degree model, enabling a detailed analysis of the interactions and growth patterns within these systems.

First, the imbalance index of economic factors of agricultural products, resources, and environment (I) is introduced to measure the degree of difference between agricultural products, resources, and environment and the economic growth level of a country or region. The calculation formula is as follows:

$$I = \sqrt{\sum_{i=1}^{n} \frac{\sqrt{2}/2(x_i - y_i)^2}{n}} \tag{2}$$

where n is the number of regions; x_i and y_i represent the proportions of agricultural products and various resources and environmental and economic factors in region i, respectively. When x_i is plotted on the *x*-axis and y_i on the *y*-axis, a smaller difference between x_i and y_i places the point (x_i, y_i) closer to the line y = x, indicating a relative balance. Conversely, a larger difference between x_i and y_i moves the point (x_i, y_i) farther from the line y = x, signifying an imbalance in the regional distribution of agricultural products and this indicator.

(1) Standardization of data

Different data dimensions will make the indicators not fall under the same reference system. To eliminate the dimensional differences in indicators, it is necessary to standardize the original data of the indicator system. There are many ways to standardize data, and the effects of each have their advantages and disadvantages. Commonly used methods include the range transformation method, linear scale transformation method, standard sample change method, normalization method, etc., and the less commonly used method is the Log function. Standard method, Arctan function standard method, Logistic/Softmax transformation, etc., as well as some methods improved from the above methods, will not be introduced in detail here. After screening and experiments, this paper uses the linear scale transformation method to standardize the data. The process is as follows:

In the matrix $X = \left(x_{ij}\right)_{m\times n}$ formed by the index system, take $x_j^* = \underset{1\le i\le m}{Max}\left(x_{ij}\right) \neq 0$ for the positive index f_j,

$$y_{ij} = \frac{x_{ij}}{x_j^*}, 1 \le i \le m, 1 \le j \le n \tag{3}$$

For the positive indicator f_j, take $x_j^* = \underset{1\le i\le m}{Max}\left(x_{ij}\right) \neq 0$,

$$y_{ij} = \frac{x_j^*}{x_{ij}}, 1 \le i \le m, 1 \le j \le n \tag{4}$$

Then, for the matrix $Y = \left(y_{ij}\right)_{m\times n}$ formed by y, it is referred to as a linear scaling normalization matrix. The advantage of this type of data standardization is that, by considering the data variances, after linear scaling transformation, the positive and negative values are averaged into positive values.

(2) Coupling Coordination Degree Model

Coupling degree refers to the degree of close relationship between systems and is used to measure the strength of the interaction between systems or elements. Coordination, on the other hand, is the state of proper coordination and coordinated growth between systems. Coupling coordination involves mutual influence, cooperation, and cooperation between systems. The coupling coordination degree serves as an indicator to measure the degree of this state. A coupling coordination degree model has been established to study the coupling and coordinated growth of agricultural products, resources, and environment systems in the country from 2010 to 2020 under a low-carbon economy. The process has been improved, and the specific operation process is as follows:

First, establish the coupling function as follows:

$$C_i = \left\{ \frac{E_i \times S_i \times R_i}{\left[\frac{1}{3}(E_i + S_i + R_i)\right]^3} \right\}^{\frac{1}{3}} \quad (5)$$

Among them, C_i ($0 \le C_i \le 1$) represents the coupling degree, with values ranging from 0 to 1. When $C_i = 0$, it indicates the three subsystems of the economy (E), agricultural products (A), and resources and environment (R) in the EARE system. Conversely, during the disorderly growth of the system, the three subsystems are highly interconnected; they are in the optional coupling state. Based on the pertinent research findings, the EARE system is categorized into six growth stages based on the value of C_i (Tables 1 and 2).

Table 1. C_i value and the stage division and standard of the EARE system.

C_i Value	EARE Stage
Ci = 0	Irrelevant
0 < Ci < 0.3	Low level
0.3 ≤ Ci < 0.5	Antagonism
0.5 ≤ Ci < 0.8	Running-in
0.8 ≤ Ci < 1	High level
Ci = 1	Optimal

Table 2. Classification of coupling evaluation criteria.

Coupling C	Coupling Class
(0, 0.50]	Uncoupled
(0.50, 0.60]	Barely coupled
(0.60, 0.70]	Primary coupling
(0.70, 0.80]	Intermediate coupling
(0.80, 0.90]	Well coupled
(0.90, 1.00]	Premium Coupling

Table 1 outlines the specific values and their corresponding stages in the EARE system's growth phases. Table 2 further elaborates on these stages, providing detailed descriptions and criteria for each phase.

E_i, A_i, and R_i are the growth level indices of the three subsystems: economy, society, resources, and environment. These values are determined based on their respective efficacy functions. The function formula is as follows:

$$E_i = \sum_{j=1}^{P} \alpha_j \times y_{ij} \quad (6)$$

$$s_i = \sum_{j=1}^{P} \beta_j \times y_{ij} \quad (7)$$

$$R_i = \sum_{j=1}^{P} \gamma_j \times y_{ij} \quad (8)$$

$$\sum_{j=1}^{P} \alpha_j = 1, \sum_{j=1}^{P} \beta_j = 1, \sum_{j=1}^{P} \gamma_j = 1, 1 \le i \le m, 1 \le j \le p < n \quad (9)$$

Among them: p is the number of data indicators of the three subsystems in the EARE system; α, β, and γ are the weights of the indicators of each subsystem, that is, the contribution of each indicator to each subsystem, and the entropy method will be used to calculate α, β, and the value of γ.

Second, establish a coupling coordination function as follows:

$$M_i = (C_i F_i)^{\frac{1}{2}} \tag{10}$$

$$F_i = a \times E_i + b \times S_i + c \times R_i \tag{11}$$

Coupling coordination degree M_i can reflect the level of coordinated growth of the three subsystems of low-carbon economy, agricultural products, and resource environment, while coupling degree Ci only reflects the degree of mutual influence between the three subsystems. F_i is the comprehensive coordination evaluation index of the three subsystems of the EARE system. The geometric mean method is used to determine the value of F_i, where a, b, and c are the weights of each subsystem (a + b + c = 1). The three subsystems of resources and environment are equally important in the growth of the economy; thus, a = b = c = 1/3. Referring to the research results of related scholars, the coupling and coordinated growth of the EARE system are divided into three categories and nine subcategories (Figure 4).

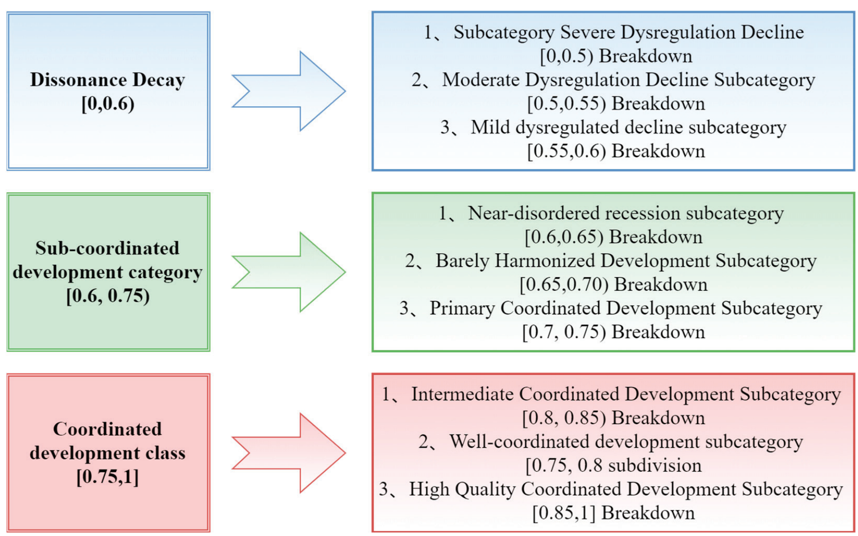

Figure 4. Type division and standard of EARE system coupling and coordinated growth. Note: Each subcategory can be subdivided into the following six types: resource–environmental balance, social lag type ($R_i > E_i > A_i$); resource–environmental balance, economic lag type ($R_i > A_i > E_i$); economic growth, social lag type ($E_i > R_i > A_i$); economic growth, resources, and environment lag type ($E_i > A_i > R_i$); social progress, economic lag type ($A_i > R_i > E_i$); social progress, resources, and environment lag type ($A_i > E_i > R_i$).

2.4. Coupling Coordination Evaluation Model

This paper establishes a mathematical model of the coupling degree of three subsystems, including the low-carbon economy, agricultural products and resources, and environment, based on relevant domestic and foreign literature, as shown in Equation (11):

$$C = 3\left\{(U_1 \times U_2 \times U_3)/\left[(U_1 + U_2 + U_3)^3\right]\right\}^{\frac{1}{3}} \tag{12}$$

where C is the system coupling degree, $C \in (0, 1)$.

The larger the value of C, the better the coupling between the subsystems, indicating a stronger interaction between them. However, the degree of coupling only signifies the strength of interaction among the three subsystems, not the level of coordination within the system. A high value of C could represent either high-level or low-level coupling. Based on system coupling, in order to intuitively reflect the degree of coordinated growth of each subsystem, a model of coordinated growth is established with reference to relevant literature. The coordinated growth model is developed based on the existing literature. This model can effectively assess the coordinated growth of the three subsystems related to agricultural product growth, resource use, and environmental significance under low-carbon conditions. Its calculation formula is as follows:

$$D = (C \times T)^{1/2} \tag{13}$$

$$T = \alpha \times U_1 + \beta \times U_2 + \gamma \times U_3 \tag{14}$$

In the formula: D represents the degree of coordinated growth of the system; T stands for the comprehensive coordination index of the α , β , γ subsystem; is the undetermined coefficient of the contribution degree of the subsystem, $\alpha + \beta + \gamma = 1$. This study considers that the low-carbon economy, agricultural products, resources, and the environment play equally important roles in regional coordinated growth.

To sum up, the Coordinated Growth Degree Model D combines the System Coupling Degree Model C and the Growth Level T of each subsystem. The Coordinated Growth Degree has a broader research scope than the Coupling Degree on the coordinated growth of the region and can provide a more comprehensive reflection. The coordinated growth of subsystems in a region can be compared and analyzed not only between different regions in the same period but also between subsystems in the same region in different periods, and it has strong operability. The evaluation criteria for Coupling Degree C and Coordinated Growth Degree D are divided as follows:

3. Result Analysis and Discussion

The coupling relationship between the resource environment system and the population economic system arises from their intricate connections and interactions. The intricate comparison of the evolution of the three interconnected subsystems—low-carbon economy, agricultural products, and resource environment—across the eight regions of China adds a layer of complexity to the study. This comparative analysis not only highlights regional disparities but also provides insights into region-specific challenges and opportunities, making the study intellectually stimulating and thought-provoking. The resource environment system furnishes essential resources and ecological services while also processing the waste generated by human activities. Conversely, the population consumes these resources and ecological services to drive economic development and enhance welfare. This interdependence prompts continuous improvements in resource efficiency and waste management practices aimed at bolstering the carrying capacity of the ecological environment. Reflecting this dynamic, the degree of influence of various factors on the spatial differentiation of agricultural products, resources, and environment is illustrated in the accompanying figure, where X represents agricultural products and Y denotes resources and environment. This visualization helps clarify the complex interplay between these elements, highlighting the interconnected nature of agricultural productivity and environmental sustainability.

Figure 5 illustrates the degree of effect of various factors affecting the spatial differentiation of agricultural products and resource–environment systems. The data include several key variables represented by different lines and colors. The Y Standardization Coefficient (Beta), shown by the blue line, indicates the standardized impact of independent variables on the dependent variable Y in standardized units, with values such as Y1 (1.073), Y2 (1.191), and Y3 (1.496). The Y Variance Inflation Factor (VIF), represented by the orange line, measures the degree of multicollinearity among the independent variables for Y, with values including Y1 (1.029), Y2 (1.063), and Y3 (1.433). The Y Significance (*p*-value), shown by the green line, indicates the statistical significance of the relationships for Y, with key values such as Y1 (0.443), Y2 (0.724), and Y3 (0.729). Similarly, the X Standardization Coefficient (Beta), represented by the yellow line, measures the standardized impact of independent variables on the dependent variable X, with values like X1 (0.102), X2 (0.083), and X3 (0.138). The X Variance Inflation Factor (VIF), shown by the red line, measures the degree of multicollinearity among the independent variables for X, with values including X1 (1.073), X2 (1.191), and X3 (1.496). The X Significance (*p*-value), indicated by the gray line, shows the statistical significance of the relationships for X, with values such as X1 (0.047), X2 (0.053), and X3 (0.062). This figure provides insights into the relative importance and significance of these factors in driving the spatial differentiation of agricultural products and resource–environment systems, aiding in the identification of key drivers and potential areas for intervention.

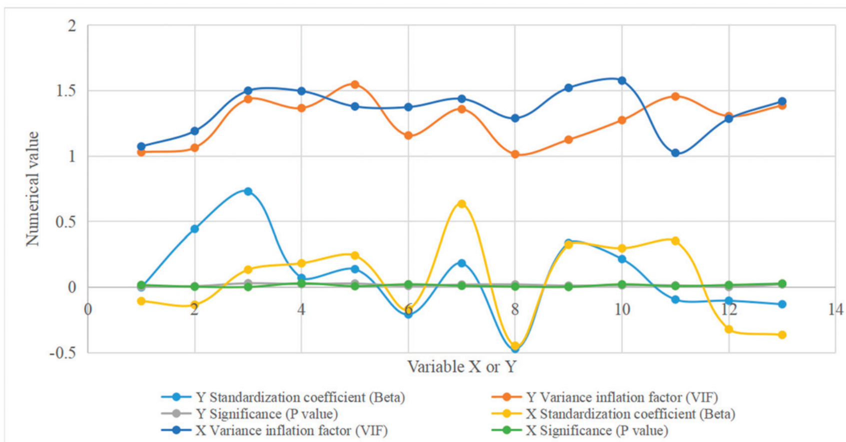

Figure 5. The effect degree of the factors affecting the spatial differentiation of agricultural products, resources, and environment.

It can be seen from the figure that the Beta values of the two fluctuate significantly, which will have a substantial impact later on, while the *p* values of the two fluctuate very little, almost close to 0, indicating a minor impact.

China's 31 provinces (autonomous regions and municipalities) are divided into eight regions. The imbalance index is introduced to analyze and compare these regions, aiming to clarify the spatial matching degree of agricultural products and related factors such as resources, environment, and economic growth in China. By using formula (1), the imbalance indices of agricultural products to population, cultivated land area, water resources, soil erosion control area, and GDP can be obtained as I_p, I_c, I_w, I_e, and I_g, respectively.

Figure 6 shows the unbalanced index of agricultural products and the associated resources, environment, and economic factors across eight major regions in China. The lines in the graph represent the indices for five factors: lp (blue), lc (orange), lw (green), le (yellow), and lg (red). Each line represents how unbalanced each factor is within the specified regions: Northeast, North China, Huang Huaihai, Northwest, Southeast, Yangtze River, South China, and Southwest. For example, the le factor (yellow line) has its highest imbalance in the Huang Huaihai region with a value of 0.241, while the lc factor (orange line) shows a significant imbalance in the Northwest region with a value of 0.1483. The table below the graph provides specific numerical values for each factor in each region, highlighting areas with a higher or lower imbalance. These data help identify regions where agricultural production and related factors are most out of balance, indicating where targeted policy interventions might be needed to improve sustainability and resource management.

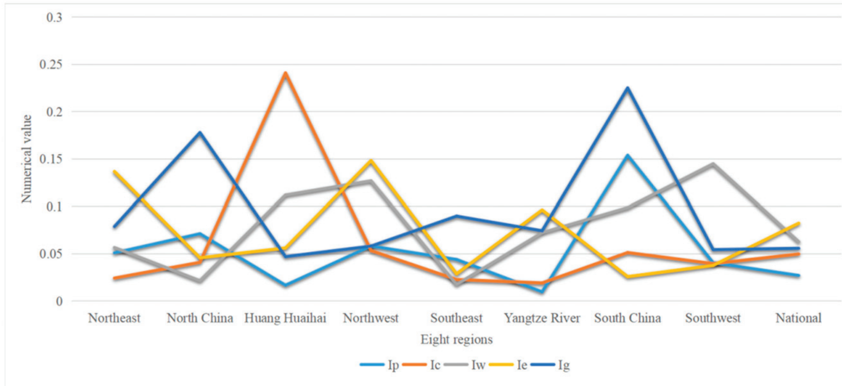

Figure 6. Unbalanced index of agricultural products and agricultural products—resources, environment, and economic factors—in eight major regions of China.

It can be seen from Figure 6 that the imbalance index of agricultural products, resources, and the environment in the country is the smallest, indicating that the spatial matching degree of agricultural products, resources, and the environment is the highest. The regions with larger imbalance indices are North China, Northwest China, and Northeast China.

After standardizing the evaluation index values of the agricultural trade system and the economic coordination degree, this paper uses SPSS 17.0 to process the data using the standardization method. Subsequently, it conducts principal component analysis and generates the variance decomposition principal component analysis diagram of the two systems, as shown in Figure 7.

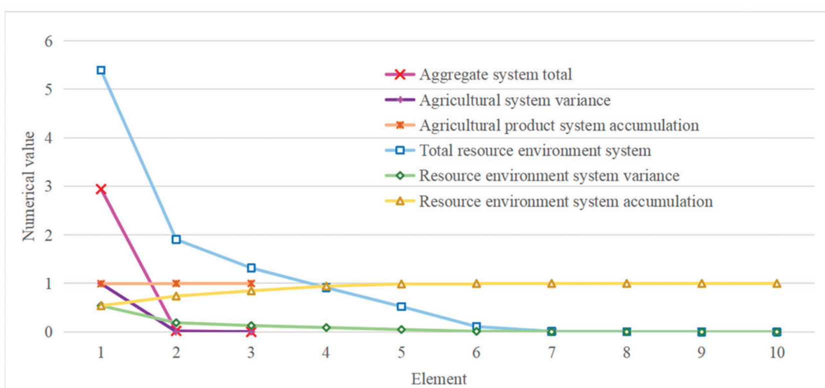

Figure 7. Variance decomposition principal component analysis diagram of agricultural products, resources, and environment system.

Figure 7 depicts the variance decomposition principal component analysis of the agricultural products, resources, and environment systems. The graph illustrates the variance contributions of different principal components to the overall system variance. The blue line represents the aggregate system total, while the orange line shows the total resource environment system variance. The green line indicates the agricultural product system accumulation, and the pink line represents the resource environment system accumulation. The table below the graph provides numerical values for each component across different variances and accumulations. For example, the aggregate system total variance for the first principal component is 2.94, while the total resource environment system variance for the same component is 5.393. These values demonstrate the significant contribution of the first few principal components to the overall variance, highlighting key factors that influence agricultural products, resources, and environmental systems. This analysis helps in understanding the primary drivers of variability within the system, aiding in more targeted and effective resource management strategies.

According to the principle that the initial characteristic root is greater than 1, this paper extracts the principal components for the two systems of agricultural products, resources, and environment, respectively. It can be seen from the figure that a principal component extracted by the agricultural product system reflects 99.502% of the information in the system, demonstrating the method's strong explanatory power. The three principal components extracted by the environmental system reflect 84.823% of the information in the system, indicating that the explanatory power of the principal component method is very good. PCA is a statistical technique that transforms the original variables into a new set of uncorrelated variables (principal components) that capture the maximum variance in the data. The steps involved in the PCA process in our study are as follows: First, the original data for agricultural products and resource–environment systems were standardized to ensure comparability, transforming the data to have a mean of zero and a standard deviation of one. Next, a covariance matrix was calculated to understand the relationships between the variables. Eigenvalues and eigenvectors were then computed from the covariance matrix, where the eigenvalues represent the amount of variance captured by each principal component, and the eigenvectors indicate the direction of the principal components. Principal components were selected based on the criterion that their eigenvalues are greater than one, capturing the most significant variance in the data. Finally, the original data were transformed into a new set of principal components. For the resource–environment system, three principal components were extracted, accounting for 84.823% of its total information, further underscoring the robustness of the principal component analysis.

Figure 8 shows the comprehensive scores of the low-carbon economy, agricultural products, and resource and environmental systems over time. The blue line represents the composite score of the economic system, the green line represents the composite score of the agricultural system, and the orange line represents the comprehensive score of the resource and environmental systems. The table below the graph provides specific numerical values for each system's score across different time periods. For example, the economic system composite score starts at −4.56762 and gradually increases to 5.97583, indicating significant growth over time. Similarly, the agricultural system composite score starts at −3.16701 and rises to 5.42576, while the resource and environmental system score improves from −5.47457 to 5.976445. This figure highlights the trends and progress in these systems, showcasing how they evolve and interact, ultimately reflecting the effectiveness of policies and practices aimed at promoting sustainability and balanced development.

In this paper, the principle component analysis method is used to calculate the comprehensive scores of agricultural products, resources, and environmental systems. The scores are illustrated in the figure below (the *x*-axis numbers 1–11 correspond to the years 2010–2020, respectively):

It can be seen from Figure 8 that the comprehensive scores of the low-carbon economy, agricultural products, resources, and environmental systems all show a growing trend over time. This growth is not linear but rather tortuous. Initially, the effect was not good; however, negative numbers are followed by continuous improvement.

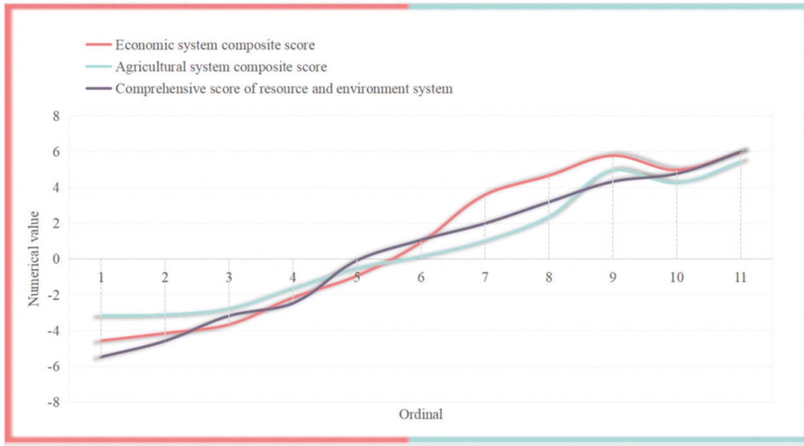

Figure 8. Comprehensive scores of low-carbon economies, agricultural products, resources, and environmental systems.

According to the coupling coordination method, the growth level index (Ei, Ai, and Ri) of the national low-carbon economy, agricultural products, resources, and environment subsystems from 2010 to 2020 is obtained. This paper asserts that the three subsystems are equally vital for regional growth. Therefore, Ei and Ai are assigned the same weight as Ri, which is 1/3 of the total weight. This calculation yields the comprehensive growth index of the EARE system (Figure 9; the X-ray numbers 1–11 in the figure correspond to 2010–2020, respectively).

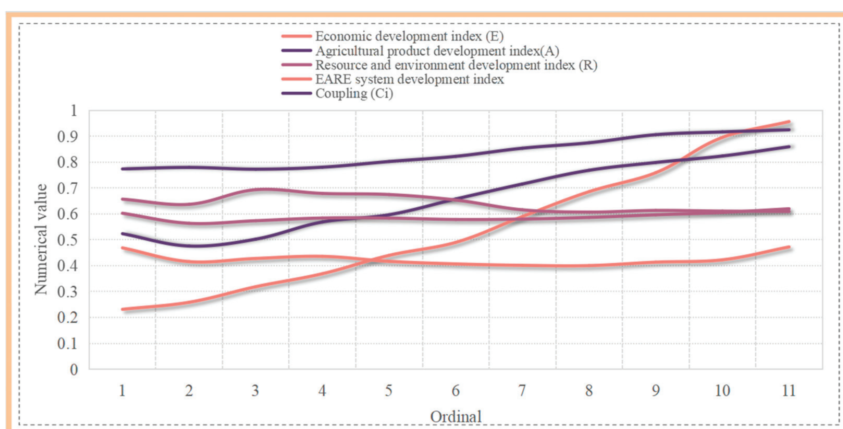

Figure 9. EARE System Comprehensive Development Index Chart.

Figure 9 illustrates the comprehensive development indices of the EARE system, which includes the economic, agricultural, resource, and environmental sectors. The chart tracks the Economic Development Index (E, blue line), Agricultural Product Development Index (A, green line), Resource and Environment Development Index (R, orange line), EARE System Development Index (red line), Coupling Index (Ci, yellow line), and Coupling Coordination Degree (Mi, pink line) over time. The indices show a general upward trend, with the Economic Development Index rising from 0.2314 to 0.9563 and the Agricultural Product Development Index increasing from 0.5234 to 0.8592. The Resource and Environment Development Index remains relatively stable. The Coupling Index and Coupling

Coordination Degree also improve, indicating enhanced integration and coordination among the economic, agricultural, and environmental systems. This figure highlights the progress and interplay between these systems, emphasizing the advancements in achieving balanced and sustainable development.

Observing Figure 9 reveals the growth trends from 2010 to 2020 across different subsystems of the low-carbon economy, agricultural products, resources, and the environment. Firstly, the economic subsystem exhibits a clear overall upward trajectory: slow growth between 2010 and 2014, rapid growth from 2015 to 2019, and stable growth in 2020. Secondly, the agricultural product system curve displays a pattern of initial decline followed by a rise, with a slow decrease from 2010 to 2013 and a rapid increase from 2014 to 2020. Thirdly, the growth trend in the resource and environmental systems is relatively stable, though it shows some fluctuations in certain years. Lastly, the EARE system curve also follows a pattern of initial decline and subsequent rise, with a slight decrease from 2010 to 2012 and a steady growth from 2013 to 2020, reflecting the combined effects of the individual subsystems.

The analysis of the coupling degree shows that from 2010 to 2020, the national EARE system was consistently in a high-level coupling stage. According to the classification criteria in Table 2, the system was in the run-in growth stage from 2010 to 2015, shifting to a high-level growth stage from 2016 to 2020, marking the transition from a run-in phase to a more advanced stage.

In terms of the coupling coordination degree, the national EARE system evolved from a low level to a medium and high level over the same period. According to the criteria in Table 2, the system was overall in a stage of imbalance and recession from 2010 to 2014, transitioned to a sub-coordinated growth stage from 2015 to 2018, and entered a coordinated growth stage from 2019 to 2020. This progression signifies a gradual shift from a mild disorder decline phase to a high-quality, coordinated growth stage. Additionally, the analysis indicates that from 2010 to 2015, the country experienced balanced resource growth with lagging economic development, which then transitioned to balanced economic growth with lagging resource and environmental growth from 2015 to 2020.

4. Conclusions

This paper investigates the coupling of agricultural products with resources and the environment within a low-carbon economy framework, yielding several key conclusions. First, given the dual objectives of ensuring national food security and promoting the sustainable growth of regional resources, environment, and economy, specific actions are recommended for various regions. For example, in areas like Huanghuaihai, Northeast China, and the middle and lower reaches of the Yangtze River, there is a critical need to enhance the efficiency of water resource utilization. Additionally, regions such as Northeast China should focus on intensifying the utilization of agricultural land. Furthermore, areas like Huanghuaihai and the middle and lower reaches of the Yangtze River are advised to bolster the construction of agricultural ecological environmental protections, including soil erosion control.

The policy implications of this research are significant, providing valuable insights into how regional resource, environmental, and economic sustainability can be balanced with the goal of maintaining food security in China. This study offers practical recommendations that can guide policy formulation and strategic planning.

The relationship between agricultural products and resource and environmental systems has emerged as a critical area of study both domestically and internationally. Investigating the alignment of these systems within the context of a low-carbon economy, particularly from a temporal and spatial perspective, is essential for understanding and optimizing their interaction.

Additionally, the growth of agricultural free trade should focus on adjusting the internal structure of agricultural products, emphasizing the expansion of agricultural product processing, local specialty product processing, and the rural tertiary industry. This approach aims to promote large-scale processing of agricultural products and develop a number of agricultural trade systems enriched with scientific and technological content. Concurrently, efforts should be made to accelerate the enhancement of China's agricultural free trade infrastructure and deepen the reform of the agricultural free trade system. Such measures are crucial for ensuring that China's agricultural free trade efforts effectively support resource conservation and environmental protection.

These conclusions are based on a comprehensive analysis using principal component analysis (PCA) and the coupling coordination degree model. The PCA results indicated that a single principal component extracted for the agricultural product system explained 99.502% of the variance, and three principal components for the resource-environment system explained 84.823% of the variance. The coupling coordination degree model revealed significant variations in the coupling degree and coordinated growth degree across different regions and time periods. These findings support our recommendations and underscore the need for targeted regional strategies to achieve balanced and sustainable development.

Author Contributions: X.L. and J.X. conceived the ideas and designed the methodology; X.L. and J.X. collected the data; X.L. and J.X. analyzed the data; X.L. led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the Heilongjiang Provincial Philosophy and Social Science Planning Project: Research on the Path of Agricultural Cooperation with Russia in the Heilongjiang Free Trade Zone, project number 22GJC285.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets used or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Panitchpakdi, S. World Investment Report 2010: Investing in a low-carbon economy (overview): Key messages: FDI trends and prospects. *Transnatl. Corp.* **2010**, *19*, 63–106.
2. Wen, Z.; Li, H. Analysis of potential energy conservation and CO2 emissions reduction in China's non-ferrous metals industry from a technology perspective. *Int. J. Greenh. Gas Control* **2014**, *28*, 45–56. [CrossRef]
3. Cui, Y. Special reports on the development of artificial intelligence and the rule of law. In *Blue Book on AI and Rule of Law in the World (2020)*; Springer Nature Singapore: Singapore, 2022; pp. 129–206.
4. Vargas-Hernández, J.G.; Vargas-González, O.C.; González-Ávila, F.J. Sustainable development and its implications in the green economy concept. In *Circular Economy and Manufacturing*; Woodhead Publishing: Sutton, UK, 2024; pp. 197–216.
5. Ullah, S. A sociological study of environmental pollution and its effects on the public health Faisalabad city. *Int. J. Educ. Res.* **2013**, *1*, 2.
6. Chen, A.; Gao, J. Urbanization in China and the coordinated development model—The case of Chengdu. *Soc. Sci. J.* **2011**, *48*, 500–513. [CrossRef]
7. Negash, M.; Kelboro, G. Effects of socio-economic status and food consumption pattern on household energy uses: Implications for forest resource degradation and reforestation around Wondo Genet Catchments, South-Central Ethiopia. *East. Afr. Soc. Sci. Res. Rev.* **2014**, *30*, 27–46. [CrossRef]
8. Kun, Y.; Peng, Z. Characteristics of China's Development in the New Era Explained in Light of Economic Principles. *China Econ.* **2018**, *13*, 2–13.
9. Ruili, G.; Linlin, W. Evaluation of Coordinated Development of Urbanization and Ecological Environment in the Efficient Ecological Economic Zone of the Yellow River Delta. *Meteorol. Environ. Res.* **2018**, *9*, 48–51.
10. Mitchell, P. Chemiosmotic coupling in oxidative and photosynthetic phosphorylation. *Biochim. Biophys. Acta (BBA) Bioenerg.* **2011**, *1807*, 1507–1538. [CrossRef] [PubMed]
11. Tang, Z. An integrated approach to evaluating the coupling coordination between tourism and the environment. *Tour. Manag.* **2015**, *46*, 11–19. [CrossRef]
12. Wang, J.; Zhai, Z.J.; Jing, Y.; Zhang, C. Optimization design of BCHP system to maximize to save energy and reduce environmental impact. *Energy* **2010**, *35*, 3388–3398. [CrossRef]

13. Li, J.; Akdeniz, N.; Kim HH, M.; Gates, R.S.; Wang, X.; Wang, K. Optimal manure utilization chain for distributed animal farms: Model development and a case study from Hangzhou, China. *Agric. Syst.* **2021**, *187*, 102996. [CrossRef]
14. Zhan, Q.; Li, G.; Zhan, W. Measurement of the coupling coordination relationship between the structures of secondary vocational school programs and industries in China. *Humanit. Soc. Sci. Commun.* **2023**, *10*, 1–10. [CrossRef]
15. Li, X.; Qian, Z.; Lu, S.; Wu, J. Energy efficient virtual machine placement algorithm with balanced and improved resource utilization in a data center. *Math. Comput. Model.* **2013**, *58*, 1222–1235. [CrossRef]
16. Higgins, S.I. Ecosystem assembly: A mission for terrestrial earth system science. *Ecosystems* **2017**, *20*, 69–77. [CrossRef]
17. Singh, S.; Bakshi, B.R. Accounting for emissions and sinks from the biogeochemical cycle of carbon in the US economic input-output model. *J. Ind. Ecol.* **2014**, *18*, 818–828. [CrossRef]
18. Fu, W.; Lin, T. Comparison of models for coupled relation between regional social-economic development and ecological environment. *Sichuan Environ.* **2010**, *29*, 102–109.
19. Meng, L.; Yang, R.; Sun, M.; Zhang, L.; Li, X. Regional sustainable strategy based on the coordination of ecological security and economic development in Yunnan Province, China. *Sustainability* **2023**, *15*, 7540. [CrossRef]
20. Zhu, X.Q. Construction and Application of Urban and Rural Coordinated Development Evaluation Index System of Xinxiang City. *J. Henan Agric. Sci.* **2013**, *49*, 109–113.
21. Hao, Y. Dynamic Study on Urban Development and Ecological Efficiency in Northern Xinjiang-Take urumqi, hami and turpan for Example. In Proceedings of the 2018 2nd International Conference on Management, Education and Social Science (ICMESS 2018), Qingdao, China, 23–24 June 2018; pp. 1278–1283.

sustainability

MDPI

Article

Spatiotemporal Responses of Vegetation to Hydroclimatic Factors over Arid and Semi-arid Climate

Brijesh Yadav [1,*], Lal Chand Malav [1], Shruti V. Singh [2], Sushil Kumar Kharia [3], Md. Yeasin [4], Ram Narayan Singh [5], Mahaveer Nogiya [1], Roshan Lal Meena [1], Pravash Chandra Moharana [6], Nirmal Kumar [6], Ram Prasad Sharma [1], Gangalakunta P. Obi Reddy [6], Banshi Lal Mina [1] and Prakash Kumar Jha [7]

[1] ICAR—National Bureau of Soil Survey & Land Use Planning, Regional Center, Udaipur 313001, India; lc.malav@icar.gov.in (L.C.M.); mahaveer.nogiya@icar.gov.in (M.N.); roshan.meena@icar.gov.in (R.L.M.); rp.sharma@icar.gov.in (R.P.S.); bl.meena1@icar.gov.in (B.L.M.)
[2] Krishi Vigyan Kendra, ICAR—Indian Institute of Vegetable Research, Kushinagar 274406, India; shrutingh21@gmail.com
[3] Department of Soil Sciences, College of Agriculture, Swami Keshwanand Rajasthan Agricultural University, Bikaner 334006, India; pausushil@gmail.com
[4] ICAR—Indian Agricultural Statistics Research Institute, New Delhi 110012, India; yeasin.iasri@gmail.com
[5] ICAR—National Institute of Abiotic Stress Management, Baramati 413115, India; rns.iari@gmail.com
[6] ICAR—National Bureau of Soil Survey & Land Use Planning, Nagpur 440033, India; pravash.moharana@icar.gov.in (P.C.M.); nirmal.kumar3@icar.gov.in (N.K.); gpo.reddy@icar.gov.in (G.P.O.R.)
[7] Department of Plant and Soil Sciences, Mississippi State University, Starkville, MS 39762, USA; pj442@msstate.edu
* Correspondence: brijesh.yadav@icar.gov.in

Abstract: Understanding the dynamics of vegetative greenness and how it interacts with various hydroclimatic factors is crucial for comprehending the implications of global climate change. The present study utilized the MODIS-derived normalized difference vegetation index (NDVI) to understand the vegetation patterns over 21 years (2001–2021) in Rajasthan, India. The rainfall, land surface temperature (LST), and evapotranspiration (ET) were also analyzed. The changes, at a 30 m pixel resolution, were evaluated using Mann–Kendall's trend test. The results reveal that the NDVI, ET, and rainfall had increasing trends, whereas the LST had a decreasing trend in Rajasthan. The NDVI increased for 96.5% of the total pixels, while it decreased for 3.4% of the pixels, of theh indicates vegetation improvement rather than degradation. The findings of this study provide direct proof of a significant reduction in degraded lands throughout Rajasthan, particularly in the vicinity of the Indira Gandhi Canal command area. Concurrently, there has been a noticeable expansion in the cultivated land area. The trend of vegetation decline, particularly in the metro cities, has occurred as a result of urbanization and industrialization. In contrast to the LST, which has a decreasing gradient from the western to eastern portions, the spatial variability in the NDVI, ET, and rainfall have decreasing gradients from the southern and eastern to western regions. The results of correlations between the vegetative indices and hydroclimatic variables indicate that the NDVI has a strong positive correlation with ET (r^2 = 0.86), and a negative correlation with LST (r^2 = −0.55). This research provides scientific insights into vegetation change across Rajasthan, and may help the state to monitor vegetation changes, conserve ecosystems, and implement sustainable ecosystem management.

Keywords: vegetation dynamics; NDVI; rainfall; land surface temperature; remote sensing; Rajasthan

Citation: Yadav, B.; Malav, L.C.; Singh, S.V.; Kharia, S.K.; Yeasin, M.; Singh, R.N.; Nogiya, M.; Meena, R.L.; Moharana, P.C.; Kumar, N.; et al. Spatiotemporal Responses of Vegetation to Hydroclimatic Factors over Arid and Semi-arid Climate. *Sustainability* **2023**, *15*, 15191. https://doi.org/10.3390/su152115191

Academic Editors: Hamid El Bilali, Tarek Ben Hassen and Carola Strassner

Received: 30 July 2023
Revised: 18 October 2023
Accepted: 20 October 2023
Published: 24 October 2023

1. Introduction

Vegetation is an integral part of the terrestrial ecosystem and is an essential component of the biosphere [1]. Vegetation is a critical element of soil–water–plant–atmospheric systems, having a considerable influence on the global energy budget, as well as hydrological, terrestrial carbon, and biogeochemical cycles from a local-to-global scale over seasonal, annual, and decadal periods [2–4]. Vegetation dynamics can act as an essential parameter for changes in the environment, including climatic and hydrological parameters like temperature, precipitation, evapotranspiration (ET), and land surface temperature, because it has a clear relationship with climate change [5,6].

In recent decades, vegetation–climate interactions have gained much attention due to global climate change [7–13]. However, past studies have been carried out worldwide by various researchers to understand vegetation dynamics using the vegetation index. Sur et al. [14] used 17 years (2000–2016) of normalized difference vegetation index (NDVI) datasets to characterize the spatiotemporal change in vegetation over the western part of Rajasthan. Mariano et al. [15] analyzed land degradation and drought events using the moderate resolution imaging spectroradiometer (MODIS)-leaf-area index, albedo, and evapotranspiration images for northeastern Brazil for 2002–2016. Many researchers have studied the changes in vegetation patterns on the Mongolian Plateau, and their responses to climatic factors and human activities [16–19]. Globally, the trend of vegetation dynamics and its interaction with associated drivers, such as precipitation, temperature, and evapotranspiration, have been studied using satellite-based products [20–24].

Ground observation is currently the most precise method for capturing local vegetation conditions. However, due to the limited number and uneven distribution of ground stations, it is challenging to use ground observation directly on a regional or global scale [19]. The utilization of long-term satellite data enables the better monitoring and evaluation of surface vegetation dynamics in relation to climate change on different spatiotemporal scales [25,26]. The land surface vegetation can be effectively characterized by using satellite-derived vegetation indices, such as the normalized difference vegetation index (NDVI) and the enhanced vegetation index (EVI) [23]. Among several vegetation indices, the NDVI is the most extensively used index as a proxy for monitoring vegetation dynamics across the world [27–30]. Globally, many researchers have explored the changes in vegetation dynamics using this remote sensing-based vegetation index for arid and semi-arid regions [14,15,24,31]. The simplicity of its calculations, its availability at several temporal and spatial scales, and its ability to eliminate noises arising from illumination conditions, topography, clouds, and other atmospheric conditions, make the NDVI an essential index for monitoring vegetation dynamics [32]. In addition, past studies primarily focused on analyzing vegetation trends using a single index. Moreover, there has been relatively little research in the Indian context, particularly in Rajasthan, highlighting vegetation–hydroclimatic interactions. Therefore, an in-depth analysis of vegetation dynamics and its response to climate change in Rajasthan still needs further clarification. This present study focused mainly on the vegetation indices' annual and seasonal variations, and their relationship with hydroclimatic variables from 2001 to 2021. We hypothesized that Rajasthan state had undergone a vegetative- greening or -browning trend due to changes in climatic factors, the intensification of canal irrigation, and urbanization. The goals of the present study were as follows: (1) to evaluate the seasonal and annual variations in the NDVI and hydroclimatic factors in Rajasthan during the past 21 years; and (2) to analyze trends at the pixel level using the Mann–Kendall (MK) test. This study will help to analyze the root causes behind drought phenomenon, the restoration of degraded lands, and ecosystem services in the study area.

2. Materials and Methods

2.1. Study Area

The current study was carried out in Rajasthan state, in western India; a peculiarly hot spot prone to substantial changes induced by climate change and anthropogenic modifications. Rajasthan is located in northwestern India and lies between the latitudes of 23°30′ and 30°11′ N and the longitudes of 69°29′ and 78°17′ E. Geographically, it occupies a 342,239 km^2 area, which covers almost 10.4% of the country's total geographical location, making it India's largest state. Rajasthan has a diverse topography, with the Aravalli Hills in the center (which extends from the northeast to the southwest), the Thar Desert in the northwest, sand plains in the northeast, and a plateau in the southeastern part. The climate in Rajasthan is characterized by insufficient (480–750 mm) and highly erratic rainfall distribution, high evaporation losses, low humidity values, strong winds, and extreme air temperature values. The Aravalli Hills significantly impact Rajasthan's climate, due to its orientation parallel to the southwest monsoon. The eastern slope of the Aravalli Hills is hit by the Arabian Sea branch of the southwest monsoon so it receives adequate rainfall, while the northwestern portion remains dry. However, moderate-to-highly humid climatic conditions prevail in the southeastern parts of the state.

Ten agro-climatic zones (ACZ) are present in the state: (i) the arid western plain; (ii) the irrigated northwestern plains; (iii) the hyper-arid partially irrigated western plain; (iv) the transitional plain with inland drainage; (v) of thethe transitional plain of the Luni Basin; (vi) the semi-arid eastern plain; (vii) the flood-prone eastern plains; (viii) the sub-humid southern plains; (ix) the humid southern plains; and (x) the humid southeastern plains (Figure 1). The hyper-arid partially irrigated western plain and the arid western plain have harsh climatic conditions with inadequate rainfall and low vegetation cover. The soil of these zones are characterized by dunes and aeolian soil. The humid southern plains and the humid southeastern plains climatic zones receive good rainfall and have high vegetation coverage. The state has two main important cropping seasons: *Kharif* and *Rabi*. In Kharif, crops are sown between June and July and are reaped between September and October; in Rabi, crops are sown between October and November and are reaped between March and April. The net sown area of Rajasthan is 18.13 Mha, which is about 53% of the TGA, while fallow land and forest cover 3.62 Mha (11%) and 2.77 M ha (8%), respectively. The other remaining areas fall under non-agricultural uses, barren land, permanent pasture, and other grazing land. Out of 20 million hectares of cultivated area, only 20% is irrigated because the state has only 1% of the country's total water resources [33].

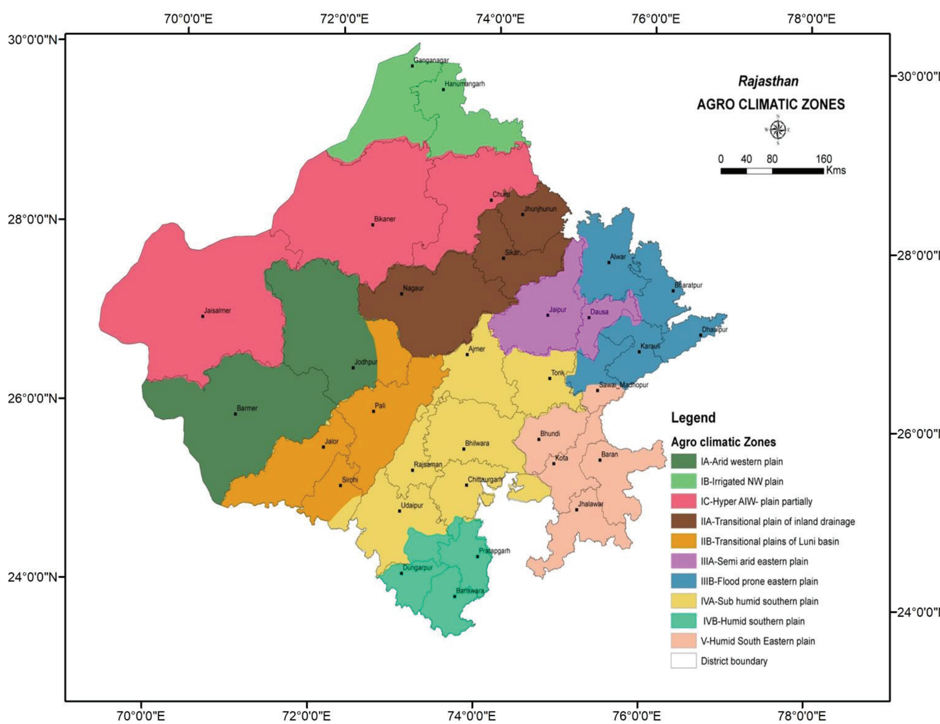

Figure 1. Agro-climatic zones of Rajasthan.

2.2. Data Set

Data from high-resolution satellite images are excellent sources for monitoring a large area's mapping and time-series analysis. Taking advantage of the accessibility of long-term satellite datasets, we have chosen four key parameters with which to characterize the spatiotemporal variation in the vegetation–hydroclimatic interactions. The current study utilized the MODIS-derived NDVI to comprehend the vegetation patterns from 2001 to 2021. Three hydroclimatic factors were also used to understand the climatic variation during 2001–2021 (Figure 2). The various datasets and their specifications are given in Table 1.

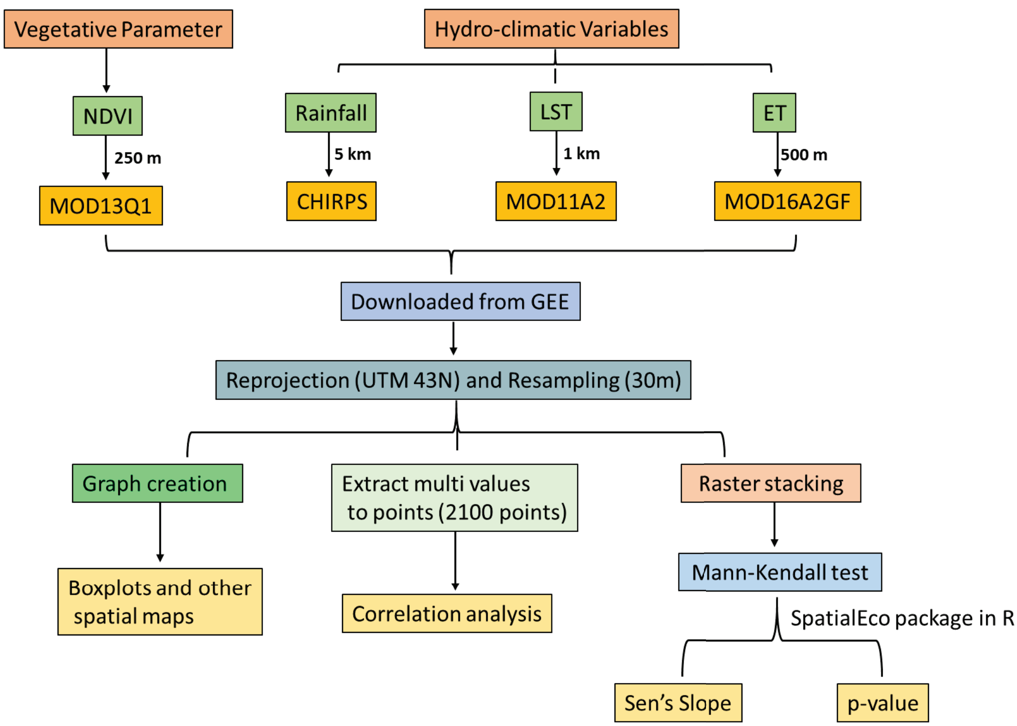

Figure 2. Flowchart of the methodology employed in this study.

Table 1. The dataset used in this study and its specifications.

S. No.	Dataset	Variable	Unit	Temporal Resolution	Spatial Resolution	Period
1	MODIS MOD13Q1	NDVI	-	16 days	250 m	2001–2021
2	CHIRPS	Rainfall	mm	Daily	5 km	2001–2021
3	MODIS MOD11A2	LST	°C	8 days	1 km	2001–2021
4	MODIS MOD16A2GF	ET	$kg/m^2/8$ d	8 days	500 m	2001–2021

2.3. Downloading and Processing of Satellite Data

2.3.1. NDVI

The NDVI data from the NASA Land Processes Distributed Active Archive Center's MODIS products (MOD13Q1) were used in the present study. The best pixel values from the acquisitions made by satellites over 16 days were selected by algorithms using the primary criteria of low clouds, small view angles, and maximum NDVI. In the current study, the NDVI product of MODIS MOD13Q1 was downloaded from Google Earth Engine for the 21 years (2001–2021). The NDVI time-series data were temporally smoothed using the Savitzky–Golay filter (SGF) [34]. The SGF uses a weighted least-squares regression to fit a polynomial function. The data sets were reprojected from the geographic coordinates system to a UTM 43 coordinate system. Furthermore, the datasets were resampled to 30 m cell size using bilinear interpolation in ArcGIS (10.5) [35].

2.3.2. Rainfall

In the present study, we used 5 km spatial resolution rainfall data from the climate-hazards group infrared precipitation with station data (CHIRPS)-based rainfall products. The datasets were downloaded using Google Earth Engine for the 21 years (2001–2021). The mean monthly rainfall was computed by taking the mean of the respective month for the 21 years (2001–2021). Similarly, the total annual rainfall was computed by calculating the sum of all the images for the individual year.

2.3.3. Land Surface Temperature

In this study, the MODIS MOD11A2 LST product was downloaded from Google Earth Engine for the 21 years (2001–2021). The data were further converted into °C [36,37] using the following formula:

$$\text{LST} = 0.02 \times \text{DN} - 273.15$$

The mean monthly LST values were computed by calculating each month's mean for 2001–2021. Similarly, the mean annual LST was computed by calculating the mean of all the images of the respective year.

2.3.4. Evapotranspiration (ET)

The evapotranspiration data were obtained from MODIS, and were highly correlated with the ET observations of the Indian conditions [38]. Based on the Penman–Monteith equation, the MOD16 data-product collection algorithm incorporates inputs from the daily reanalysis of meteorological data and MODIS data products, like vegetation dynamics, land cover, and albedo. The pixel values for the ET layer were calculated by adding data from an 8-day composite period. The data product MOD16A2GF was downloaded from Google Earth Engine from 2001 to 2021 using the following steps: (i) the monthly ET was computed by aggregating the 8-day composite images within the respective month of the particular year. (ii) After that, the long-term (21 years) mean monthly ET for each month was computed by calculating the mean of the respective month. (iii) Similarly, the total annual ET was calculated by aggregating the monthly ETs for the respective year.

2.4. Trend Analysis

We used the nonparametric MK test and Sen's slope estimator [39,40] to assess the significant trends and magnitudes, respectively. Hamed and Rao (1998) [41] introduced a modified version of the MK test to consider the effect of autocorrelation on the data. They proposed a correction of the variance for the adequate number of observations. The null hypothesis (H0) of no trend, and the alternative hypothesis of there being a trend, were tested at a 5% level of significance. The trend tests were implemented using R 4.2.1 software.

Four factors (NDVI, LST, ET, and rainfall) were downloaded using Google Earth Engine for the 21 years (2001–2021). All these input layers had varying resolutions (Table 1). To harmonize the datasets, all the raster layers were resampled to 30 m using a bilinear resampling method. After that, these datasets were used for the MK test. First, all the images were stacked in one raster in ascending order of year. Then, the MK test was implemented using a raster and the Kendall function from the spatialEco package.

Methodology Description:

The computational procedure for the MK test for the time-series data, $y_1, y_2, y_3, \ldots, y_n$, was as follows:

Step 1: Calculate all-possible differences of $y_i - y_j$, where $i > j$, i.e., $\frac{n(n-1)}{2}$ for the given time-series data. The differences are

$$y_2 - y_1, \, y_3 - y_2, \, \ldots, \, y_n - y_{n-1}$$

Step 2: Determine the sign of all the differences $\left(y_i - y_j\right)$.

Step 3: Assign numerical values to the sign differences. The assignment rule is as follows:

$$sign\ \left(y_i - y_j\right) = \begin{cases} 1; if\ \left(y_i - y_j\right) > 0 \\ 0; if\ \left(y_i - y_j\right) = 0 \\ -1; if\ \left(y_i - y_j\right) < 0 \end{cases}$$

Step 4: Now, calculate the sum of

$$S = \sum_{j=1}^{n-1} \sum_{i=j+1}^{n} sign\ \left(y_i - y_j\right)$$

which is the number of positive differences minus the number of negative differences.

If $n \leq 10$, the value of $|S|$ can be compared directly to the theoretical distribution of S derived by Mann and Kendall, i.e., the Gilbert table of probabilities. If $n \geq 10$, the statistic S is about normally distributed with the mean and variance as follows:

$$E(S) = 0$$

$$var\ (S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{g} t_p(t_p - 1)(2t_p + 5)\right.$$

where g is the number of tied groups, and t_p is the number of observations in the p^{th} group. The tie correction method was given by Hensel (2005) [42] for ties in the data due to equal values or non-detects. To infer the test, the test statistic Z_{MK} is computed by the equation:

$$Z_{MK} = \begin{cases} = \frac{S-1}{\sqrt{var(S)}}\ if\ S > 0 \\ \quad = 0\ if\ S = 0 \\ = \frac{S-1}{\sqrt{var(S)}}\ if\ S > 0 \end{cases}$$

If $|Z_{MK}|$ is greater than $Z_{\alpha/2}$, where α represents the significance level, then there is evidence of a significant trend. Positive values of Z_{MK} indicate increasing trends, while negative Z_{MK} values show decreasing trends.

The MK test is used on uncorrelated data because serial correlation can increase or decrease the probability of detecting significant trends. When serial correlation is present, pre-whitening is used to identify a trend in a time series. Hamed and Rao (1998) [41] suggested a modified MK test for serially correlated data that corrects the variance (S) for the effective number of observations.

The corrected variance (S) is given by

$$var\ (S) = \frac{1}{18}[n(n-1)(2n+5)] * \frac{n}{n^*}$$

where $\frac{n}{n^*} = 1 + \frac{2}{n(n-1)(n-2)} * (n-k)(n-k-1)(n-k-2) * \rho_k$.

n^* is the effective number of observations to account for data autocorrelation, whereas ρk represents the serial correlation between the observation ranks for lag-k.

Sen's slope estimator:

Sen (1968) [43] devised a nonparametric, robust approach for evaluating the slope of a trend in time-series data. The slope-estimator methods of Sen (1968) [43] and Theil

(1950) [44] are used for the prediction of the magnitude of the trend. The algorithms for Sen's slope for a time-series data, $y_1, y_2, y_3, \ldots, y_n$, are as follows:

Step 1: Calculate all $\left(\frac{n(n-1)}{2}\right)$ possible differences of $y_i - y_j$, where $i > j$. These differences are

$$y_2 - y_1, y_3 - y_2, \ldots, y_n - y_{n-1}$$

Step 2 Find T_i as

$$T_i = \frac{y_i - y_j}{i - j}$$

Step 3: Calculate the median of these T_i, which are represented as Sen's estimator.

$$\mathrm{T_{med}} = \begin{cases} T_{\frac{N+1}{2}} \;; if\ N\ is\ odd \\ \frac{T_{\frac{N+2}{2}} + T_{\frac{N}{2}}}{2} ; if\ N\ is\ even. \end{cases}$$

A positive value of $\mathrm{T_{med}}$ indicates an upward or increasing trend, and a negative value of $\mathrm{T_{med}}$ gives a downward or decreasing trend for the variables under study.

2.5. Relationship of Vegetative Indices with Hydroclimatic Factors

Pearson's correlation was used to identify the potential correlations between natural vegetation dynamics and climatic parameters. The Pearson correlation coefficient, which ranges from −1 to +1, quantifies the degree and direction of a monotonic relationship between two variables, where −1 and +1 represent monotonically decreasing and increasing associations, respectively. The correlation coefficients were calculated by implementing a Pearson correlation analysis. Subsequently, these correlations were subjected to a t-test at a 5% significance level.

3. Results

3.1. Rainfall

3.1.1. Characterization of Annual Change

The inter-annual or temporal variability in rainfall for the 21 years (2001–2021) is depicted in Figure 3. The maximum rainfall (~2400 mm) and minimum rainfall (0.0 mm) were recorded in 2011 and 2002, respectively. It can be observed that 2011, followed by 2019 and 2010, received the highest rainfall during the last 21 years. Further, 2002, followed by 2015, received the lowest rainfall. The median rainfall varied between ~380 and ~1400 mm throughout the perio[d.] The 25th and 75th percentile values ranged from ~200 to ~750 mm and ~500 to ~1750 mm, respectively, across the years. The maximum fluctuations in the temporal pattern of rainfall were observed in 2011, while the minimum were in 2002. of theThe boxplots for rain suggest that the mean rainfall varied slightly between 2001 and 2021.

3.1.2. Characterization of Intra-Annual Change

Figure 4 shows the mean monthly variability in rainfall (monsoon and non-monsoon) for 2001–2021 in Rajasthan. The maximum precipitation was observed in the month of July (~640 mm), followed by August (~625 mm), September (~305 mm), and June (125 mm), respectively. Among all the months, June to September showed higher temporal fluctuations. The boxplot related to the rainfall received shows that the rainfall ranged from 0.0 to ~ 640.0 mm across all twenty-one years. The median of monthly rainfall varied between 0.0 and ~340.0 mm throughout the period. It is also noticeable that the rain has its seasonal peak in July and August, while the lowest mean rainfall values in Rajasthan are observed to occur in December.

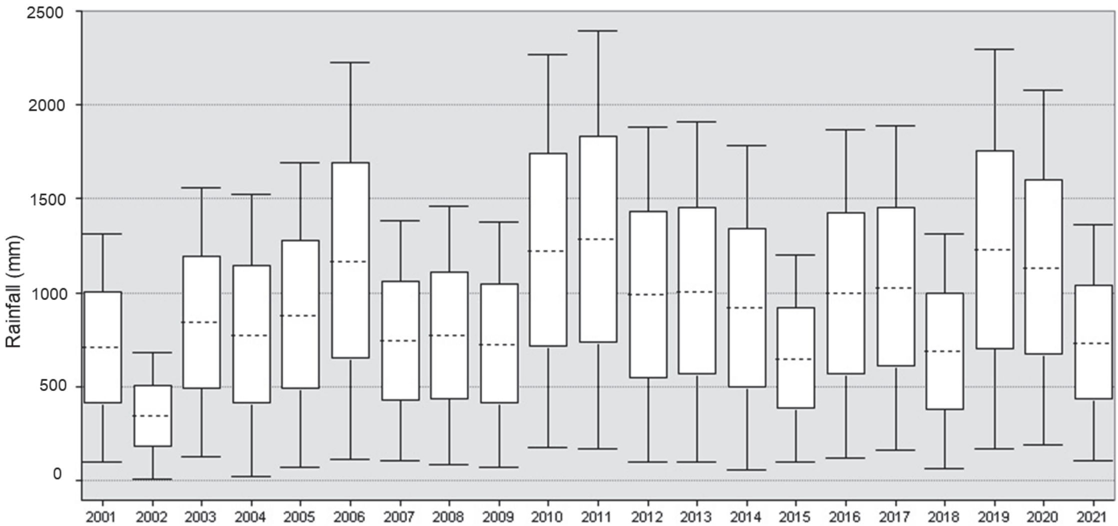

Figure 3. Boxplot for the inter-annual variability in rainfall during 2001–2021.

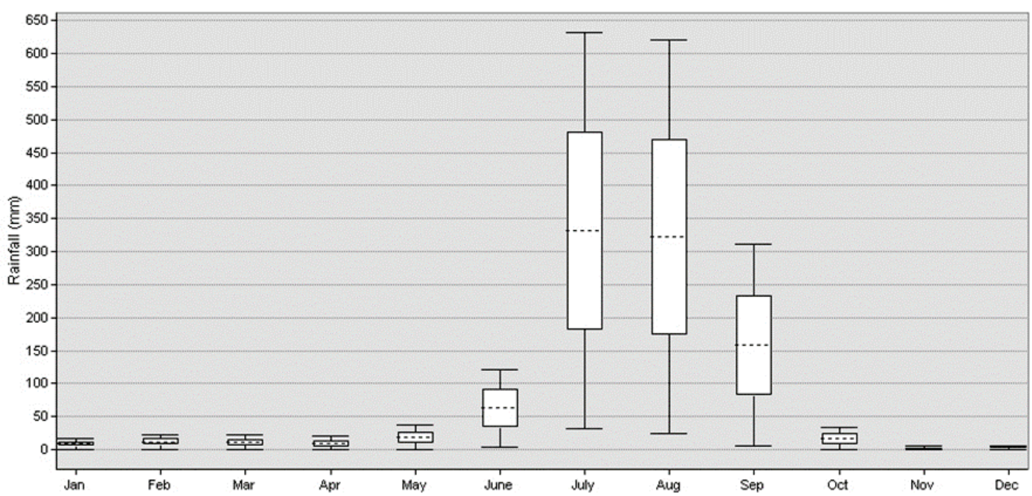

Figure 4. Mean monthly rainfall during 2001–2021.

3.1.3. Characterization of Spatial Change

Figure 5 illustrates the spatial variance in the mean annual rainfall for 2001 to 2021 at a 30 m resolution, which varies from 8 to 2397 mm. The maximum rainfall ranged between 1920 and 2397 mm, and was observed in 2006, 2010, 2011, 2019, and 2020. These maps indicate a decreasing rainfall trend from the southern and eastern regions to the western region of the study area. The south and southeastern part of Rajasthan receive higher rainfall. The west of Rajasthan receives the lowest rainfall, which includes the hyper-arid partially irrigated zone, the arid western plains, the irrigated northwestern plains, and a transitional plain with inland drainage. Due to the deficient rainfall, most of the state's drought occurrences occur in the western region.

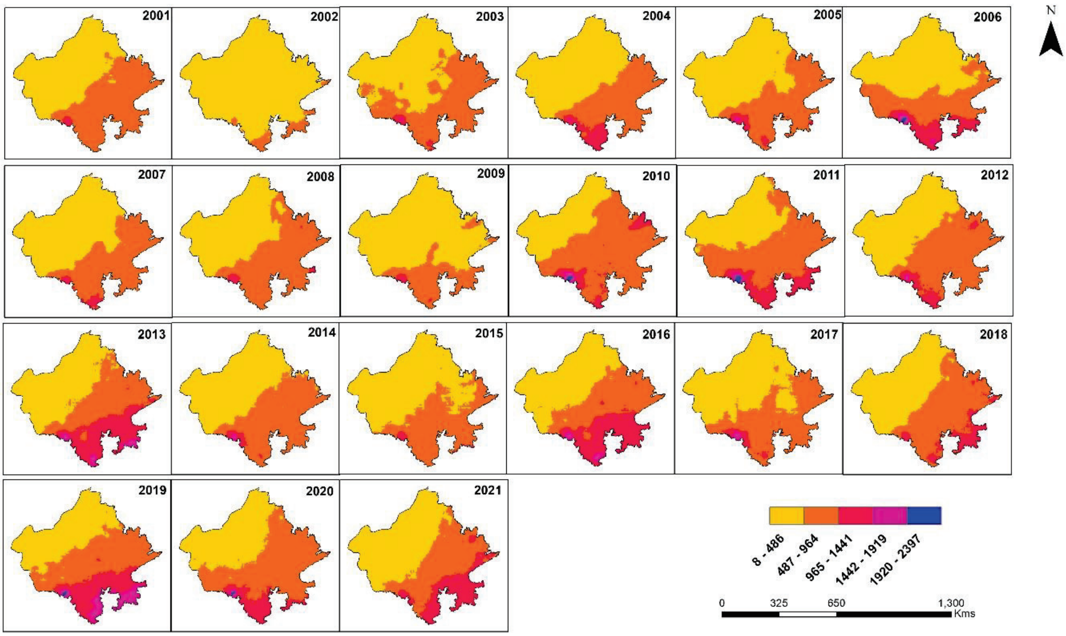

Figure 5. Spatial variation in total annual rainfall (mm) during 2001–2021.

3.1.4. Trend Analysis for Rainfall

Over the years from 2001 to 2021, it was noticed that rainfall values had an overall temporal increase, with a positive correlation of 0.37 (Figure 6). There was a sharp decline in rainfall between 2002 and 2009. In order to analyze these trends, we implemented the MK test and Sen's slope estimator; the computed results are depicted in Figure 7. Sen's slope (SS) is the median slope and is used to estimate the magnitude of the trend. Increasing and decreasing trends are represented by positive and negative SS values, respectively, and range from 2 to 31 mm per year. Rainfall increased for 99.9% of the study area, including the 61.83% which showed a significant increasing trend ($S > 0$, $p < 0.05$). Pixels with increasing trends ($S > 0$, $p < 0.05$) were mainly concentrated in the irrigated northwestern plains, of thethe transitional plains with inland drainage, the sub-humid southern plains, and the humid southeastern plains.

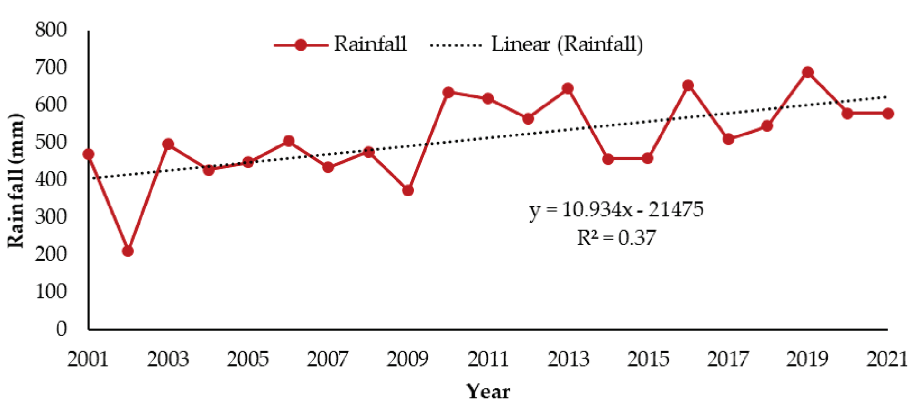

Figure 6. Inter-annual variability in mean rainfall during 2001–2021.

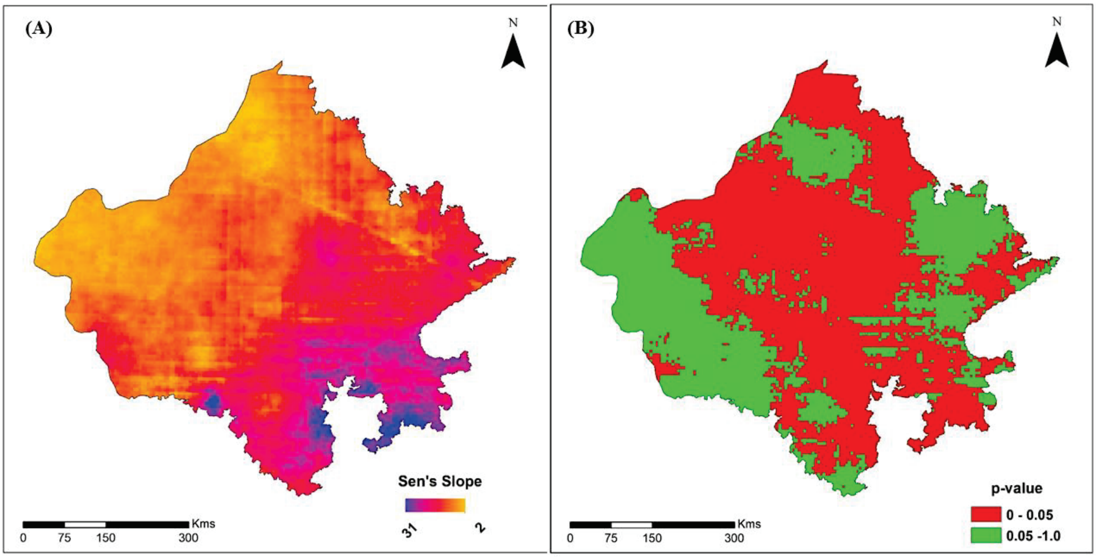

Figure 7. (**A**) Sen's slope values for rainfall changes and (**B**) Mann–Kendall test for statistically significant trends in mean annual rainfall at the pixel level.

3.2. Land Surface Temperature

3.2.1. Characterization of Annual Change

The boxplot of the annual LST shows that the LST fluctuated slightly between 2001 and 2021 (Figure 8). For instance, compared to the other years taken into consideration here, the LST values for 2006 and 2012 appear to be lower. Interestingly, the LST data points for each year include data for each month from January through December. The highest and lowest LST levels were observed to have occurred in 2016 and 2021, respectively. The median of the LST varied between ~34 and ~36 °C throughout the period. The 25th and 75th percentile of the LST varied between ~29 and ~30 °C and ~39 and ~41 °C, respectively, across 2001–2020.

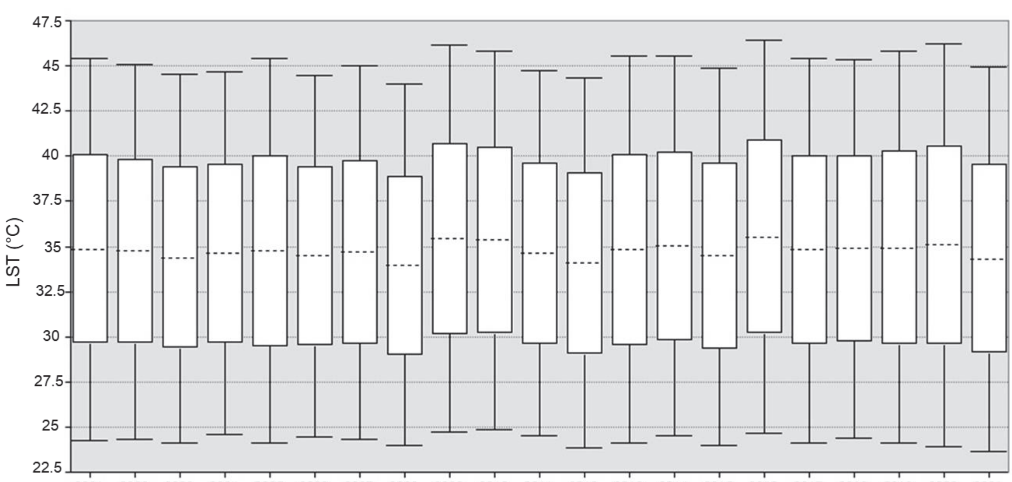

Figure 8. Boxplot for the inter-annual variability in land surface temperature during 2001–2021.

3.2.2. Characterization of Intra-Annual Change

Figure 9 shows the seasonal variability in the LST over the period 2001–2021, and it can be observed that the LST fluctuates throughout the year. The LST has a seasonal peak from April to June, while December and January have the lowest LST mean values. Further, it can be seen from Figure 9 that the LST usually starts to rise in January, reaches its maximum in May, and then decreases until December.

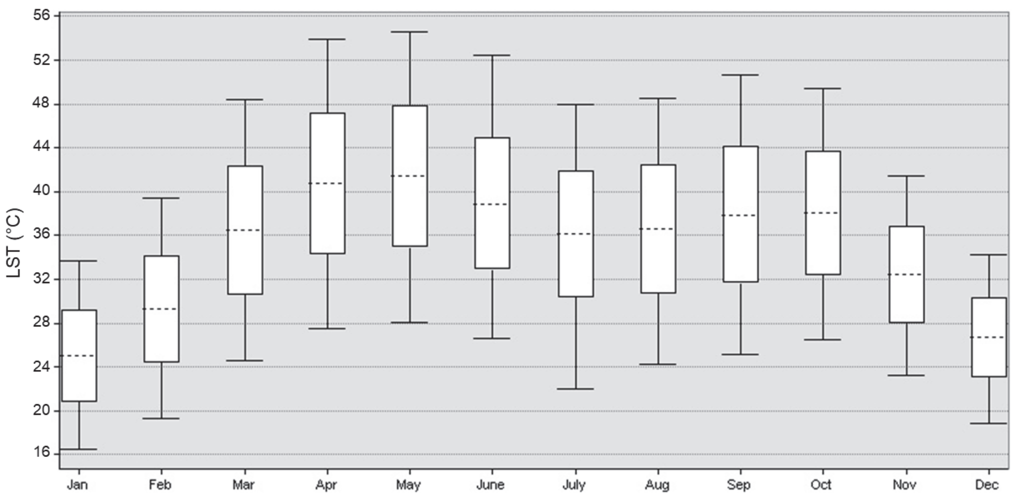

Figure 9. Mean monthly LST during 2001–2021.

3.2.3. Characterization of Spatial Change

Spatial variations in the long-term mean annual LST for 2001 to 2021 at a 30 m resolution are depicted in Figure 10, and vary from 24 to 47 °C. It can be observed that the western parts have higher temperatures compared to the eastern and southern parts of Rajasthan. The hyper-arid partially irrigated zone and the arid western plains show less variation, while the sub-humid southern plains show the maximum variation over the 21 years. The maximum number of pixels which had a 43–47 °C LST was observed in 2016, followed by 2009 and 2001. Similarly, the maximum area which had a 24–33 °C LST was observed in 2021, followed by 2020.

3.2.4. Trend Analysis of LST

Figure 11 depicts the trend in the mean LST across Rajasthan for the 21 years (2001–2021). A linear regression model was developed to detect temporal variations in the LST since 2001 by calculating the average LST for all pixels for the whole of Rajasthan. The results indicate an overall decreasing trend in the LST, with a negative correlation of 0.38 over 2001–2021. The mean LST values vary from ~35.9 to 38.3 °C. In Figure 12A, both increasing and decreasing trends are shown for the mean annual LST data. The magnitude of the change in the LST ranges from −0.26 to 0.30 °C per year. It can be observed that the majority of the pixels (78.65%) have a decreasing trend ($S < 0$), with the southern and southeastern parts showing the highest declining rates, whereas 21.35% of the pixels have increasing rates, and are concentrated mainly in the western parts of Rajasthan. Figure 12B shows the statistical significance level of the LST trend over the 21 years, and reveals that all of the regions' trends are insignificant. About 50% of the pixels show significant changes ($p < 0.05$), and are located mainly in the southern and southeastern parts, whereas the rest of the pixels show a non-significant difference ($p > 0.05$) in the annual LST.

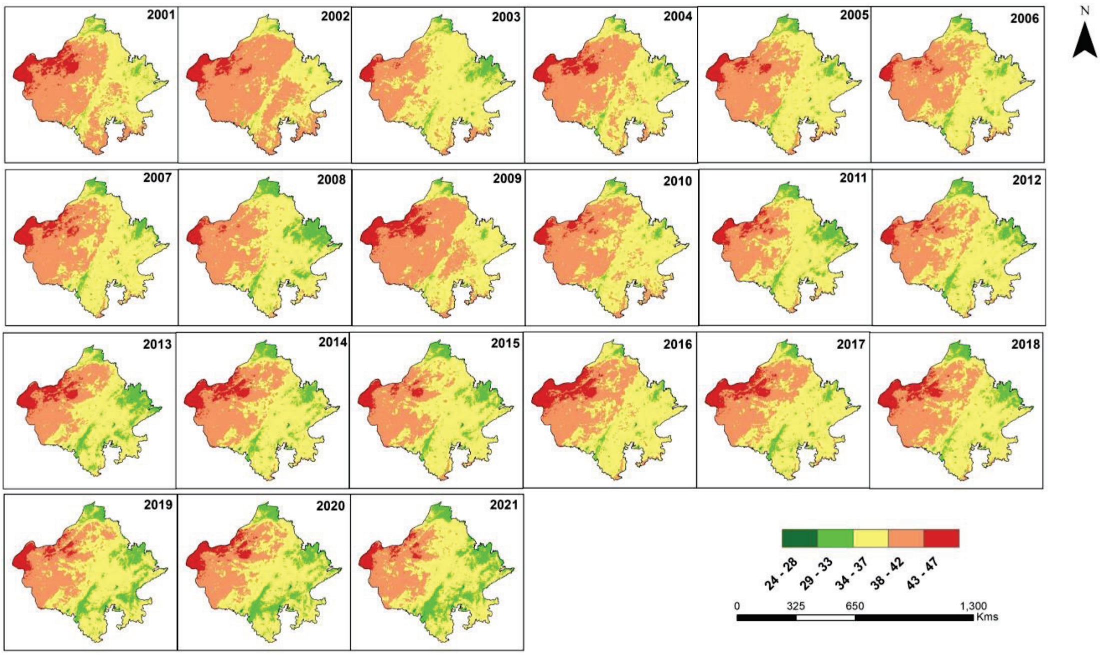

Figure 10. Spatial variation in LST (°C) during 2001–2021.

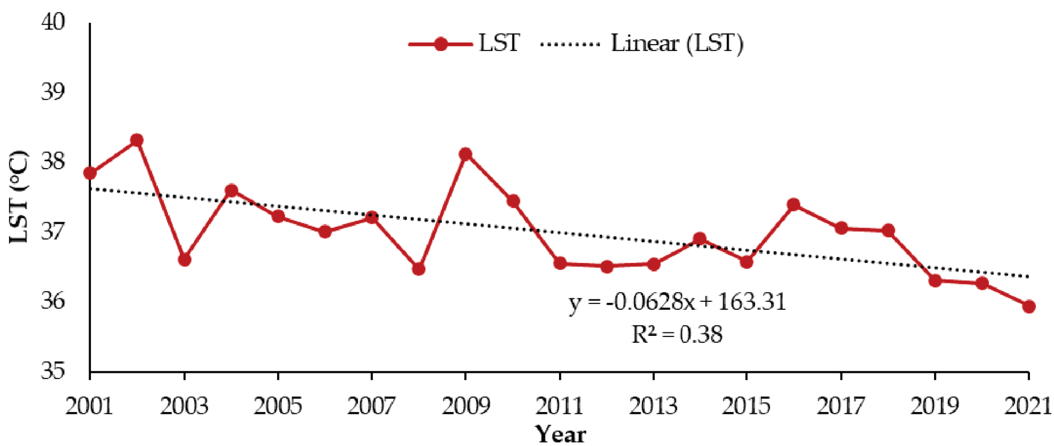

Figure 11. Inter-annual variability in mean LST in Rajasthan during 2001–2021.

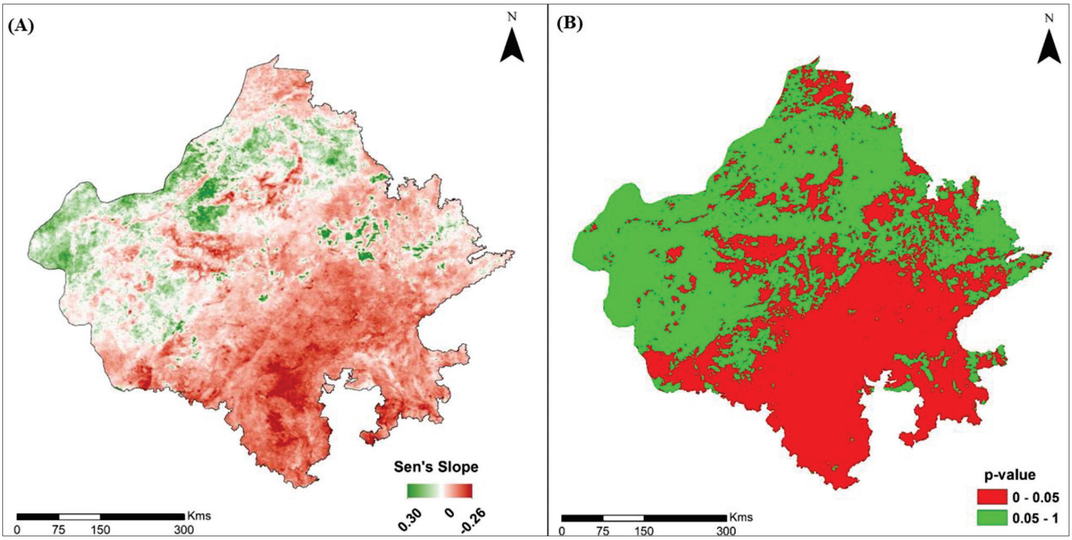

Figure 12. (**A**) Sen's slope values for changes in LST and (**B**) Mann–Kendall test for statistically significant trends in mean annual LST at the pixel level.

3.3. Evapotranspiration

3.3.1. Characterization of Annual Change

The annual temporal variations in ET for the 21 years is presented in Figure 13. The maximum fluctuations in the temporal ET pattern are observed to have occurred in 2020, while the minimum was in 2002. The ET values corresponding to 2002 and 2003 appear lower (~350 mm) when compared to the other years considered here. The maximum and minimum ET values occurred in 2020 and 2002, respectively. The median ET varies between ~240 and ~390 mm throughout the period. The 25th and 75th percentile values range from ~120 to ~200 mm and from ~350 to ~590 mm, respectively, from 2001 to 2020.

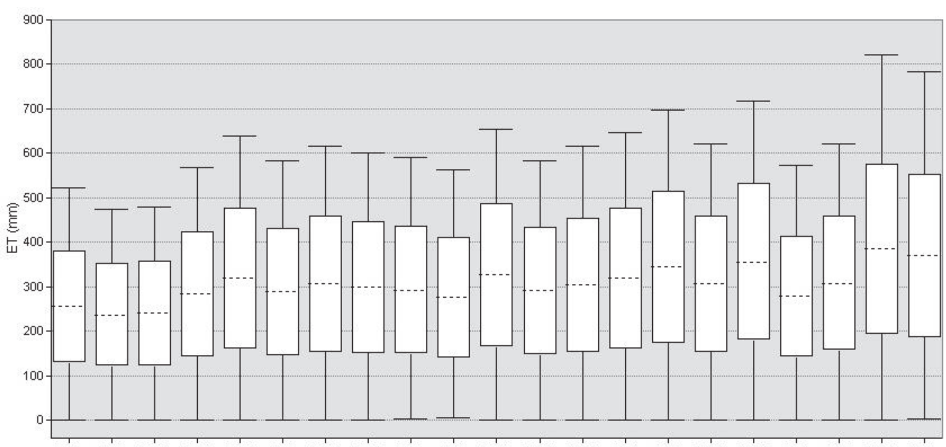

Figure 13. Boxplot for inter-annual variability in total ET during 2001–2021.

3.3.2. Characterization of Intra-Annual Change

Figure 14 depicts the mean monthly ET for the twenty-one years (2001–2021). Further, we noticed that the monthly ET values fluctuate throughout the year. It can also be observed that ET reaches its seasonal peak in February, while the lowest values for ET occur in April. Additionally, it has been noted that ET often begins to rise in January, peaks in February, and then declines until April, and then, once more, it starts increasing until September, and decreases until December.

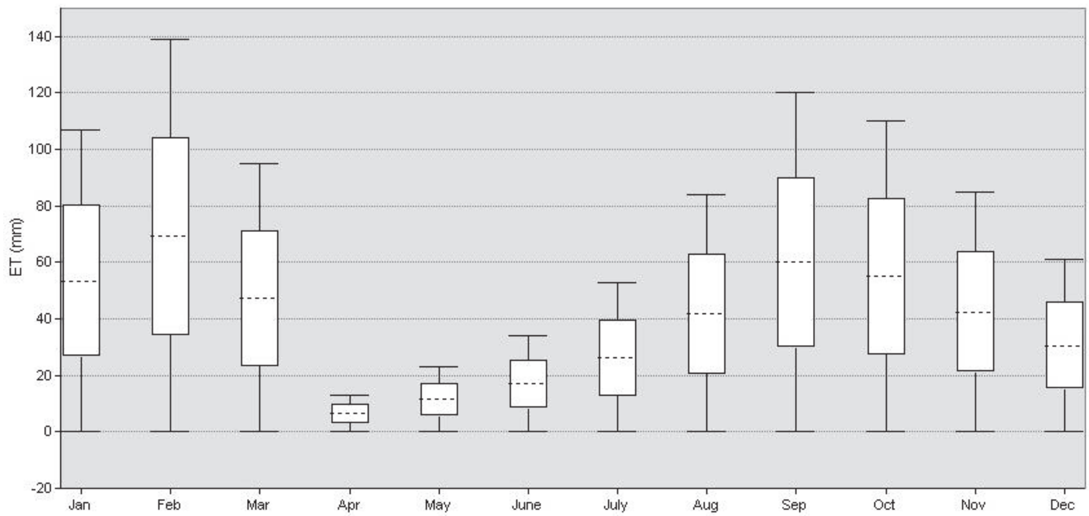

Figure 14. Mean monthly ET during 2001–2021.

3.3.3. Characterization of Spatial Change

Spatial variations in the annual ET from 2001 to 2021 at a 30 m resolution are depicted in Figure 15. The yearly ET varies from 0 to 821 mm. These maps indicate a decreasing trend in ET from the southern and eastern parts to the northern and western parts of Rajasthan. The south and southeastern parts of Rajasthan have a higher ET, which includes the humid southern plains, the sub-humid southern plains, and the humid southeastern plains. The maximum number of pixels with a low ET (0–50 mm) were observed in 2002, followed by 2009. It can also be observed that ET increased in most parts, particularly in the southern and southeastern regions, between 2001 and 2021.

3.3.4. Trend Analysis of ET

Figure 16 depicts the trend in the mean ET for the twenty-one years (2001–2021) for Rajasthan. A linear regression model was created to determine the ET variations since 2001, by averaging the mean ET across all the pixels for the whole state of Rajasthan. With a positive correlation of 0.71 between the ET values over 2001–2021, an overall increasing temporal trend in ET was observed. The mean annual ET values for Rajasthan vary from ~54 to 181 mm.

Figure 17A indicates that most of the area (98.24%) shows a positive trend. Only a few pixels (1.76%) have a negative for the mean annual ET and, by incorporating the significance level from Figure 17B, it is found that 90.21% of the area shows a significant positive change in ET, and only 16.80% of the area shows no trend in ET.

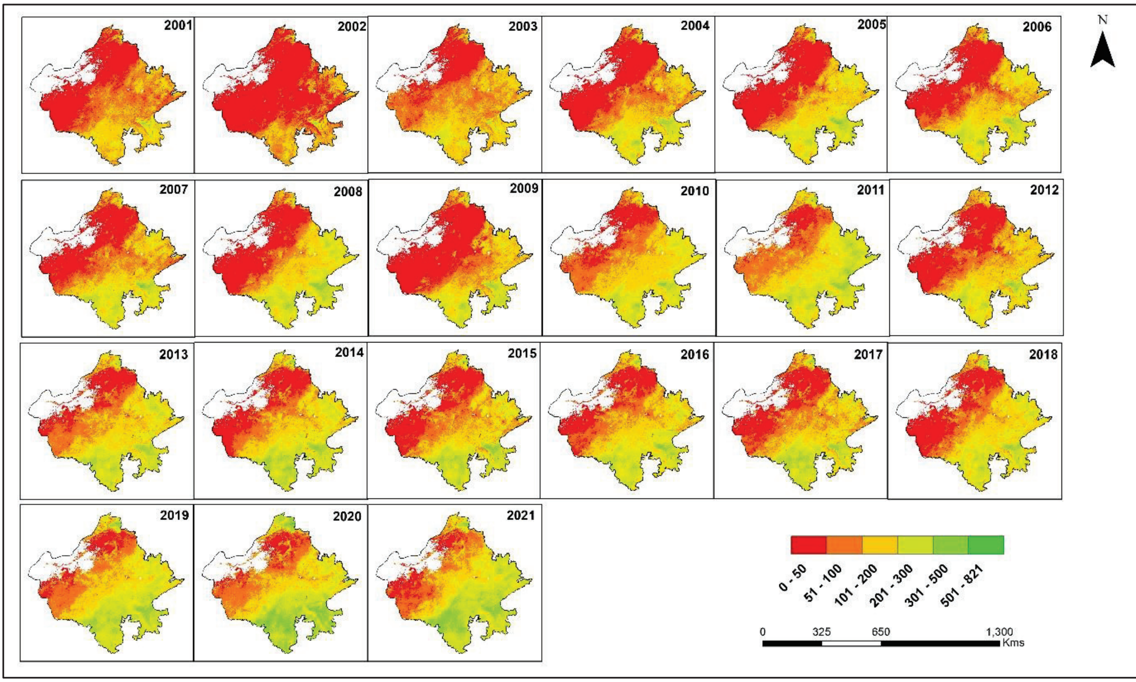

Figure 15. Spatial variation in total annual ET (mm) during 2001–2021.

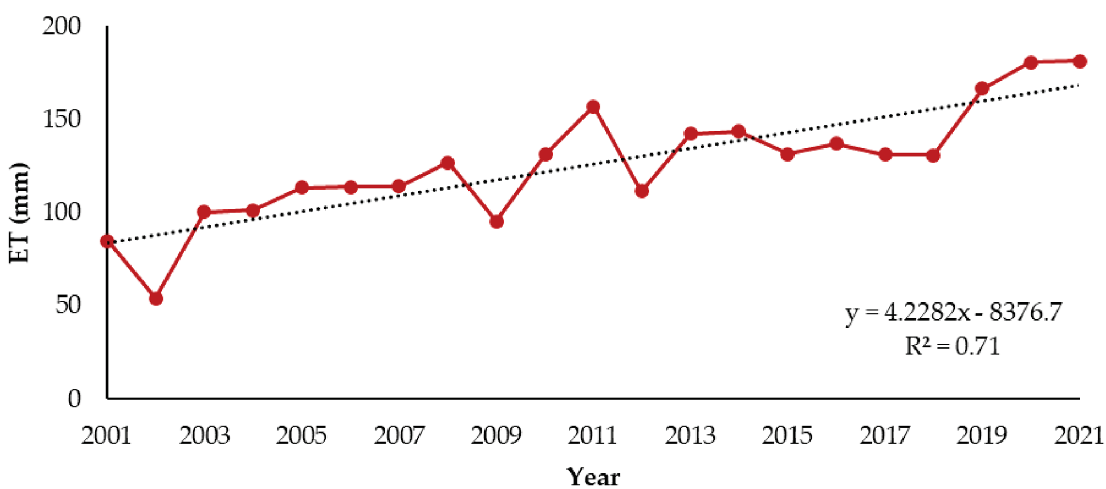

Figure 16. Inter-annual variability in mean ET (mm) for Rajasthan during 2001–2021.

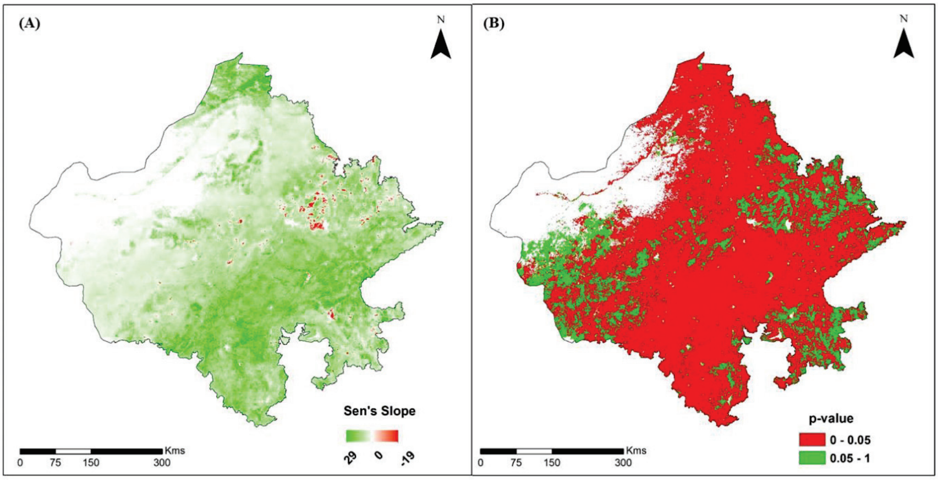

Figure 17. (**A**) Sen's slope values for changes in ET and (**B**) Mann–Kendall test for statistically significant trends in mean annual ET at pixel level.

3.4. Normalized Difference Vegetation Index (NDVI)

3.4.1. Characterization of Annual Change

The boxplot corresponding to the annual NDVI temporal patterns indicates that the NDVI varied slightly between 2001 and 2021 (Figure 18). The mean of all the NDVI values from January to December is contained in the NDVI data from 2001 to 2021. The NDVI values were at their highest (~0.74) and lowest (~−0.15) points in 2020 and 2005, respectively. The NDVI experienced its highest variations in 2017 and 2020, while its greatest downward fluctuations were in 2008 and 2010. Additionally, the NDVI's 75th percentile lies between 0.43 and 0.52, while the 25th percentile of the NDVI did not show any significant variations across the twenty-one years. In addition to this, the NDVI varied between −0.15 and 0.75 from 2001 to 2021.

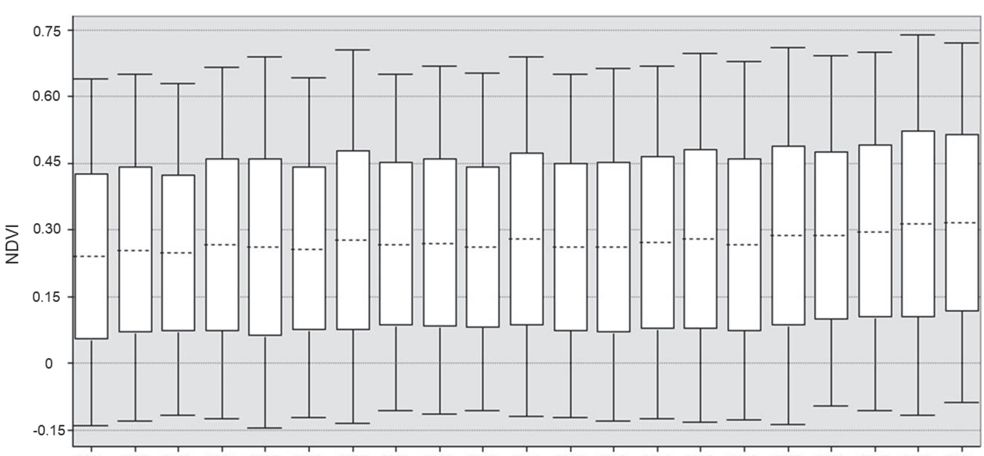

Figure 18. Boxplot for inter-annual variability in NDVI during 2001–2021.

3.4.2. Characterization of Intra-Annual Change

Figure 19 shows the NDVI seasonal patterns for the entire Rajasthan state. The boxplot displays the mean monthly NDVI values for 2001 to 2021. This study area's NDVI values are shown to be lowest in June, with seasonal peaks in the NDVI occurring in February and September. Additionally, it can be demonstrated that the monthly NDVI values fluctuate less during the summer than during the monsoon and winter seasons. Further, it has been noted that vegetation greening (NDVI) often begins in May or June, peaks in September, then shows a slight decrease from October to December, and again reaches its maximum value in the month of February, and after that decreases until April or May. This shows the relationship of the NDVI values with the cropping season (*Kharif*, *Rabi*, and *Zaid*).

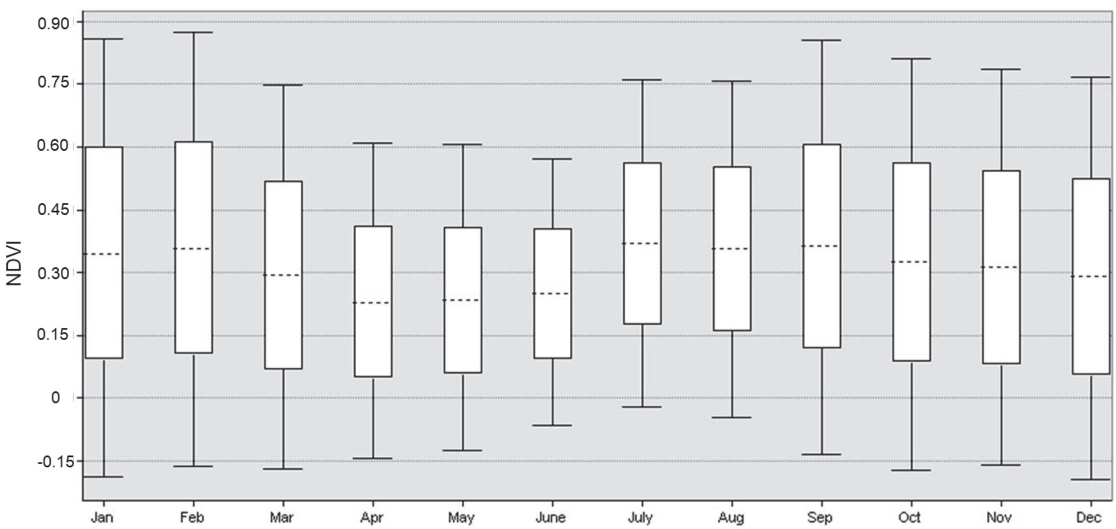

Figure 19. Mean monthly variability in NDVI during 2001–2021.

3.4.3. Characterization of Spatial Change

Figure 20 depicts the variations in the mean annual NDVI for 2001–2021 at a 30 m resolution. The NDVI varied from −0.15 to 0.74. The NDVI increased in Rajasthan over time, which reflects the increased greenness in Rajasthan. Among all the years, the maximum number of green pixels was recorded in 2021. In 2001, on the other hand, the trend was the exact opposite, with lower NDVI values covering much of the basin. Despite a solid upward trend in the NDVI, the inter-annual variation has increased since 2009. Most of the areas with high NDVI values fall under the following ACZs: the semi-arid eastern plains, the humid southeastern plain, the humid southern plains, the sub-humid southern plains, and the flood-prone eastern plain. The lowest NDVI values were observed in the following areas of the ACZs: the arid western plain and the hyper-arid partially irrigated zone. Overall, a significantly increasing trend in the NDVI was observed across the study area.

3.4.4. Trend Analysis of NDVI

Figure 21 shows the mean NDVI trend for Rajasthan during 2001–2021. A linear regression model was developed by computing the mean NDVI over all the pixels for the entirety of Rajasthan. With a positive correlation of 0.85 between 2001 and 2021, an overall increasing trend in the NDVI was detected. The mean annual NDVI varied between ~0.20 and 0.31. Sen's slope values and the MK test for significant trends in the mean annual NDVI at the pixel level are presented in Figure 22A,B. From 2001 to 2021, there were more pixels with improved vegetation than with degraded vegetation. The NDVI increased for 96.5% of the studied area ($S > 0$), primarily in the south and east, while it dropped for 3.4% of the pixels ($S < 0$). A statistically significant difference ($p < 0.05$) was observed for 83.7% of the total pixels. In addition to this, it was also observed that the NDVI significantly increased over the Indira Gandhi Canal command area in the Jaisalmer district of Rajasthan, which is in the hyper-arid and drought-prone regions. The NDVI decreased for some of the pixels in the Jaipur and Jaisalmer districts.

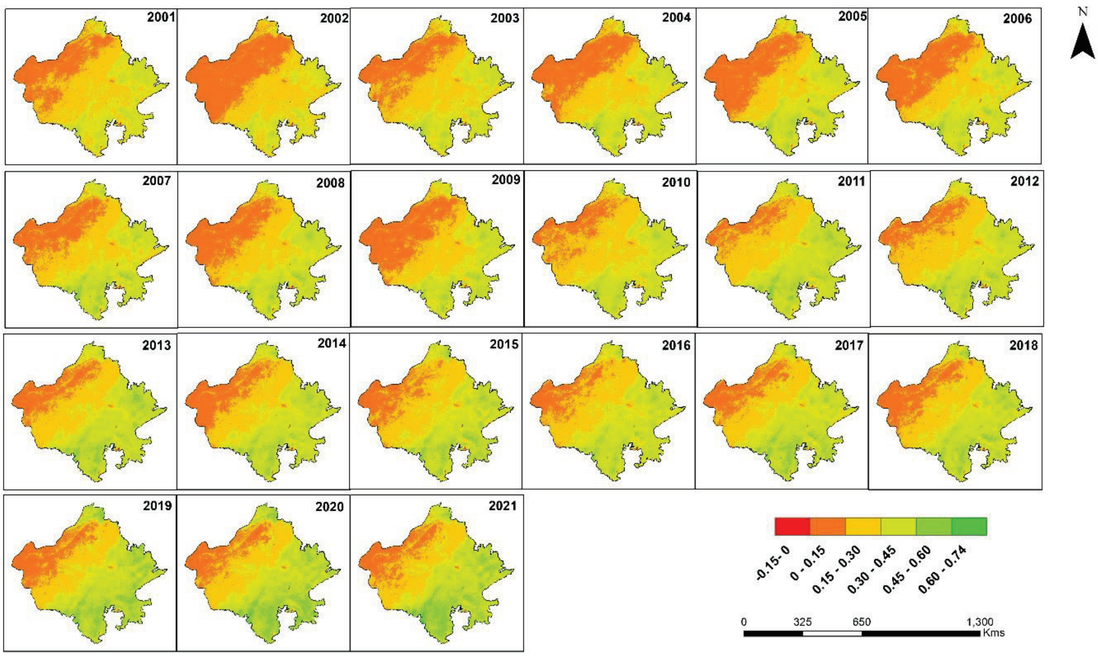

Figure 20. Spatial variation in NDVI during 2001–2021.

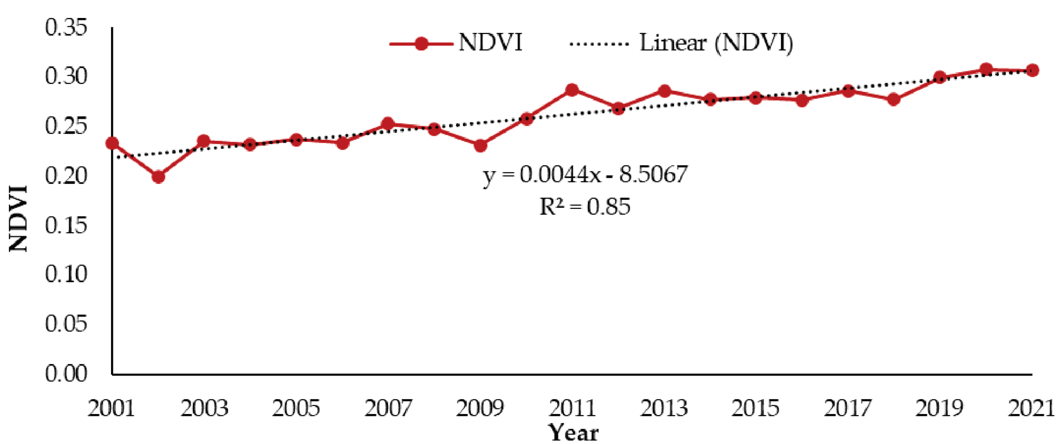

Figure 21. Inter-annual variability in mean NDVI for Rajasthan during 2001–2021.

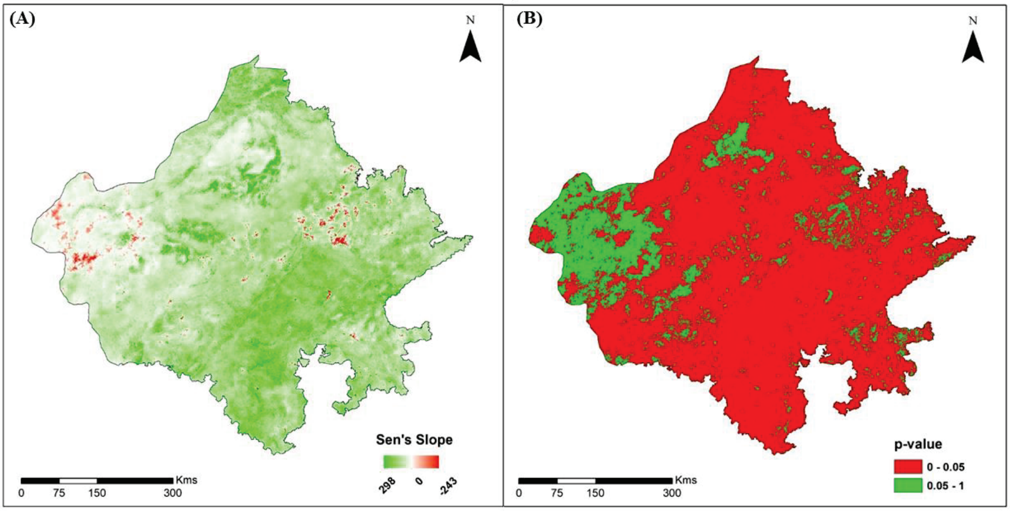

Figure 22. (**A**) Sen's slope values for changes in NDVI and (**B**) Mann–Kendall test for statistically significant trends in mean annual NDVI at the pixel level.

3.5. Correlation between Hydroclimatic Parameters and Vegetative Indices

A pair-wise Pearson correlation coefficient test was implemented to quantify the association between the study parameters. Except for the RF-LST, all the pairs had a significant association between themselves (Figure 23). The highest positive correlation can be observed for ET-NDVI (0.86), followed by ET-RF, whereas the NDVI-LST shows the highest negative correlation (−0.55), followed by ET-LST (−0.46). Overall, we can infer that the LST is negatively correlated with the other parameters, and the other variables are positively correlated.

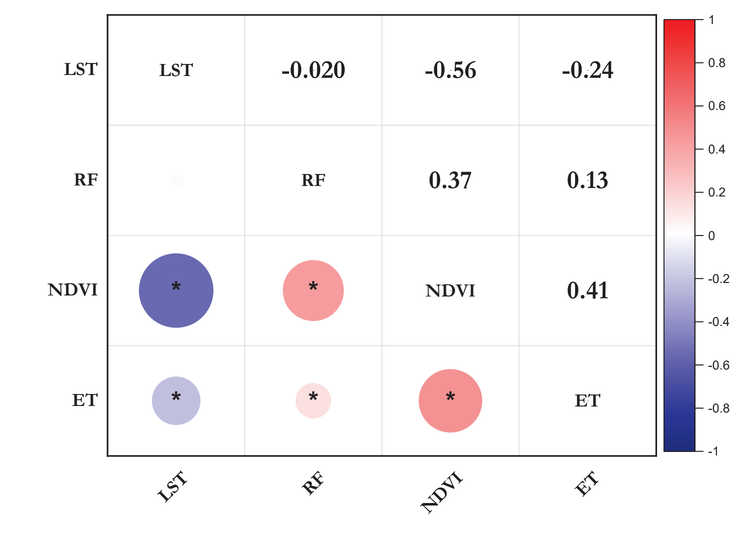

Figure 23. Relationship of vegetative indices and associated hydroclimatic factors.

4. Discussion

4.1. Spatiotemporal Variation in Rainfall

The annual rainfall exhibited a high inter-annual variability during 2001–2021. Strong El Nino conditions were pervasive in 2002, resulting in the lowest rainfall received [33,45,46]. For the 21 years, the median of the annual rainfall is observed to lie in the center of the box, indicating that the annual rainfall follows a normal distribution. The mean monthly variations in precipitation over the last twenty-one years in Rajasthan show that the maximum rainfall is received in July (~640 mm), followed by August (~625 mm) and September (~305 mm), while the lowest mean rainfall is recorded in December. This concurs with previous research conducted in Rajasthan [47,48]. Saini et al. [33] also stated that around two-thirds of the annual rainfall is received in only two months, viz., July and August, while December accounts for only around 0.49% of the yearly rainfall. The spatial variation in the annual rainfall shows decreasing gradients from the southern and southeastern to the western regions of Rajasthan. The western ACZs received the lowest rainfall (8–486 mm), which includes a hyper-arid partially irrigated zone, the arid western plains, the irrigated northwestern plains, and an internal- drainage dry zone. In contrast, more than 1400 mm fell on the transitional plateau of the Luni Basin, and the humid and sub-humid southern plains. A similar result was reported by Meena et al. [47]. The presence of the Aravalli Mountains, which spread from the northeast to southwest in central Rajasthan, is primarily responsible for this decrease in annual average rainfall from east to west [31,49]. Relatively low annual- rainfall variability has been observed in areas of high precipitation. Therefore, the frequent occurrence of drought conditions in the arid and semi-arid regions is attributed to low rainfall and high variability. These findings concur with those of Saini et al. [33], Narain et al. [50], and Kundu and Datta [51].

The MK test and Sen's slope estimator assessed the spatial distribution of annual rainfall trends and their magnitude from 2001 to 2021. All the pixels with $S > 2$ mm per year show an increasing trend in annual rainfall. Among all the ACZs, three ACZs, namely the humid southeastern plains, the sub-humid southern plains, and the transitional plains of the Luni Basin, have observed a high positive magnitude ($S \sim 31$ mm per year). These findings are consistent with earlier studies [33,52,53]. All the pixels in western Rajasthan exhibited increasing trends, but the magnitude was less, and this result is consistent with those of Meena et al. [47], Basistha et al. [54], Kharol et al. [55], Kumar et al. [56], and Singh et al. [57]. This increasing trend is significant mainly in four ACZs: the irrigated northwestern plains, the internal-drainage dry zone, the sub-humid southern plains, and the humid southeastern plains. Similar findings were observed by Meena et al. [47], Sharma et al. [48], and Deoli and Rana [58]. To comprehend these trends, it seems most likely that rising sea surface temperatures and surface latent heat flow across the tropical Indian Ocean [59,60] are accountable. The increasing rainfall intensity may also be primarily influenced by the increasing atmospheric moisture content [61]. The western arid region, which is assumed to be the most drought-prone area, has observed an increase in its mean annual rainfall, which could be highly beneficial for agricultural and groundwater recharge. Meena et al. [47] and Poonia and Rao [62] also reported an increasing trend in rainfall in the arid climate of Rajasthan. Saini et al. [33] studied rainfall variability and trends for 1961–2017, and found a significant increasing trend in the arid and semi-arid regions.

4.2. Spatiotemporal Variation in Land Surface Temperature

The LST is an essential indicator of the Earth's surface energy balance [63]. Remote sensing-based LST data are used to explore the consequences of vegetative greenness and LULC change [10,64]. The annual LST temporal patterns show that the LST fluctuated slightly between 2001 and 2021. These fluctuations might be due to the heterogeneity of vegetation coverage and rainfall patterns [65]. In addition to these factors, some natural factors, such as parent material, soil condition, surface roughness, and albedo, are some important factors influencing the LST [66]. The monthly evaluation revealed that April, May, and June had regions with higher LST values, whereas December and January showed lower LST values. Due to the variations in the angle of inclination of the Earth with the Sun throughout the year, there is significant variation in the Incoming solar radiation at different locations [67]. The LST showed a decreasing trend during the monsoon season (June to August), which may be because, in the monsoon season, most of the land is occupied with dense crops or vegetation, which reduces the LST; however, in summer, the vegetation cover over the land is at a minimum, resulting in high LSTs [63]. Several studies have shown a relationship between lower vegetation greenness or NDVI values with higher LST values [65]. So, the LST decreased during the peak vegetative growth of the *Rabi* and *Kharif* crops.

It was observed that the western parts have higher temperatures as compared to the eastern and southern parts of Rajasthan. Different climatic and landscape components, such as rainfall, solar insolation, air temperature, elevation, sparse vegetation, and soil properties, significantly impact heat emission and absorption, affecting the LST variations [68]. The annual rainfall also decreases from east to west, creating moisture fluxes in arid and semi-arid regions [55]. This is primarily due to the Aravalli mountains, which extend from central Rajasthan's northeast to southwest [49]. The western part of Rajasthan has unsuitable soil conditions and texture, low vegetation cover, and arid climatic conditions [66]. Therefore, this zone has a higher LST than the eastern and southern parts. The LST is significantly impacted by the study area's elevation, which varies from −6 to 1698 m. The temperature falls with increasing elevation, which is evident from many studies, and the same was observed in this study [69].

To analyze the annual trend of the LST over the 21 years (2001–2021), a linear regression model shows a decrease in the LST by 6.2 °C for the entirety of Rajasthan. It was observed that the LST increased in 2002 and 2009, which may be attributed to the prevalence of drought or low rainfall and low vegetation cover [33,70]. The MK test and Sen's slope were used to determine the spatial pattern of annual rainfall trends at the pixel level in 2001 and 2021. A decreasing trend ($S < 0$) was observed in the southern and southeastern regions as rainfall increased, a significant factor for high vegetative greenness. There is a general declining trend in the LST as vegetation becomes denser (exhibited by the higher value of the NDVI). The dense vegetation canopy provides an efficient barrier against incoming solar radiation and enhances the evaporative cooling effect, which has a moderating effect on an increasing surface temperature. Thus, the land surface temperature decreases with increasing vegetation cover. Furthermore, a noticeable decreasing trend was found over the Indira Gandhi Canal, which could be due to the area under irrigation increasing over time, as a result of the expanding canal system [71]. As in other tropical regions [72–74], our results also indicate that eastern Rajasthan is experiencing a colder shift yearly.

4.3. Spatiotemporal Variation in Evapotranspiration

The spatiotemporal pattern of the mean annual ET clearly indicates strong variations corresponding to native vegetation types and prevailing climatic conditions. The annual pattern of ET exhibits an increasing trend. This can be attributed to the fact that rainfall has increased during the last 21 years and is a prime factor for high vegetation greenness. Several studies have also reported that changes in ET are most likely caused by changes in climatic parameters (rainfall and LST), rather than changes in the NDVI and EVI [73,75]. All the parameters, including the median, the 25th, and the 75th percentile, were at a minimum during 2002 because it was a drought year in Rajasthan [33,70]. The seasonal variation in ET clearly shows peaks and valleys based on the crop season. The ET rate was high during the peak vegetative stage of the Rabi and Kharif seasons, while it was low during the summer due to less vegetation coverage. The low ET levels during the summer were accompanied by the senescence of deciduous forests and crops, low relative humidity, very high temperatures, and low soil moisture [76]. The low ET rate in the winter may be due to low mean temperature and more diffuse solar insolation [77,78]. The results of this study are highly consistent with the output of Poonia and Rao (2013) [62]. The annual ET varied between 0 and 821 mm for the entire state of Rajasthan (2001–2021). Rajasthan's arid regions, with deserts and sparsely vegetated areas in the western parts, had the lowest ET (50 mm), while the southern part of the state had the highest ET (>500 mm). In the western region, low rainfall, very little or no available soil moisture, and poor vegetation are the reasons for the low ET rate. Our results are consistent with those of Goroshi et al. [76]. The mean annual ET of the state was 126 mm, with maximum and minimum values of 54.3 mm and 181.3 mm in 2002 and 2021, respectively. The ET rate decreased in 2002 due to the drought phenomenon [70]. Researchers from various climatic and geographical regions have performed this sort of analysis. Matzneller et al. [79] analyzed the annual ET trends over Bologna–Cadriano, Italy, from 1952 to 2007, using the Hargreaves and Samani Method, and suggested that rising air temperatures are accountable for the changes. Specifically, in the western arid and semi-arid regions, the enormous increase in the amount of land irrigated by canals, and a modification in cropping patterns and cultivars, may have enhanced the annual ET [71,80].

The estimation of the ET trend from the MK test and Sen's slope estimator revealed that most of the area (98.24%) showed a positive trend ($S > 0$), while 1.76% of the pixels had a negative trend ($S < 0$). This significant increasing ($p < 0.05$, $S > 0$) trend was mainly concentrated in the southern, southeastern, and northern regions, and was highly dependent on native vegetation, soil properties, and climatic conditions. In addition to this, a significant increasing ($p < 0.05$, $S > 0$) trend was observed for the canal area, and this is mainly attributed to a proportionate increase in crop area as a result of the increasing canal networks [71]. Figure 24 depicts a part of the Indira Gandhi Canal (IGC) in the western dry lands that has entirely changed over time. Before human interference, this area was covered sandy barren land, but greenness spread with the distinctively visible expansion of agricultural fields as time passed. There is a decreasing trend for ET, particularly in the Jaipur district, which is experiencing vegetative degradation due to urbanization and industrialization over the years [63,81]. Extensive industrialization has caused substantial cropland losses [82,83] and regional climate change [84,85]. Google Earth images also confirm that the built-up areas and industries have expanded over the years (Figures 25 and 26).

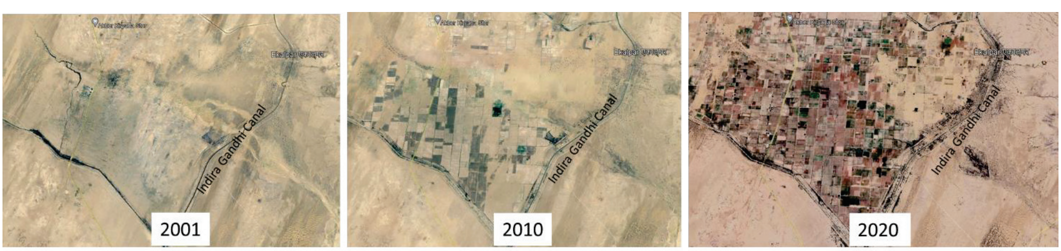

Figure 24. Spatial changes in vegetation greenness over the Indira Gandhi Canal command area in Jaisalmer district (images collected from Google Earth).

Figure 25. Spatial changes in urbanization over time (images collected from Google Earth).

Figure 26. Spatial changes in industrialization over time (images collected from Google Earth).

4.4. Spatiotemporal Variation in NDVI

The annual temporal pattern of the NDVI shows that it fluctuated slightly between 2001 and 2021. Rajasthan's uneven rainfall distribution caused this variation in vegetation greenness. Several researchers have revealed that temporal variations in the NDVI are closely related to precipitation [10,86–88]. However, a one- or two-month lag exists between the NDVI and rainfall [10,89].

The spatial variability in the mean annual NDVI ranged from −0.15 to 0.74 during 2001 to 2021. This spatial variability has arisen primarily due to the uneven rainfall distribution in the state [31]. The ACZ regions encompassing the humid southern plains, the humid southeastern plain, the flood-prone eastern plain, and the sub-humid southern plains have a high NDVI as a result of sufficient precipitation, ranging from 800 to 1000 mm, which helps to increase the cultivation of *Kharif* crops and the residual moisture helps to grow crops in the *Rabi* season also. The central part of Rajasthan state, denoted by the internal-drainage dry zone, the transitional plain of the Luni Basin, and the semi-arid eastern plains, had a medium NDVI. This could be explained by the medium rainfall and high LST, along with the seasonal fallow situation of the agricultural lands. The western part of Rajasthan had NDVI values of less than 0.15. The sandy Thar Desert, located in the western part of Rajasthan, has a typical arid climate with very little rainfall and intense heat waves, making it difficult for vegetation to grow there, other than Caryophyllales (cactus) plants [14,90]. However, recent irrigation management strategies have resulted in some changes in these areas [14]. Crops are currently grown widely in the heart of the desert. As a result, a spatial shift in the spread of greenness has become evident over time. However, vegetation conditions were substantially stressed in 2002. Several researchers have also reported that a severe drought prevailed during *Kharif* in 2002 [31,91]. Despite the predominance of drought conditions in Rajasthan in 2002, the eastern parts of the state remained unharmed. Furthermore, the topography of Rajasthan exhibits significant variations, with an elevation range of −6 to 1698 m above sea level. These topographical conditions have a significant influence on the patterns of vegetation distribution across Rajasthan.

Regarding this temporal trend, the NDVI values increased from 2001 to 2021, with a positive correlation of 0.85. However, the NDVI values in 2002 were far less than those of 2001 and 2003, indicating the stressed vegetation during the monsoon due to drought. It is more interesting that the NDVI showed an increasing trend around the Indira Gandhi Canal. This might be due to the enhancement of irrigation facilities due to the Indira Gandhi Canal, the restoration of degraded land, cropping-pattern changes, sufficient rainfall, the cultivation of wastelands, and rainwater-harvesting structures, while proper policy interventions might be the reasons in other parts of the study area [71]. The Indira Gandhi Nahar Pariyojana (IGNP) stretches over seven districts in Rajasthan: Churu, Barmer, Sriganganagar, Hanumangarh, Bikaner, Jodhpur, and Jaisalmer, and has brought about tremendous changes over time [14]. After 2012, the canal's impact was felt widely over the western drylands, resulting in a substantial surge in agricultural productivity due to improved irrigation facilities. Sur and Chauhan (2019) [71] also reported a significant change (1–78%) in the net primary productivity (NPP) during 1982–2012 across the IGC area. Figure 24 illustrates an area of the IGNP canal located in the western drylands, which has undergone significant transformations over a period of time. Some of the pixels exhibit a noticeable decrease in the NDVI, particularly within the Jaipur district. This decline may be attributed to factors such as industrialization, urbanization, groundwater depletion, inadequate irrigation practices, and alterations in cropping patterns. According to Dangayach et al. [92], there has been a significant decrease in agricultural land, which reduced from 47.20% to 25.50%, while the built-up land recorded a rise from 22.80% to 44.2% during the period of the past two decades (2000–2020). Urbanization and industrialization have led to significant reductions in cropland [82,83], and have also contributed to regional climate change [84,85]. Google Earth images (Figures 25 and 26) have also confirmed that the built-up areas and industries have expanded over the years.

4.5. Correlation between Hydroclimatic Parameters and Vegetative Index

Temperature and rainfall are widely recognized as the primary factors which characterize the climate of a region and exert significant effects on vegetation [93]. ET-NDVI has a significant positive correlation (0.86), while ET-RF shows a slightly lower positive correlation (0.40). On the contrary, the NDVI-LST has the highest negative correlation (−0.55), followed by ET-LST, with a negative correlation of −0.46. These findings reveal a significant relationship between the NDVI and climatic factors, and vegetation growth is affected by precipitation, the LST, and ET. The NDVI value increases with an increase in precipitation [94]. Generally, high LST values are usually associated with low NDVI areas, and vice versa. The areas with high LST values are characterized by the presence of built-up areas and exposed bare-ground surfaces. In contrast, the low LST zones are primarily associated with the presence of water bodies and extensive vegetation cover. The presence of a dense vegetation canopy serves as an effective shield against incoming solar radiation, hence, enhancing the evaporative cooling process of the vegetation and reducing the surface temperature. In general, a negative NDVI is indicative of the existence of water bodies or wetlands. Therefore, it may be concluded that the LST–NDVI relationship for water bodies or wetlands is not consistent. This result is highly consistent with that of Abera et al. [95], Guha and Govil [96], and Garai et al. [97]. Furthermore, it has been observed that there is a negative relationship between rainfall and LST, indicating that the LST is influenced by variations in rainfall. The combination of low rainfall and a higher LST value suggests that the vegetation has a low moisture content, which could be one of the factors contributing to forest fires [98]. Overall, these findings show a relationship between the NDVI, rainfall, and LST.

Assessing climate change and its influence on vegetation dynamics using high-resolution satellite data is the first step in providing valuable information for researchers, planners, and agricultural decision makers to mitigate climate change's impact, restore degraded lands, and achieve sustainable development goals by establishing land exploration and restoration policies. We advocate for the authorities to draw particular attention to achieving land degradation neutrality in the study area, as a significant portion of Rajasthan is affected by desertification disasters. This study employed high-resolution remote sensing products to analyze the vegetation dynamics of Rajasthan. However, it is important to note that there is a degree of uncertainty associated with these products, due to possible product quality issues. The present study, however, primarily concentrated on performing an initial analysis of vegetation change. Nonetheless, it is important to conduct more investigations in order to fully investigate the underlying mechanisms responsible for the observed inconsistencies. There is a need to quantify the relative contributions climate change and human activities have made to vegetation changes using geospatial modeling.

5. Conclusions

Vegetation monitoring is difficult in Rajasthan due to the intricate topography and extreme climatic variability. Thus, a remote sensing technique is a boon for analyzing and monitoring vegetation trends, and evaluating its response to a changing climate. This study explored the long-term (21 years) spatiotemporal variability in vegetation greenness using the NDVI and its relationship with three hydroclimatic factors, viz., rainfall, LST, and ET, which were derived from satellite images of Rajasthan. The results show a significant change in all five parameters during the study period from 2001 to 2021. This study's results provide direct evidence of a considerable decrease in degraded lands in Rajasthan, especially in the Indira Gandhi Canal command area, and a simultaneous increase in cropping area. The climatic impact of the increasing or decreasing vegetation trend across Rajasthan is confirmed by the strong correlation between the NDVI and the associated hydroclimatic factors. This study also reveals the efficiency of high-resolution satellite images for monitoring vegetation greenness on a regional level. This study's outcomes can help to restore degraded lands, achieve ecosystem conservation, and achieve sustainable development goals.

Author Contributions: Conceptualization, B.Y., L.C.M., P.C.M. and N.K.; methodology, B.Y., G.P.O.R., M.N. and R.P.S.; software, B.Y. and L.C.M.; formal analysis, B.Y., S.K.K. and R.N.S.; investigation, B.Y.; resources, B.Y., M.Y. and B.L.M.; data curation, B.Y., M.Y., R.P.S. and R.L.M.; writing—original draft preparation, B.Y., L.C.M., M.N., R.L.M. and S.K.K..; writing—review and editing, B.Y., R.N.S., B.L.M., P.K.J. and G.P.O.R.; visualization, B.Y., S.V.S., P.K.J. and G.P.O.R.; supervision, B.L.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank the ICAR-NBSS&LUP for their help and support.

Conflicts of Interest: The authors declare that there are no conflict of interest, either financial or otherwise.

References

1. Kundu, A.; Denis, D.M.; Patel, N.R.; Dutta, D. Long-Term Trend of Vegetation in Bundelkhand Region (India): An Assessment Through SPOT-VGT NDVI Datasets. In *Climate Change, Extreme Events and Disaster Risk Reduction*; Springer: Cham, Switzerland, 2018; pp. 89–99.
2. Liu, Y.; Lei, H. Responses of natural vegetation dynamics to climate drivers in China from 1982 to 2011. *Remote Sens.* **2015**, *7*, 10243–10268. [CrossRef]
3. Huang, F.; Xu, S. Spatio-temporal variations of rain-use efficiency in the west of Songliao Plain, China. *Sustainability* **2016**, *8*, 308. [CrossRef]
4. Srivastava, A.; Rodriguez, J.F.; Saco, P.M.; Kumari, N.; Yetemen, O. Global Analysis of Atmospheric Transmissivity Using Cloud Cover, Aridity and Flux Network Datasets. *Remote Sens.* **2021**, *13*, 1716. [CrossRef]
5. Hou, W.; Gao, J.; Wu, S.; Dai, E. Interannual variations in growing-season NDVI and its correlation with climate variables in the southwestern karst region of China. *Remote Sens.* **2015**, *7*, 11105–11124. [CrossRef]
6. Wu, C.; Venevsky, S.; Sitch, S.; Yang, Y.; Wang, M.; Wang, L.; Gao, Y. Present-day and future contribution of climate and fires to vegetation composition in the boreal forest of China. *Ecosphere* **2017**, *8*, e01917. [CrossRef]
7. Scheffer, M.; Holmgren, M.; Brovkin, V.; Claussen, M. Synergy between small-and large-scale feedbacks of vegetation on the water cycle. *Glob. Change Biol.* **2005**, *11*, 1003–1012. [CrossRef]
8. Quillet, A.; Peng, C.; Garneau, M. Toward dynamic global vegetation models for simulating vegetation–climate interactions and feedbacks: Recent developments, limitations, and future challenges. *Environ. Rev.* **2010**, *18*, 333–353. [CrossRef]
9. Hamid, M.; Khuroo, A.A.; Malik, A.H.; Ahmad, R.; Singh, C.P.; Dolezal, J.; Haq, S.M. Early evidence of shifts in alpine summit vegetation: A case study from Kashmir Himalaya. *Front. Plant Sci.* **2020**, *11*, 421. [CrossRef]
10. Kumari, N.; Srivastava, A.; Dumka, U.C. A long-term spatiotemporal analysis of vegetation greenness over the himalayan region using google earth engine. *Climate* **2021**, *9*, 109. [CrossRef]

11. Kumar, K.C.A.; Reddy, G.P.O.; Masilamani, P.; Sandeep, P.; Turkar, S.Y. Integrated drought monitoring index: A tool to monitor agricultural drought by using time series space-based earth observation satellite datasets. *Adv. Space Res.* **2021**, *67*, 298–315. [CrossRef]
12. Singh, R.N.; Sah, S.; Chaturvedi, G.; Das, B.; Pathak, H. Innovative trend analysis of rainfall in relation to soybean productivity over western Maharashtra. *J. Agrometeorol.* **2021**, *23*, 228–235. [CrossRef]
13. Singh, R.N.; Sah, S.; Das, B.; Chaturvedi, G.; Kumar, M.; Rane, J.; Pathak, H. Long-term spatiotemporal trends of temperature associated with sugarcane in west India. *Arab. J. Geosci.* **2021**, *14*, 1955. [CrossRef]
14. Sur, K.; Dave, R.; Chauhan, P. Spatio-temporal changes in NDVI and rainfall over Western Rajasthan and Gujarat region of India. *J. Agrometeorol.* **2018**, *20*, 189–195.
15. Mariano, D.A.; dos Santos, C.A.; Wardlow, B.D.; Anderson, M.C.; Schiltmeyer, A.V.; Tadesse, T.; Svoboda, M.D. Use of remote sensing indicators to assess effects of drought and human-induced land degradation on ecosystem health in Northeastern Brazil. *Remote Sens. Environ.* **2018**, *213*, 129–143. [CrossRef]
16. Guo, E.; Wang, Y.; Wang, C.; Sun, Z.; Bao, Y.; Mandula, N.; Jirigala, B.; Bao, Y.; Li, H. NDVI indicates long-term dynamics of vegetation and its driving forces from climatic and anthropogenic factors in Mongolian Plateau. *Remote Sens.* **2021**, *13*, 688. [CrossRef]
17. Rihan, W.; Zhang, H.; Zhao, J.; Shan, Y.; Guo, X.; Ying, H.; Deng, G.; Li, H. Promote the advance of the start of the growing season from combined effects of climate change and wildfire. *Ecol. Indicat.* **2021**, *125*, 107483. [CrossRef]
18. Zeng, Z.; Wu, W.; Ge, Q.; Li, Z.; Wang, X.; Zhou, Y.; Zhang, Z.; Li, Y.; Huang, H.; Liu, G.; et al. Legacy effects of spring phenology on vegetation growth under preseason meteorological drought in the Northern Hemisphere. *Agric. For. Meteorol.* **2021**, *310*, 108630. [CrossRef]
19. Bai, Y.; Li, S.; Liu, M.; Guo, Q. Assessment of vegetation change on the Mongolian Plateau over three decades using different remote sensing products. *J. Environ. Manag.* **2022**, *317*, 115509. [CrossRef]
20. Nemani, R.R.; Keeling, C.D.; Hashimoto, H.; Jolly, W.M.; Piper, S.C.; Tucker, C.J.; Myneni, R.B.; Running, S.W. Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *Science* **2003**, *300*, 1560–1563. [CrossRef]
21. Zhu, Z. Change detection using landsat time series: A review of frequencies, preprocessing, algorithms, and applications. *ISPRS J. Photogramm. Remote Sens.* **2017**, *130*, 370–384. [CrossRef]
22. Srivastava, A.; Sahoo, B.; Raghuwanshi, N.S.; Singh, R. Evaluation of variable-infiltration capacity model and MODIS-terra satellite-derived grid-scale evapotranspiration estimates in a River Basin with Tropical Monsoon-Type climatology. *J. Irrig. Drain. Eng.* **2017**, *143*, 04017028. [CrossRef]
23. Piao, S.; Wang, X.; Park, T.; Chen, C.; Lian, X.U.; He, Y.; Bjerke, J.W.; Chen, A.; Ciais, P.; Tømmervik, H.; et al. Characteristics, drivers and feedbacks of global greening. *Nat. Rev. Earth Environ.* **2020**, *1*, 14–27. [CrossRef]
24. Venter, Z.S.; Scott, S.L.; Desmet, P.G.; Hoffman, M.T. Application of Landsat-derived vegetation trends over South Africa: Potential for monitoring land degradation and restoration. *Ecol. Indic.* **2020**, *113*, 106206. [CrossRef]
25. Huete, A. Vegetation's responses to climate variability. *Nature* **2016**, *531*, 181–182. [CrossRef]
26. Yang, J.; Gong, P.; Fu, R.; Zhang, M.; Chen, J.; Liang, S.; Xu, B.; Shi, J.; Dickinson, R. The role of satellite remote sensing in climate change studies. *Nat. Clim. Change* **2013**, *3*, 875–883. [CrossRef]
27. Wardlow, B.D.; Egbert, S.L. A comparison of MODIS 250-m EVI and NDVI data for crop mapping: A case study for southwest Kansas. *Int. J. Remote Sens.* **2010**, *31*, 805–830. [CrossRef]
28. Hereher, M.E. The status of Egypt's agricultural lands using MODIS Aqua data. Egypt. *J. Remote Sens. Space Sci.* **2013**, *16*, 83–89.
29. Garroutte, E.L.; Hansen, A.J.; Lawrence, R.L. Using NDVI and EVI to map spatiotemporal variation in the biomass and quality of forage for migratory elk in the Greater Yellowstone Ecosystem. *Remote Sens.* **2016**, *8*, 404. [CrossRef]
30. Reddy, G.P.O.; Kumar, N.; Sahu, N.; Srivastava, R.; Singh, S.K.; Naidu, L.G.K.; Chary, G.R.; Biradar, C.M.; Gumma, M.K.; Reddy, B.S.; et al. Assessment of spatio-temporal vegetation dynamics in tropical arid ecosystem of India using MODIS time-series vegetation indices. *Arab. J. Geosci.* **2020**, *13*, 704. [CrossRef]
31. Dutta, D.; Kundu, A.; Patel, N.R.; Saha, S.K.; Siddiqui, A.R. Assessment of agricultural drought in Rajasthan (India) using remote sensing derived Vegetation Condition Index (VCI) and Standardized Precipitation Index (SPI). *Egypt. J. Remote Sens. Space Sci.* **2015**, *18*, 53–63. [CrossRef]
32. Matsushita, B.; Yang, W.; Chen, J.; Onda, Y.; Qiu, G. Sensitivity of the enhanced vegetation index (EVI) and normalized difference vegetation index (NDVI) to topographic effects: A case study in high-density cypress forest. *Sensors* **2007**, *7*, 2636–2651. [CrossRef]
33. Saini, D.; Bhardwaj, P.; Singh, O. Recent rainfall variability over Rajasthan, India. *Theor. Appl. Climatol.* **2021**, *148*, 363–381. [CrossRef]
34. Chen, J.; Jönsson, P.; Tamura, M.; Gu, Z.; Matsushita, B.; Eklundh, L. A simple method for reconstructing a high-quality NDVI time-series data set based on the Savitzky–Golay filter. *Remote Sens. Environ.* **2004**, *91*, 332–344. [CrossRef]
35. Yadav, B.; Malav, L.C.; Jiménez-Ballesta, R.; Kumawat, C.; Patra, A.; Patel, A.; Jangir, A.; Nogiya, M.; Meena, R.L.; Moharana, P.C.; et al. Modeling and assessment of land degradation vulnerability in arid ecosystem of Rajasthan using analytical hierarchy process and geospatial techniques. *Land* **2023**, *12*, 106. [CrossRef]
36. Wan, Z. Collection-6 MODIS Land Surface Temperature Products Users' Guide. 2013. Available online: https://lpdaac.usgs.gov/documents/118/MOD11_User_Guide_V6.pdf (accessed on 29 July 2023).

37. Malav, L.C.; Yadav, B.; Tailor, B.L.; Pattanayak, S.; Singh, S.V.; Kumar, N.; Reddy, G.P.; Mina, B.L.; Dwivedi, B.S.; Jha, P.K. Mapping of land degradation vulnerability in the semi-arid watershed of Rajasthan, India. *Sustainability* **2022**, *14*, 10198. [CrossRef]
38. Srivastava, A.; Sahoo, B.; Raghuwanshi, N.S.; Chatterjee, C. Modelling the dynamics of evapotranspiration using Variable Infiltration Capacity model and regionally calibrated Hargreaves approach. *Irrig. Sci.* **2018**, *36*, 289–300. [CrossRef]
39. Mann, H.B. Nonparametric Tests against Trend. *Econometrica* **1945**, *13*, 245–259. [CrossRef]
40. Kendall, M.G. *Rank Correlation Methods*, 4th ed.; Charles Grifin: London, UK, 1975.
41. Hamed, K.H.; Rao, A.R. A Modified Mann-Kendall Trend Test for Autocorrelated Data. *J. Hydrol.* **1998**, *204*, 182–196. [CrossRef]
42. Hansen, B.E. Challenges for econometric model selection. *Econom. Theory* **2005**, *21*, 60–68. [CrossRef]
43. Sen, P.K. Estimates of the Regression Coefficient Based on Kendall's Tau. *J. Am. Stat. Assoc.* **1968**, *63*, 1379–1389. [CrossRef]
44. Theil, H. A Rank-Invariant Method of Linear and Polynomial Regression Analysis, Part I; Confidence Regions for the Parameters of Polynomial Regression Equations. *Proc. R. Neth. Acad. Sci.* **1950**, *53*, 386–392.
45. Mahala, B.K.; Nayak, B.K.; Mohanty, P.K. Impacts of ENSO and IOD on tropical cyclone activity in the Bay of Bengal. *Nat. Hazards* **2015**, *75*, 1105–1125. [CrossRef]
46. Bhardwaj, P.; Pattanaik, D.R.; Singh, O. Tropical cyclone activity over Bay of Bengal in relation to El Niño-Southern Oscillation. *Int. J. Climatol.* **2019**, *39*, 5452–5469. [CrossRef]
47. Meena, H.M.; Machiwal, D.; Santra, P.; Moharana, P.C.; Singh, D.V. Trends and homogeneity of monthly, seasonal, and annual rainfall over arid region of Rajasthan, India. *Theor. Appl. Climatol.* **2019**, *136*, 795–811. [CrossRef]
48. Sharma, S.K.; Sharma, D.P.; Sharma, M.K.; Gaur, K.; Manohar, P. Trend Analysis of Temperature and Rainfall of Rajasthan, India. *J. Probab. Stat.* **2021**, *2021*, 6296709. [CrossRef]
49. Yadav, R.K.; Rupa Kumar, K.; Rajeevan, M. Characteristic features of winter precipitation and its variability over north-west India. *J. Earth Syst. Sci.* **2012**, *121*, 611–623. [CrossRef]
50. Narain, P.; Rathore, L.S.; Singh, R.S.; Rao, A.S. *Drought Assessment and Management in Arid Rajasthan*; Central Arid Zone Research Institute; Jodhpur and NCMRWF: Noida, India, 2006; p. 64.
51. Kundu, A.; Dutta, D. Monitoring desertification risk through climate change and human interference using remote sensing and GIS techniques. *Int. J. Geomat. Geosci.* **2011**, *2*, 21.
52. Pant, G.B.; Hingane, L.S. Climatic changes in and around the Rajasthan desert during the 20th century. *J. Climatol.* **1988**, *8*, 391–401. [CrossRef]
53. Singh, R.S.; Narain, P.; Sharma, K.D. Climate changes in Luni river basin of arid western Rajasthan (India). *Vayu Mandal* **2001**, *31*, 103–106.
54. Basistha, A.; Goel, N.K.; Arya, D.S.; Gangwar, S.K. Spatial pattern of trends in Indian sub-divisional rainfall. *Jalvigyan Sameeksha* **2007**, *22*, 47–57.
55. Kharol, S.K.; Kaskaoutis, D.G.; Badarinath, K.V.S.; Sharma, A.R.; Singh, R.P. Influence of land use/land cover (LULC) changes on atmospheric dynamics over the arid region of Rajasthan state, India. *J. Arid Environ.* **2013**, *88*, 90–101. [CrossRef]
56. Kumar, V.; Jain, S.K.; Singh, Y. Analysis of long-term rainfall trends in India. *Hydrolog. Sci. J.* **2010**, *55*, 484–496. [CrossRef]
57. Singh, R.N.; Sah, S.; Das, B.; Potekar, S.; Chaudhary, A.; Pathak, H. Innovative trend analysis of spatio-temporal variations of rainfall in India during 1901–2019. *Theor. Appl. Climatol.* **2021**, *145*, 821–838. [CrossRef]
58. Deoli, V.; Rana, S. Seasonal trend analysis in rainfall and temperature for Udaipur district of Rajasthan. *Curr. World Environ.* **2017**, *14*, 312. [CrossRef]
59. Goswami, B.N.; Venugopal, V.; Sengupta, D.; Madhusoodanan, M.S.; Xavier, P.K. Increasing trend of extreme rain events over India in a warming environment. *Science* **2006**, *314*, 1442–1445. [CrossRef] [PubMed]
60. Rajeevan, M.; Bhate, J.; Jaswal, A.K. Analysis of variability and trends of extreme rainfall events over India using 104 years of gridded daily rainfall data. *Geophys. Res. Lett.* **2008**, *35*, 1–6.
61. Lacombe, G.; McCartney, M. Uncovering consistencies in Indian rainfall trends observed over the last half century. *Clim. Change* **2014**, *123*, 287–299. [CrossRef]
62. Poonia, S.; Rao, A.S. Climate change and its impact on Thar desert ecosystem. *J. Agric. Phy.* **2013**, *13*, 71–79.
63. Khandelwal, S.; Goyal, R.; Kaul, N.; Mathew, A. Assessment of land surface temperature variation due to change in elevation of area surrounding Jaipur, India. Egypt. *J. Remote Sens. Space Sci.* **2018**, *21*, 87–94.
64. Dos Santos, C.A.; Mariano, D.A.; Francisco das Chagas, A.; Dantas, F.R.D.C.; de Oliveira, G.; Silva, M.T.; da Silva, L.L.; da Silva, B.B.; Bezerra, B.G.; Safa, B.; et al. Spatio-temporal patterns of energy exchange and evapotranspiration during an intense drought for drylands in Brazil. *Int. J. Appl. Earth Obs. Geoinf.* **2020**, *85*, 101982. [CrossRef]
65. Pal, S.; Ziaul, S.K. Detection of land use and land cover change and land surface temperature in English Bazar urban centre. Egypt. *J. Remote Sens. Space Sci.* **2017**, *20*, 125–145.
66. Dutta, S.; Chaudhuri, G. Evaluating environmental sensitivity of arid and semi-arid regions in northeastern Rajasthan, India. *Geogr. Rev.* **2015**, *105*, 441–461. [CrossRef]
67. Hicham, B.; Abbou, A.; Abousserhane, Z. Model for maximizing fixed photovoltaic panel efficiency without the need to change the tilt angle of monthly or seasonal frequency. In Proceedings of the 2022 2nd International Conference on Innovative Research in Applied Science, Engineering and Technology (IRASET), Meknes, Morocco, 3–4 March 2022; pp. 1–5.
68. Peng, J.; Jia, J.; Liu, Y.; Li, H.; Wu, J. Seasonal contrast of the dominant factors for spatial distribution of land surface temperature in urban areas. *Remote Sens. Environ.* **2018**, *215*, 255–267. [CrossRef]

69. Lakra, K.; Sharma, D. Geospatial assessment of urban growth dynamics and land surface temperature in Ajmer Region, India. *J. Indian Soc. Remote Sens.* **2019**, *47*, 1073–1089. [CrossRef]
70. Dhakar, R.; Sehgal, V.K.; Pradhan, S. Study on inter-seasonal and intra-seasonal relationships of meteorological and agricultural drought indices in the Rajasthan State of India. *J. Arid Environ.* **2013**, *97*, 108–119. [CrossRef]
71. Sur, K.; Chauhan, P. Dynamic trend of land degradation/restoration along Indira Gandhi Canal command area in Jaisalmer District, Rajasthan, India: A case study. *Environ. Earth Sci.* **2019**, *78*, 472. [CrossRef]
72. Asoka, A.; Wardlow, B.; Tsegaye, T.; Huber, M.; Mishra, V. A Satellite-Based Assessment of the Relative Contribution of Hydroclimatic Variables on Vegetation Growth in Global Agricultural and Nonagricultural Regions. *J. Geophys. Res. Atmos.* **2021**, *126*, e2020JD033228. [CrossRef]
73. Zhou, R.; Wang, H.; Duan, K.; Liu, B. Diverse responses of vegetation to hydroclimate across temporal scales in a humid subtropical region. *J. Hydrol. Reg. Stud.* **2021**, *33*, 100775. [CrossRef]
74. Ukasha, M.; Ramirez, J.A.; Niemann, J.D. Temporal Variations of NDVI and LAI and Interactions With Hydroclimatic Variables in a Large and Agro-Ecologically Diverse Region. *J. Geophys. Res. Biogeosci.* **2022**, *127*, e2021JG006395. [CrossRef]
75. Li, G.; Zhang, F.; Jing, Y.; Liu, Y.; Sun, G. Response of evapotranspiration to changes in land use and land cover and climate in China during 2001–2013. *Sci. Total Environ.* **2017**, *596*, 256–265. [CrossRef] [PubMed]
76. Goroshi, S.; Pradhan, R.; Singh, R.P.; Singh, K.K.; Parihar, J.S. Trend analysis of evapotranspiration over India: Observed from long-term satellite measurements. *J. Earth Syst. Sci.* **2017**, *126*, 113. [CrossRef]
77. Goyal, R.K. Sensitivity of evapotranspiration to global warming: A case study of arid zone of Rajasthan (India). *Agric. Water Manag.* **2004**, *69*, 1–11. [CrossRef]
78. Madhu, S.; Kumar, T.V.; Barbosa, H.; Rao, K.K.; Bhaskar, V.V. Trend analysis of evapotranspiration and its response to droughts over India. *Theor. Appl. Climatol.* **2015**, *121*, 41–51. [CrossRef]
79. Matzneller, P.; Ventura, F.; Gaspari, N.; Rossi Pisa, P. Analysis of climatic trends in data from the agrometeorological station of Bologna-Cadriano, Italy (1952–2007). *Clim. Change* **2010**, *100*, 717–731. [CrossRef]
80. Gholkar, M.D.; Goroshi, S.; Singh, R.P.; Parihar, J.S. Influence of agricultural developments on net primary productivity (NPP) in the semi-arid region of India: A study using GloPEM model. Int. Arch. Photogramm. *Remote Sens. Spat. Inf. Sci.* **2014**, *40*, 725. [CrossRef]
81. Mathew, A.; Khandelwal, S.; Kaul, N. Investigating spatial and seasonal variations of urban heat island effect over Jaipur city and its relationship with vegetation, urbanization and elevation parameters. *Sustain. Cities Soc.* **2017**, *35*, 157–177. [CrossRef]
82. Guan, X.; Shen, H.; Li, X.; Gan, W.; Zhang, L. A long-term and comprehensive assessment of the urbanization-induced impacts on vegetation net primary productivity. *Sci. Total Environ.* **2019**, *669*, 342–352. [CrossRef]
83. Lyu, R.; Zhang, J.; Xu, M.; Li, J. Impacts of urbanization on ecosystem services and their temporal relations: A case study in Northern Ningxia, China. *Land Use Policy* **2018**, *77*, 163–173. [CrossRef]
84. Yao, R.; Wang, L.; Huang, X.; Guo, X.; Niu, Z.; Liu, H. Investigation of urbanization effects on land surface phenology in Northeast China during 2001–2015. *Remote Sens.* **2017**, *9*, 66. [CrossRef]
85. Du, J.; Fu, Q.; Fang, S.; Wu, J.; He, P.; Quan, Z. Effects of rapid urbanization on vegetation cover in the metropolises of China over the last four decades. *Ecol. Indic.* **2019**, *107*, 105458. [CrossRef]
86. Budde, M.E.; Tappan, G.; Rowland, J.; Lewis, J.; Tieszen, L.L. Assessing land cover performance in Senegal, West Africa using 1-km integrated NDVI and local variance analysis. *J. Arid Environ.* **2004**, *59*, 481–498. [CrossRef]
87. Wang, J.; Rich, P.M.; Price, K.P. Temporal responses of NDVI to precipitation and temperature in the central Great Plains, USA. *Int. J. Remote Sens.* **2003**, *24*, 2345–2364. [CrossRef]
88. Ji, L.; Peters, A.J. A spatial regression procedure for evaluating the relationship between AVHRR-NDVI and climate in the northern Great Plains. *Int. J. Remote Sens.* **2004**, *25*, 297–311. [CrossRef]
89. Moses, O.; Blamey, R.C.; Reason, C.J. Relationships between NDVI, river discharge and climate in the Okavango River Basin region. *Int. J. Climatol.* **2022**, *42*, 691–713. [CrossRef]
90. Rao, A.S. Climatic changes in the irrigated tracts of Indira Gandhi Canal Region of arid western Rajasthan, India. *Ann. Arid Zone* **1996**, *35*, 111–116.
91. Malik, D. Without Rain, a Bleak Outlook, India Together. *The News in Proportion*, 29 March 2014. 29 March.
92. Dangayach, R.; Jain, R.; Pandey, A.K. Long-term variation in aerosol optical depth and normalized difference vegetation index in Jaipur, India. *Total Environ. Res. Themes* **2023**, *5*, 100027. [CrossRef]
93. Raymondi, R.R.; Cuhaciyan, J.E.; Glick, P.; Capalbo, S.M.; Houston, L.L.; Shafer, S.L.; Grah, O. Water resources: Implications of changes in temperature and precipitation. In *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*; Island Press: Washington, DC, USA, 2013; pp. 41–66.
94. Zhang, H.; Chang, J.; Zhang, L.; Wang, Y.; Li, Y.; Wang, X. NDVI dynamic changes and their relationship with meteorological factors and soil moisture. *Environ. Earth Sci.* **2018**, *77*, 582. [CrossRef]
95. Abera, T.A.; Heiskanen, J.; Pellikka, P.; Maeda, E.E. Rainfall–vegetation interaction regulates temperature anomalies during extreme dry events in the Horn of Africa. *Glob. Planet. Change* **2018**, *167*, 35–45. [CrossRef]
96. Guha, S.; Govil, H. An assessment on the relationship between land surface temperature and normalized difference vegetation index. *Environ. Dev. Sustain.* **2021**, *23*, 1944–1963. [CrossRef]

97. Rahaman, S.M.; Khatun, M.; Garai, S.; Das, P.; Tiwari, S. Forest Fire Risk Zone Mapping in Tropical Forests of Saranda, Jharkhand, Using FAHP Technique. In *Geospatial Technology for Environmental Hazards: Modeling and Management in Asian Countries*; Springer International Publishing: Berlin/Heidelberg, Germany, 2022; pp. 177–195.
98. Garai, S.; Khatun, M.; Singh, R.; Sharma, J.; Pradhan, M.; Ranjan, A.; Rahaman, S.M.; Khan, M.L.; Tiwari, S. Assessing correlation between Rainfall, normalized difference Vegetation Index (NDVI) and land surface temperature (LST) in Eastern India. *Saf. Extreme Environ.* **2022**, *4*, 119–127. [CrossRef]

sustainability

Review

Closing the Loop: Exploring Food Waste Management in the Near East and North Africa (NENA) Region during the COVID-19 Pandemic

Chedli Baya Chatti [1,*], Tarek Ben Hassen [2] and Hamid El Bilali [3]

[1] Department of Social Sciences, College of Arts and Sciences, Qatar University, Doha 2713, Qatar
[2] Program of Policy, Planning, and Development, Department of International Affairs, College of Arts and Sciences, Qatar University, Doha 2713, Qatar; thassen@qu.edu.qa
[3] International Centre for Advanced Mediterranean Agronomic Studies (CIHEAM-Bari), Valenzano, 70010 Bari, Italy; elbilali@iamb.it
* Correspondence: cchatti@qu.edu.qa

Abstract: The COVID-19 pandemic disrupted global food waste patterns through unanticipated shifts in composition and quantities. This review explores the impacts of COVID-19 on food waste generation and management approaches in the Near East and North Africa (NENA) region during the recovery phase. This paper comprehensively explores food loss and waste in the NENA region. It presents a detailed analysis of pandemic-induced changes in household food waste behaviors, analyses the integration of circular economy principles in recovery strategies and policy implications, and outlines potential avenues for future research in this critical area. The key findings are threefold: First, this study reaffirms that food waste is a critical challenge in NENA, contributing to food insecurity, water scarcity, and environmental issues. Second, the pandemic catalyzed a dichotomy in consumer behaviors—panic buying initially increased waste, while hardship measures later encouraged sustainable waste reduction practices like meal planning and leftover use. Third, adopting a circular economy approach holds potential, yet its implementation remains limited in terms of curbing food waste and promoting sustainability in NENA. Overall, while the pandemic accentuated the urgency of tackling food waste, it also stimulated innovative policy thinking and strategic planning for building more resilient food systems. This paper concludes that leveraging pandemic-driven sustainability mindsets while addressing systemic drivers of waste will be key to mitigating food waste and its impacts moving forward. This paper offers timely insights into the evolving food waste management landscape in NENA, underscoring the need for integrated policies to navigate post-pandemic recovery effectively.

Keywords: food waste; COVID-19; circular economy; circularity; sustainability; waste recycling; waste reuse; Near East and North Africa (NENA)

Citation: Baya Chatti, C.; Ben Hassen, T.; El Bilali, H. Closing the Loop: Exploring Food Waste Management in the Near East and North Africa (NENA) Region during the COVID-19 Pandemic. *Sustainability* **2024**, *16*, 3772. https://doi.org/10.3390/su16093772

Academic Editor: Xiaowei Li

Received: 10 November 2023
Revised: 8 February 2024
Accepted: 27 February 2024
Published: 30 April 2024

1. Introduction

Food loss and waste (FLW) is defined as "a decrease, at all stages of the food chain, from harvest to consumption in mass, of food that was originally intended for human consumption, regardless of the cause" [1,2]. Food waste occurs at the downstream end of the supply chain, such as at the retail, food service, and household consumption stages. It refers to discarded edible food, regardless of whether it is still within the expiry date or has been left to rot [2–5]. Household food waste behavior may be influenced by several activities, including planning, grocery shopping, storage, cooking, and consuming [6]. As a result, a wide range of variables influences food waste, including behavioral (e.g., shopping and storage attitudes, insufficient knowledge), personal (e.g., level of education, experience, etc.), and product (e.g., packaging sizes, sale promotions, and discounts), as well as socio-economic characteristics (e.g., wages, food subsidies, etc.) [7].

The COVID-19 pandemic prompted a devastating international economic and financial downturn, negatively affecting socio-economic development and people's lives [8]. It tremendously influenced people's daily lives, including various substantial effects on diet and food-related practices, such as FLW [9]. The lack of proper storage facilities, transit disruptions, and labor shortages at the production level resulted in the loss of perishable products and excessive food waste in many countries [10]. At the consumer level, on the one hand, the pandemic significantly impacted household food shopping and planning, resulting in increased panic buying and food waste. On the other hand, some consumers began to adopt more sustainable behaviors, such as better food shopping planning and reusing leftovers to reduce food waste [11–13].

Due to several factors, including socio-economic development level and the efficiency of national healthcare systems, these habits are context-specific rather than global [14]. In the Near East and North Africa (NENA) region, which includes 20 countries spanning across North Africa and the Near East, the COVID-19 pandemic-related measures, as seen globally, led to many lifestyle changes and a shift in food habits. Even before the pandemic, FLW in the NENA region was a significant issue, leading to decreased food availability, exacerbated water crises and environmental challenges, and amplified food imports in an already heavily import-dependent region [15]. However, COVID-19's long-term economic recovery gives the NENA region a chance for sustainable growth by applying the circular economy approach. Certainly, the current socio-economic emergency triggered by the pandemic in the NENA region has generated unique opportunities for promoting a circular economy and circular resource management, which might stimulate economic recovery [16].

Moreover, the COVID-19 pandemic has highlighted the vulnerabilities of food systems in the NENA region and the importance of ensuring food security and sustainability. Understanding the impact of the pandemic on food waste and circular economy practices in the region is critical to developing effective policies and strategies to promote sustainable food systems and reduce food waste. However, there is a lack of research on the specific challenges and opportunities related to circular economy practices in the agrifood industry in the NENA region. The existing literature mostly focuses on developed countries, and there is a need for more research tailored to the unique socio-economic, cultural, and environmental contexts of the NENA region.

Consequently, this paper makes several valuable contributions to the academic literature on food loss and waste (FLW). First, it provides crucial new insights into the complex dynamics of FLW in the Near East and North Africa (NENA) region, specifically focusing on how the COVID-19 pandemic impacted food waste attitudes, behaviors, and quantities at the household level. Examining these pandemic effects within the unique socio-economic and environmental context of NENA represents a significant advancement, as this critical region has been understudied in existing FLW research. Second, this paper offers an original perspective on the relationship between global crises and localized FLW patterns, elucidating how disruptions caused by the COVID-19 pandemic influenced food waste in NENA households and food systems. This advances our theoretical understanding of the linkages between global events and regional FLW trends.

Third, this paper conducts an innovative assessment of how circular economy principles are integrated into post-pandemic recovery strategies and policies for curbing food waste in the NENA region. This analysis of policy and government responses provides practical guidance to policymakers on more sustainable solutions for managing FLW. Finally, the paper goes beyond analysis to propose tangible recommendations tailored to improving FLW reduction and management, specifically in the NENA context. This applied focus on actionable solutions contributes meaningfully to developing more resilient and sustainable food systems in the region.

In summary, by offering the first in-depth examination of pandemic-catalyzed changes in food waste dynamics and connections to policy in NENA, this paper significantly advances academic and practical understanding of FLW challenges and opportunities. The insights from this timely research provide invaluable knowledge to guide policymakers, stakeholders, and researchers in building more sustainable food waste strategies as part of a green recovery in the NENA region and beyond. This paper makes pivotal contributions by elucidating global food waste transformations and corresponding policy responses to inform sustainable FLW management.

This paper is structured into seven main sections. Section 1 reviews the literature on the scale and characteristics of food loss and waste (FLW) in the Near East and North Africa (NENA) region, summarizing current knowledge on the magnitude of the issue. Section 2 outlines the study methodology, describing the data collection and analysis approach. Section 3 presents findings on attitudes, awareness, and self-reported behaviors related to household food waste during the COVID-19 pandemic. Quantitative and qualitative results provide insights into the pandemic's impacts on food waste awareness and actions. Section 4 uses empirical data to examine how the pandemic influenced food waste generation, composition, and quantities. Trends in household food waste levels and types are analyzed. Section 5 discusses integrating circular economy principles and food waste management strategies into post-pandemic recovery policies and initiatives in NENA countries. Policy documents are scrutinized to assess sustainability considerations. Section 6 summarizes this study's implications through a discussion and conclusion. Finally, Section 7 presents this paper's limitations and suggests promising directions for future research on this pressing topic.

2. Materials and Methods

The methodology of this study is based on two steps. The first step is a systematic review based on a search conducted on Web of Science (WoS) on 17 March 2023. The search utilized a specific query string: *("COVID-19" OR COVID19 OR Coronavirus OR "SARS-CoV-2") AND (food) AND (waste) AND ("Near East" OR "Middle East" OR "West* Asia" OR "North* Africa" OR Maghreb OR "East* Mediterranean" OR "South* Mediterranean" OR Arab OR Gulf OR Algeria OR Bahrain OR Egypt OR Iraq OR Jordan OR Kuwait OR Lebanon OR Libya OR Mauritania OR Morocco OR Oman OR Qatar OR Saudi OR Sudan OR Syria OR Tunisia OR "United Arab Emirates" OR UAE OR Yemen)*. From this search, 14 documents were retrieved [12,13,17–28] and subsequently evaluated for their suitability based on two key criteria: geographical relevance (i.e., the document pertains to at least one country within the NENA region) and thematic pertinence (i.e., the document encompasses aspects of both COVID-19 and food waste issues). Consequently, only 10 documents [12,13,17–21,24–26] were eligible and included in this study.

Given the limited number of suitable scholarly documents obtained from Web of Science (WoS), the methodology was expanded to include a broader spectrum of the literature. Indeed, a further search was undertaken in other databases, including Google Scholar, which is renowned for its vast collection of non-indexed scholarly literature as well as grey literature. This supplementary search sought to include a broader range of information, such as reports, working papers, and policy briefs that are not commonly found in traditional academic databases but are important for understanding the full scope of COVID-19's impact on food waste issues in the NENA region. This inclusive method ensured that the research included a broader range of perspectives and facts, resulting in a more comprehensive understanding of the subject matter.

This extensive review process included a thorough examination of publications from international organizations, such as the United Nations, the Food and Agriculture Organization of the United Nations (FAO), the High-Level Panel of Experts on Food Security and Nutrition (HLPE), the World Bank, the World Food Program (WFP), the International Monetary Fund (IMF), and the United Nations Development Program (UNDP). Moreover, the research embraced contributions from regional bodies, notably the United Nations Economic and Social Commission for West Asia (ESCWA), to ensure a comprehensive understanding of the NENA region's unique context. This review was further enriched by insights from other research and policy institutions, such as the Economist Intelligence

Unit, the Centre for Strategic and International Studies (CSIS), and Wageningen University and Research.

In addition to scholarly and organizational sources, our methodology also incorporated valuable insights from leading regional newspapers and specialized news outlets, such as Arab News, Khaleej Times, The Peninsula Qatar, and Egypt Today, which were instrumental in providing real-time data, expert opinions, and ground-level perspectives on food waste challenges and initiatives within the region during the pandemic. These multiple sources gave an extensive viewpoint, which was critical for conducting a comprehensive analysis of food waste management dynamics in the NENA area during the COVID-19 pandemic.

3. Magnitude and Nature of Food Losses and Waste in the NENA Region

The NENA region is politically heterogeneous, with nations at various levels of economic development and unequal natural resources [29]. Food systems in the region are also marked by significant inequities, which may influence consumer choices and decisions and, consequently, food waste, in diverse ways. There are considerable income disparities between those in natural resource-rich countries (e.g., the Gulf Cooperation Council—GCC) and those in middle-income ones [29]. For instance, since GCC nations are capital-rich, food imports are exempt from financial restrictions. As a result, these countries have been less vulnerable to food price volatility than other food importers, and they have overcome local production shortfalls due to their solid fiscal position [11,30]. Consequently, in 2022, the Global Food Security Index ranked GCC countries as having the highest levels of food security globally and among Arab countries [31]. Moreover, food security vulnerabilities are more significant in conflict-affected countries such as Syria and Yemen [32,33].

Food waste is a major issue in the NENA region [15,34–40]. It leads to decreased food availability, exacerbated water crises, and several environmental consequences [37]. Food waste is chronically high in the NENA region, pointing to the inefficiencies, unsustainability, and inequality that characterize most agrifood systems in the region [41]. High food waste is not only uneconomical but also affects food security by increasing food imports in an already heavily import-dependent area due to the scarcity of natural resources [42]. According to the FAO [3], the share of lost or wasted food is about 34% across the NENA region. Several FAO reports [37,43] revealed that fruits and vegetables are the most wasted foods in the NENA region (in some cases, close to 50% of production), followed by fish and seafood (28%) and roots and tubers (26%). For example, research conducted in 2015 on post-harvest food losses in Morocco indicates that loss rates were much higher for fruits than soft wheat (Table 1).

Table 1. Estimation of food loss in wheat and fruit value chains in Morocco using survey and sampling methods, 2015 (percentage of physical losses).

<table>
<tr><th>Product</th><th>Harvest</th><th>Storage</th><th>Transport</th><th>Wholesale</th><th>Retail</th><th>Processing</th></tr>
<tr><td>Soft Wheat</td><td>10</td><td>14</td><td>1</td><td>10</td><td></td><td>2</td></tr>
<tr><td>Apple</td><td>10</td><td>19</td><td>2</td><td>14</td><td>9</td><td>---</td></tr>
<tr><td>Citrus</td><td>5</td><td>1–2</td><td>2</td><td>1–2</td><td>---</td><td>---</td></tr>
<tr><td>Fig (fresh)</td><td>---</td><td>---</td><td>---</td><td colspan="2">5</td><td>---</td></tr>
<tr><td>Fig (dried)</td><td>---</td><td>2–5</td><td>---</td><td>Minimal</td><td>2–5</td><td>5–10</td></tr>
<tr><td>Prickly pear</td><td>16</td><td>---</td><td>---</td><td>---</td><td>---</td><td>---</td></tr>
<tr><td>Dates</td><td>14</td><td>19</td><td>2</td><td>Minimal</td><td>---</td><td>---</td></tr>
</table>

Source: FAO [44].

Nevertheless, apart from some rough estimates, there is a critical lack of accurate data on the causes and magnitude of FLW in the NENA region [37]. The FAO [3] estimates that per capita FLW is more than 200 kg/year in North Africa and West and Central Asia (cf. NENA region). To address the critical need for a more granular understanding of the extent and nuances of household food waste across the NENA region, the following table (Table 2) provides a comparative analysis based on the numbers provided by the United Nations Environment Programme (UNEP) in the Food Waste Index Report of 2021 [5]. The table presents estimated household food waste per capita (kg/year) and total volume (tons/year) for nineteen nations in the area. It is worth noting that many countries in the region have very low or low confidence in these statistics, highlighting data collecting issues and the urgent need for more precise and thorough research. The outlier in the area is Saudi Arabia, the only country with a high confidence estimate, indicating a more robust data system than its counterparts in the region. This stark difference in data confidence levels across the region highlights not only disparities in data availability and reliability but also the need for more robust data collection and research to accurately assess the impact of household food waste and effectively tailor interventions.

Table 2. Comparative analysis of household food waste: a country-by-country overview of the NENA Region.

Country	Household Food Waste Estimate (kg/Capita/Year)	Household Food Waste Estimate (Tons/Year)	Confidence in Estimate
Algeria	91	3,918,529	Very low confidence
Bahrain	132	216,161	Medium confidence
Egypt	91	9,136,941	Very low confidence
Iraq	120	4,734,434	Medium confidence
Jordan	93	939,897	Low confidence
Kuwait	95	397,727	Low confidence
Lebanon	105	717,491	Medium confidence
Libya	76	513,146	Very low confidence
Mauritania	100	450,720	Low confidence
Morocco	91	3,319,524	Very low confidence
Oman	95	470,322	Low confidence
Palestine	101	501,602	Low confidence
Qatar	95	267,739	Low confidence
Saudi Arabia	105	3,594,080	High confidence
Sudan	97	4,162,396	Very low confidence
Syria	104	1,771,842	Low confidence
Tunisia	91	1,064,407	Very low confidence
United Arab Emirates	95	923,675	Low confidence
Yemen	104	3,026,946	Very low confidence

Source: UNEP [5].

According to more recent data [37], 32% of food waste in the NENA region happens at the consumer level and is concentrated in urban areas. In comparison, up to 68% occurs in the early phases of the food supply chain (production, transportation, manufacturing, and distribution/retail). The FAO [45] indicated that the drivers of FLW differ within the NENA area and consist of insufficient and poor infrastructure (e.g., cold chain, marketplaces) and inadequate regulatory and legislative frameworks. Baig et al. [46] highlighted that "the factors responsible for food waste include lack of awareness; insufficient and inappropriate shopping planning. Food waste in restaurants, celebrations, social events, and occasions is enormous. Waste is common in festivals and special events where the customs is to provide more food than required" (p. 1743). Therefore, according to Baig et al. [39], the most significant causes of food waste in the region are culture, food pricing, policy and industry issues, and awareness. Indeed, enormous food waste occurs on religious holidays, particularly in the fasting month of Ramadan, as well as on social occasions such as weddings and family reunions [37]. Food waste is a complex problem in the region, where consumers' and retailers' attitudes toward food waste are partly shaped by the region's unique culture, traditions, and history [42]. This assumption is corroborated by the results of surveys on household food wastage in different NENA countries such as Tunisia [47], Egypt [48], Algeria [49], and Morocco [50].

Moreover, residents in the NENA region, especially in GCC countries, take food for granted. This is due to the highly subsidized nature of food items and groceries, especially essential items such as bread, sugar, oil, and other staples. These subsidized items are widely available to all residents, contributing to a perception that food is abundant and easily accessible [51]. In the NENA region, governments have traditionally relied on subsidies to lessen the cost of food, primarily to protect the poor and share wealth [52]. In many countries in the region, governments subsidize bread and make it cheap to ensure societal access to basic foodstuffs. For instance, the Egyptian government spends over USD 3 billion annually on wheat imports, predominantly to support the country's long-running bread subsidy program. This program, known as the Tamween ration card system, provides subsidized bread to 73% of Egyptian households [53]. As a result, bread is both a critical source of nutrition and the most wasted food item. At the same time, recycling rates are low. In many parts of the region, only the informal sector carries out waste collection and recycling [54].

However, while the prevalence of subsidized food items in the NENA region might engender a perception of abundance and potentially contribute to increased food waste, it is imperative to consider the broader, more intricate socio-economic and cultural factors that play significant roles. As a matter of fact, the relationship between food abundance, prices, and waste is complex and not solely determined by subsidy schemes. For instance, subsidizing bread is often cited as contributing to high bread waste levels in the NENA region. However, it is critical to note that bread is the most consumed food and one of the most wasted foods in the world, even in many countries without such subsidy schemes, suggesting that other factors are also at play. Due to its brief shelf life and excess production, approximately 10% (900,000 tons) of bread is discarded throughout the supply chain, from production to consumer use [55]. For example, in the United Kingdom, 32% of household bread is wasted even without subsidies [56]. Similarly, over 50% of bread waste in Sweden happens at bakeries and retailers without subsidies [57]. Additionally, according to Jung et al. [58], wasted bread accounts for 13% of total food waste generated in Finland, 22% in the Netherlands, 23% in New Zealand, 27% in Norway, 7.9% in Portugal, 2.2% in South Korea, and between 12% and 17% in Sweden. The high levels of waste in these unsubsidized countries demonstrate that factors beyond subsidies, like cultural attitudes and retail practices, drive bread waste worldwide.

4. Food Loss and Waste during the COVID-19 Pandemic in the NENA Region

The COVID-19 pandemic affected global waste generation dynamics with unforeseen composition and quantity shifts, especially in food waste [59]. However, since it was caused by a human virus with no direct impact on agriculture production, the COVID-19 pandemic is not considered a direct food waste driver [60]. Consequently, FLW during the COVID-19 pandemic resulted from demand, supply, and logistics disruptions in the agrifood supply chain rather than direct food loss, as opposed to other epidemics (such as bird or swine flu), which caused direct food loss. Indeed, the pandemic influences food waste indirectly by causing changes in key food waste drivers [61].

At the production level, the lack of adequate storage facilities, transport interruptions, and a drop in demand in several countries led to losses of fresh items such as milk and vegetables. Labor shortages also affected crop harvesting [62]. Subsequently, social distancing measures and health checks at borders caused container delays, thus leading to the loss of perishable products and high food wastage [63]. For instance, in Iraq, vegetable farmers could not sell their products in local markets because of the curfew, resulting in spoiled produce and lost income [64]. Furthermore, limitations on mobility prohibited farmers from reaching markets, obtaining inputs, and vending their products, resulting in losses at the production level [63]. For instance, Jordan's severe local emergency plan prohibited farmers from accessing their fields, delaying daily operations and disrupting the harvest season. Likewise, in Tunisia, due to movement limitations, agricultural workers had difficulty reaching their fields, and local markets faced a shortage of locally cultivated fruits [65].

At the consumer level, the pandemic considerably impacted household food buying and planning, including features identified as the leading causes of food waste in households [66]. However, the COVID-19 pandemic had paradoxical repercussions. On the one hand, panic buying was common in the early stages of the pandemic because of a lack of information about the virus and its severity. Stockpiling of non-perishable foods (such as flour, pasta, canned food, rice, etc.) increased in several countries in the region due to anticipated shortages in the near future [67,68]. In fact, panic buying and hoarding are prompted not by supply deficiencies but by consumers' concerns and anxiety over a prospective shortage [69–71]. Panic buying and stockpiling of food items was also triggered by fear and anxiety surrounding potential exposure to the COVID-19 virus. For example, a study conducted in Morocco discovered that most consumers reduced the number of food shopping visits they made and shopped less often than usual. To minimize the need for store visits and limit perceived risks of exposure to COVID-19 while shopping, consumers compensated by purchasing larger quantities and stocking up on more items during each trip (Table 3).

Table 3. Shopping behavior and purchasing changes during the COVID-19 pandemic in Morocco (n = 340).

Variable	Statement	Frequency	Percentage
Shopping behavior change	I go shopping less than usual	186	54.71
	I go shopping like I used to	102	30
	I go shopping more than usual	52	15.29
Change in food purchase	I buy more than usual	120	35.29
	I buy the same as usual	165	48.53
	I buy less than usual	55	16.17

Source: El Bilali et al. [72].

This obsessive purchasing behavior may have raised food prices, aggravated overconsumption (cf. obesity), and caused inadequate food availability [73]. Several countries, for example, experienced temporary shortages and price increases. These did not persist long since certain governments soon intervened to stabilize prices via numerous strategies [67]. Moreover, those who have the financial wherewithal to purchase more food may end up hoarding it, causing havoc among underprivileged residents [74] and depriving some vulnerable groups (e.g., the elderly or the poor) of accessing particular food products [75]. Due to storage constraints, inappropriate cooking techniques, or the overpreparation of meals, panic buying may result in increased household food waste, particularly for fresh items. Excessive purchases caused by panic buying imply that more food will spoil before it can be eaten [9,76].

On the other hand, the COVID-19 pandemic opened up hitherto unforeseen opportunities for a more conscientious approach to consumption [77]. During the pandemic, several consumers in the region adopted a thriftier attitude and reduced food waste. Indeed, several studies conducted in the region revealed that household food waste decreased. Additionally, more and more people were cooking and baking at home due to the closing of the HORECA channel (hotels, restaurants, and caterers). For instance, a survey of 284 people in Tunisia revealed that about 89% of the participants indicated being aware of food waste. It was shown that COVID-19 measures led to better food shopping habits and an overall reduction in food waste. Also, 85% of those polled said they would not waste any food they purchased, and the majority outlined that they had a system for storing and consuming any leftovers [9]. Despite widespread panic shopping, there was no rise in food waste in Lebanon [78]. Since COVID-19 became a significant problem in the country, 73% of respondents said they had stockpiled food. However, 86% said they were not wasting more food, and 80% said they were more conscious of how much they were wasting. Likewise, in Qatar and Oman, food waste dropped due to the absence of panic buying and food stockpiling [13,24] (Figure 1).

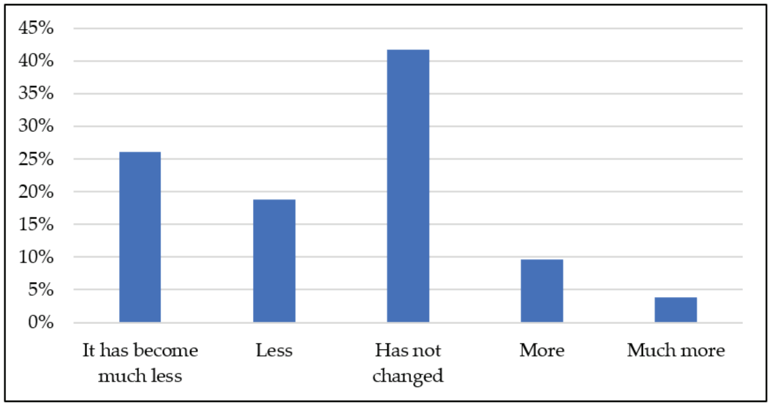

Figure 1. Food waste change during the COVID-19 pandemic in Qatar. Source: Ben Hassen, et al. [13].

Food waste also decreased in Qatar during the Omicron variant wave, with 76.17% of survey respondents reporting that they had reduced their food waste since the start of the wave and 68.82% reporting that they were more aware of the amount of food waste [79].

These results may be due to several factors. Firstly, the hospitality and tourism sectors are the two most prominent causes of food waste in the region [80]. COVID-19 had a substantial negative impact on the hospitality industry [81]. Lockdowns and social distancing regulations imposed the closure of the HORECA channel. Also, the closing of international borders halted incoming tourism. Consequently, many countries in the region, especially the GCC, saw decreased food waste in 2020 [82]. Secondly, family reunions became less frequent due to social distancing restrictions, reducing the waste caused by laying out massive spreads during holidays and social events such as Ramadan or weddings [82]. For instance, usually, during Ramadan, 30–50% of the food produced in Saudi Arabia is thrown away; this figure stands at 25% in Qatar and 40% in the UAE [83].

Thirdly, across the region, numerous good food management practices were adopted by households throughout the pandemic, including increased pre-shop planning, improved at-home food storage, and innovative ways of cooking/preparation (e.g., batch cooking and using up leftovers) [9]. Many households began purchasing more selectively and conserving what they could not finish for later [82]. Adopting these practices is driven by various motives, including a desire to save time and money, a desire to prevent running out of food, and a deep suspicion of grocery stores. Because individuals spent more time in their homes, they could spend more time in the kitchen without feeling pressured [84].

Furthermore, according to a poll of 200 participants from 10 West Asian nations conducted between July and November 2020, the use of leftovers changed following the pandemic. Undoubtedly, when questioned about the use of leftovers in their households, the proportion of respondents who stated “regularly/frequently” rose between the pre-COVID (42%) and post-COVID (50%) periods (Figure 2). This might have been due to an increased focus on healthy eating to promote immunity, since home-cooked meals are often considered more beneficial. This would encourage individuals to save leftovers for later instead of throwing them away [83].

However, according to Jribi et al. [9], the socio-economic circumstances of the pandemic (i.e., food supply, restricted mobility, and loss of income) are more likely to have influenced customer behavior towards food waste than a pro-sustainability attitude. Aside from being a public health concern, COVID-19 was a far more severe issue. The pandemic also triggered a global financial and economic crisis, leading to rising unemployment and widespread poverty [85]. Due to necessity, consumers reduced their food waste during the crisis. When faced with hardships, people tend to save rather than discard food, resulting in a noteworthy decrease in waste generation. These difficult circumstances compelled consumers to waste less food out of need [86], as observed during previous recessions in Greece and Italy [87,88] and during the ongoing economic crises in Lebanon [89] and Iran [17]. Nevertheless, the factors that aided in minimizing food waste during the COVID-19 pandemic were temporary and may not endure now that these measures have been abandoned and consumers have returned to their former habits and behaviors.

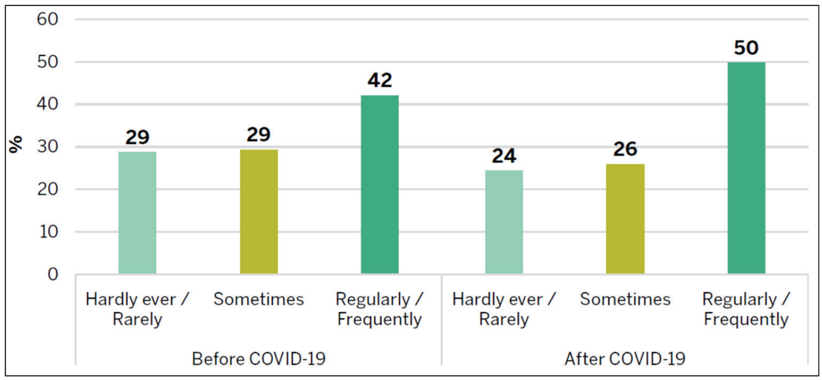

Figure 2. Recycling of food leftovers in West Asia pre and post COVID-19. Source: UNEP [83].

5. The Circular Economy and Food Waste in the NENA Region: Potential and Challenges

Long-term economic recovery from COVID-19 provides the NENA region with an exceptional chance for sustainable development [16]. While environmental preservation is often deprioritized, the present socio-economic crisis triggered by the pandemic in the NENA region has created a unique potential for fostering a circular economy and circular resource management, which might catalyze economic recovery. Circular business models use local resources to minimize import reliance and diversify suppliers for increased resilience [90]. Further, putting circularity at the center of natural resource plans will increase resource availability and value extraction. According to Al-Saidi et al. [91], it is possible to solve environmental challenges while simultaneously ensuring long-term supply security in the water and food sectors by promoting consumer awareness and resource circularity. The main goal is to “close the loops” by promoting reuse and recycling via economic structures. Circularity has the potential to be highly useful for arid regions, and it is typically hailed as a means to preserve resources while still creating prosperity [92,93].

Aside from immediate economic gains, circularity provides additional concrete and significant advantages that are incredibly relevant to the current NENA context, such as food waste. Indeed, addressing food waste with a circular mindset helps to reduce or reuse the volume of surplus food generated [94]. Indeed, on the one hand, circular economy approaches would reduce pollution and waste in the region, improving health and environmental circumstances. On the other hand, they would bring new economic possibilities to local populations, contributing to the region’s political stability and economic diversification [95].

More recently, in the NENA region, we noticed a growing awareness of the importance of addressing the issue of FLW at the level of public institutions and policy, civil society and NGOs, and the private sector. Firstly, policymakers in the region have started to recognize the importance of the circular economy and reducing food waste. For instance, at the policy level, in January 2021, the Cabinet of the United Arab Emirates (UAE) Government approved the Circular Economy Policy (2021–2031), a comprehensive plan identifying the country’s framework for sustainable governance and better usage of natural resources, by implementing consumption and production processes that assure the quality of life for present and future generations. The strategy has many important goals, including improving environmental health, assisting the private sector in implementing clean manufacturing techniques, and lowering natural environmental stress to accomplish the country's ambition of becoming a worldwide leader in green development [96]. Reducing food waste is considered a priority in the strategy. Indeed, the strategy states, "By adopting circular economy strategies in the food sector, the UAE expects that its ecosystems will be healthier, its food healthier and more nutritious, its food wasted reduced and its organic wastes more productively used." (p. 15). The strategy also aims to raise public awareness and implement educational campaigns focused on nutritional guidelines and food waste reduction. These efforts would inform consumers about correctly interpreting best-before and use-by labels to decrease unnecessary waste. Outreach related to social events like weddings and religious celebrations would further promote less wasteful food habits. The strategy seeks to spread knowledge on mitigating food waste [97].

Likewise, in Qatar, in August 2021, the Ministry of Municipality and Environment announced a resolution on food waste. All outlets must now sort their garbage into solid and organic categories. The Ministry also established a strategic plan to eliminate agricultural overproduction and food waste. Due to this endeavor, organic waste will also be recycled into fertilizers and fodders. According to the plan, the school curriculum will include lessons on food waste reduction and public awareness campaigns will be created to promote a food-saving mindset. These programs will also be conducted in conjunction with restaurants to teach them how to prepare and serve meals that meet the needs of their consumers [98].

Moreover, there was a discussion of new legislation in the Egyptian House of Representatives in May 2022 to regulate food waste and encourage its redistribution, recycling, and donation. Food service providers such as restaurants and grocery stores face various fines under the new rule if they do not donate food that is fit for human consumption. The policy encourages and incentivizes recycling and a more reasonable approach to food consumption to prevent wasting surplus food people cannot consume [99].

In addition, food waste might be reduced with the help of startups and digital technologies [90]. Recently, many startups have been created in the NENA region to address the issue of food waste. For instance, in 2021, a food waste and climate change app, EroeGo, was created in the United Arab Emirates. EroeGo is an online grocery marketplace that allows consumers to purchase fresh products that are about to expire at reduced prices [100]. The startup also aims to change the notion of "unwanted" food in the region by providing a transparent platform that offers its consumers basic nutritional information, an efficient purchasing cycle for fresh items, and fair remuneration for its delivery drivers. Likewise, the startup Foodeals, created in Morocco in 2020, intends to become the greatest anti-food waste movement in the Middle East and Africa. Users may geolocate themselves and discover nearby companies providing specials or unsold items of the day using its application, inspired by the circular economy. Thus, the customer saves money, and the shopkeeper makes up for their loss of income while increasing their exposure. Currently functioning in Fez (central Morocco), Foodeals plans to expand to the Kingdom's other main cities shortly, with a dozen pilot firms already in place. As part of its business-to-business (B2B) strategy, the startup aims to connect significant supermarkets and agribusinesses with NGOs with daily food requirements [101]. In the United Arab Emirates, Winnow, a British startup, makes kitchens smarter to aid food service and hospitality businesses. Artificial intelligence tools enabled by Winnow are used by some of Dubai's most prestigious hotels to identify the kind of food items that are thrown out, as well as the amount of food that is thrown away. To reduce food wastage, commercial kitchens might use the information provided by the data to monitor their purchases and menus [102].

6. Discussion and Conclusions

Addressing FLW drivers throughout value chains gives us a chance to address some of the key issues within the NENA region's agrifood systems and contribute to goals such as increasing income and employment, enhancing access to healthy food, and minimizing climate change impact, as well as achieving a better use of finite natural resources, notably arable land, and water [41]. With unexpected changes in content and amount, the COVID-19 pandemic significantly influenced worldwide FLW generation patterns, particularly food waste. This paper highlights that the current socio-economic crisis triggered by the pandemic in the NENA region has generated unique opportunities for creating a circular economy and circular resource management, which might stimulate economic recovery. Further, putting circularity at the center of natural resource management plans will increase resource availability and value extraction. Consequently, in the NENA region, we notice a growing awareness of the importance of addressing the issue of FLW at all levels (regional, national, and local) and from different stakeholders (from the public, civil society, and private sectors).

The previous section highlighted some promising developments related to circular economy and food waste reduction emerging in a few NENA countries. It is important to acknowledge that circular economy strategies in the region are still in their infancy, especially when it comes to concrete policies and national plans targeting food loss and waste. Consequently, few countries in the NENA region have designed and implemented strategies or policies promoting a circular economy. This study highlighted individual cases from the UAE, Qatar, and Egypt. However, there is no comprehensive regional circular economy policy or plan for reducing food waste. Specific themes, such as increasing home waste sorting, school education campaigns, and regulating food donations, have been explored on a national or municipal level rather than as part of a coordinated regional effort.

Based on a recent report by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) (German Society for International Cooperation) [103] examining the condition of circular economy in seven countries within the region (Algeria, Egypt, Jordan, Lebanon, Morocco, Tunisia, and the Palestinian Territories), it is evident that the CE encounters several challenges in this area. Firstly, the interpretation of the CE in these countries primarily focuses on steps aimed at mitigating the effect of current activities rather than adapting to reduce the impact of new activities from the start. In reality, the MENA area seems deficient in material circularity-focused CE projects that aim to close the loop by concentrating on the entire life cycle of products and services. Second, although the governments of these countries have developed national waste management policies, their actual enforcement and execution are limited, reducing their overall effectiveness. In certain countries, such as Morocco, strong legal frameworks have been put in place, and specialized government organizations have been entrusted with aiding the transition to a circular economy.

On the other hand, countries such as Algeria, Lebanon, the West Bank, and Gaza have challenges in moving these efforts forward, principally due to political instability and shaky governance institutions. Finally, research on CE themes in the MENA area is limited and focused on specific industries for each nation, with Morocco and Tunisia being the most active. Most of the available literature comes from foreign organizations rather than local research institutions, and it lacks information on themes like circular design and innovation [103].

As a general observation, short-term post-pandemic recovery strategies in the region encouraged business as usual, and most countries did not aggressively pursue green, resilient, or merely longer-term recoveries in the immediate aftermath of the pandemic [16]. However, given the future issues the region will face, such as climate change and rising population, strengthening circularity becomes even more imperative. While the circular economy can potentially reduce food loss and waste in NENA, the actual implementation is still in its early stages. More studies are required to evaluate the policies and initiatives in all NENA countries comprehensively. Standardized objectives and measuring methodologies would help nations learn from one other's circular economy projects for reducing food waste. Regional collaboration might also aid in the rapid adoption of circular processes. As a result, policymakers must consider how best to encourage circular economy principles in the public and private sectors [95].

To solve these issues, addressing the distorting effects of food subsidies, the lack of community engagement, the inadequacy of current policies, and the inadequate channels for coordination between the many sectors engaged in reducing food waste is compulsory. Subsidies are financially unsustainable for governments, yet they are socio-economically necessary to maintain social peace [104]. Further, the impact of the present conflict in Ukraine on global food systems and supply chains (e.g., price increases) may provide a unique chance to increase awareness of the necessity of reducing food waste to support food security in the NENA region. The war emphasizes that the shift towards more sustainable and resilient food systems that guarantee food and nutrition security in the face of crises is timely, urgent, and highly needed. Given the interconnected nature of global agricultural markets, the conflict between Russia and Ukraine, two major players in the global food and fertilizer industries, has provoked extensive concerns regarding food security worldwide and sustaining global food supplies [105,106]. The conflict challenges many countries, particularly food import-reliant NENA countries [107,108].

Finally, reducing food waste and promoting the circular economy in the NENA region require collaborative efforts between different stakeholders, effective policies and regulations, innovation, and a more holistic and systemic approach that operationalizes connections between the circular economy and other alternative economic models. Moving from fragmented efforts to comprehensive food waste reduction roadmaps supported by solid monitoring and evaluation systems is required. A circular economy approach that prioritizes renewable energy, minimizes waste, and optimizes resource use can contribute to environmental sustainability. In contrast, a green and blue economy approach can promote sustainable economic growth and enhance social welfare. By adopting these strategies, the NENA region can achieve a sustainable food system that benefits both the environment and society [109].

First, collaborative efforts and networking between governments, the business sector, consumer groups, and non-governmental organizations are essential to meet the challenges the agrifood industry poses. This collaborative approach can promote the exchange of ideas and best practices, enabling the sharing of resources and building partnerships to address the issue of food waste. Policies and regulations play a significant role in driving measures to reduce FLW, but their effectiveness depends on faithful execution and mechanisms to verify compliance. The Food and Agriculture Organization (FAO) emphasizes the importance of implementing policies and regulations that encourage responsible production and consumption patterns to reduce food waste [37].

Second, innovation is crucial to reducing food waste and promoting circularity and circular economy in the food system in the NENA region. Technological innovations such as developing efficient packaging and storage systems can minimize food spoilage and waste. Social innovations such as education and awareness campaigns that encourage responsible consumption and discourage food waste can also reduce food waste. Likewise, efforts should be made to increase awareness among residents about the environmental, social, and economic consequences of food waste. Launching food waste awareness programs tailored to cultural contexts, focusing on families, and training food industry actors is required. Messaging should encourage better buying habits, storage methods, portion proportions, and waste separation, which can help change consumer behavior and promote responsible food consumption and waste reduction practices. Third, efforts should be made to encourage and control waste reduction in the retail sector via training, certification programs, and legal restrictions on discarding unsold edible food.

Fourthly, future policies and initiatives addressing food waste in the NENA area should expressly include and recognize the informal sector's contribution. The informal sector, primarily involved in garbage collection and recycling, is a largely neglected resource for achieving the most significant waste reduction and prevention goals. This sector's extensive knowledge of local waste management techniques, agility, and community involvement make it an ideal partner in building a more robust and efficient circular economy. To realize this potential, strategic actions should include extensive research to document the sector's current practices and challenges, policy integration to formalize and regulate operations, capacity-building initiatives to improve worker skills, stakeholder collaboration for innovative waste management solutions, and the implementation of incentive mechanisms to encourage active participation in food waste reduction initiatives. Adopting these strategic activities will not only address the environmental and economic aspects of waste management, but will also promote social inclusion and equality. Moreover, the countries of the region should develop national food loss and waste reduction objectives that are connected with Sustainable Development Goals (SDGs) and implement food waste taxes to promote change.

Finally, given the lessons learned from the COVID-19 pandemic, it is critical to understand food waste management not as a separate issue but as an important component of more extensive public health emergency preparation and response. The pandemic has highlighted our food system's vulnerability to global health crises, emphasizing the need of robust and adaptable food waste management measures. The lessons learned during this era provide essential information for future situations, implying that food waste management should be included in public health emergency preparedness to maintain food security, sustainability, and community well-being. This study adds to our knowledge of the complex interaction between food waste management and crisis response mechanisms by putting our results in the context of public health catastrophes. It is believed that these findings will help policymakers and stakeholders create resilient systems capable of overcoming the multiple difficulties offered by future global crises.

7. Limitations and Future Directions

The main limitation of this paper is that it focuses specifically on the NENA region. As a result, our findings and recommendations may have limited generalizability to other areas or contexts. The specific socio-economic, cultural, and environmental characteristics of the NENA region may influence the applicability of the suggested strategies in different geographical areas. Future research on sustainable food waste management in the NENA region can focus on the following directions to further advance knowledge and address existing gaps. Firstly, conducting in-depth studies that delve into the specific socio-economic, cultural, and environmental contexts of individual countries or sub-regions within the NENA region would provide a more nuanced understanding of food waste management practices. Such research would help identify region-specific challenges, opportunities, and potential solutions tailored to local contexts.

Secondly, although the preliminary results indicated that COVID-19 hardship measures decreased household waste in the short term, longitudinal research is required to determine long-term attitudinal and behavioral changes. Monitoring whether enhanced planning and storage practices remain after the pandemic gives essential insights into social habit formation processes. Follow-up surveys may reveal if the increased waste awareness is a temporary crisis reaction or an incentive for a proper move to sustainability.

Thirdly, studies should be conducted to assess the efficacy of context-specific behavioral nudges and social marketing approaches in encouraging home waste reduction. Environmental triggers, customized messages, and social comparisons are all approaches that should be tested and refined depending on cultural variations. Similarly, analyzing educational efforts may help to optimize welfare and sustainability results.

Finally, more research is needed to assess the effectiveness and impacts of policy interventions, regulations, and governance frameworks to reduce food waste in the NENA region. Comparative studies analyzing the outcomes of different policy approaches can inform evidence-based decision-making and support the development of robust policies that encourage sustainable practices. Community-engaged research may also explore the feasibility and acceptability of suggested policy initiatives to increase their acceptance. It is critical to foster such research–policy cooperation to transform academic knowledge into significant societal shifts.

Author Contributions: Conceptualization, C.B.C. and T.B.H.; methodology, H.E.B.; validation, C.B.C., T.B.H. and H.E.B.; formal analysis, C.B.C., T.B.H. and H.E.B.; writing—original draft preparation, C.B.C.; writing—review and editing, C.B.C., T.B.H. and H.E.B.; supervision, C.B.C.; project administration, C.B.C.; funding acquisition, C.B.C. All authors have read and agreed to the published version of the manuscript.

Funding: Open Access funding provided by Qatar National Library.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. HLPE. Food Losses and Waste in the Context of Sustainable Food Systems. Available online: www.fao.org/cfs/cfs-hlpe (accessed on 3 July 2020).
2. FAO. *Food Wastage Footprint. Impacts on Natural Resources*; FAO: Rome, Italy, 2013.
3. FAO. *Global Food Losses and Food Waste: Extent, Causes and Prevention*; FAO: Rome, Italy, 2011.
4. FAO. *The State of Food and Agriculture 2019. Moving forward on Food Loss and Waste Reduction*; FAO: Rome, Italy, 2019.
5. UNEP. UNEP Food Waste Index Report 2021. Available online: https://www.unep.org/resources/report/unep-food-waste-index-report-2021 (accessed on 19 April 2022).
6. Amicarelli, V.; Tricase, C.; Spada, A.; Bux, C. Households' Food Waste Behavior at Local Scale: A Cluster Analysis after the COVID-19 Lockdown. *Sustainability* **2021**, *13*, 3283. [CrossRef]
7. Roodhuyzen, D.M.A.; Luning, P.A.; Fogliano, V.; Steenbekkers, L.P.A. Putting Together the Puzzle of Consumer Food Waste: Towards an Integral Perspective. *Trends. Food Sci. Technol.* **2017**, *68*, 37–50. [CrossRef]
8. United Nations. *Shared Responsibility, Global Solidarity: Responding to the Socio-Economic Impacts of COVID-19*; United Nations: New York, NY, USA, 2020.
9. Jribi, S.; Ben Ismail, H.; Doggui, D.; Debbabi, H. COVID-19 Virus Outbreak Lockdown: What Impacts on Household Food Wastage? *Environ. Dev. Sustain.* **2020**, *22*, 3939–3955. [CrossRef] [PubMed]
10. Wageningen University & Research. Rapid Country Assessment: Kenya. Available online: https://www.wur.nl/upload_mm/a/5/3/e99ab70b-5b12-435a-8c73-8b445a71e913_COVID-19%20Food%20System%20-%20Rapid%20Country%20Assessment-Kenya%20(July).pdf (accessed on 16 August 2020).
11. Ben Hassen, T.; El Bilali, H. Impacts of the COVID-19 Pandemic on Food Security and Food Consumption: Preliminary Insights from the Gulf Cooperation Council Region. *Cogent. Soc. Sci.* **2022**, *8*, 2064608. [CrossRef]
12. Ben Hassen, T.; El Bilali, H.; Allahyari, M.S.; Kamel, I.M.; Ben Ismail, H.; Debbabi, H.; Sassi, K. Gendered Impacts of the COVID-19 Pandemic on Food Behaviors in North Africa: Cases of Egypt, Morocco, and Tunisia. *Int. J. Environ. Res. Public Health* **2022**, *19*, 2192. [CrossRef] [PubMed]
13. Ben Hassen, T.; El Bilali, H.; Allahyari, M.S. Impact of COVID-19 on Food Behavior and Consumption in Qatar. *Sustainability* **2020**, *12*, 6973. [CrossRef]
14. HLPE. *Interim Issues Paper on the Impact of COVID-19 on Food Security and Nutrition (FSN) by the High-Level Panel of Experts on Food Security and Nutrition (HLPE)*; HLPE: Rome, Italy, 2020.
15. Abiad, M.G.; Meho, L.I. Food Loss and Food Waste Research in the Arab World: A Systematic Review. *Food Secur.* **2018**, *10*, 311–322. [CrossRef]
16. Luomi, M.; Bayoumi, M. Aligning Policies with Green, Resilient and Just Recoveries in the Middle East. Available online: https://www.sustainablefinance.hsbc.com/carbon-transition/a-green-resilient-and-just-recovery-in-the-middle-east (accessed on 15 June 2022).
17. Allahyari, M.S.; Marzban, S.; El Bilali, H.; Ben Hassen, T. Effects of COVID-19 Pandemic on Household Food Waste Behaviour in Iran. *Heliyon* **2022**, *8*, e11337. [CrossRef] [PubMed]
18. Ben Hassen, T.; El Bilali, H.; Allahyari, M.S.; Morrar, R. Food Attitudes and Consumer Behavior towards Food in Conflict-Affected Zones during the COVID-19 Pandemic: Case of the Palestinian Territories. *Br. Food J.* 2021, *ahead-of-print*. [CrossRef]
19. Ben Hassen, T.; El Bilali, H.; Allahyari, M.S. Food Shopping during the COVID-19 Pandemic: An Exploratory Study in Four Near Eastern Countries. *J. Islam. Mark.* **2022**, *14*, 2084–2108. [CrossRef]
20. Olaimat, A.N.; Al-Nabulsi, A.A.; Nour, M.O.; Osaili, T.M.; Alkhalidy, H.; Al-Holy, M.; Ayyash, M.; Holley, R.A. The Effect of the Knowledge, Attitude, and Behavior of Workers Regarding COVID-19 Precautionary Measures on Food Safety at Foodservice Establishments in Jordan. *Sustainability* **2022**, *14*, 8193. [CrossRef]

21. Alazaiza, M.Y.D.; AbdelFattah, F.A.M.; Al Maskari, T.; Bashir, M.J.K.; Nassani, D.E.; Albahnasawi, A.; Abushammala, M.F.M.; Hamad, R.J. Effect Of COVID-19 Pandemic on Food Purchasing and Waste Generation during the Lockdown Period in The Sultanate of Oman. *Glob. NEST J.* **2022**, *24*, 59–64. [CrossRef]
22. Alshubaith, I.H.; Alhajri, S.; Alhajri, A.; Alsultan, R.A.; Azhar, E.I.; Alhussaini, B.H.; Al Solami, L.S.; de Oliveira, M.C.; Khafaga, A.F.; Alqurashi, A.D.; et al. The Impact of COVID-19 on the Sustainability of the Environment, Animal Health and Food Security, and Safety. *Environ. Sci. Pollut. Res.* **2022**, *29*, 70822–70831. [CrossRef]
23. Mertens, E.; Peñalvo, J.L. The Burden of Malnutrition and Fatal COVID-19: A Global Burden of Disease Analysis. *Front. Nutr.* **2021**, *7*, 619850. [CrossRef] [PubMed]
24. Ben Hassen, T.; El Bilali, H.; Allahyari, M.S.; Al Samman, H.; Marzban, S. Observations on Food Consumption Behaviors during the COVID-19 Pandemic in Oman. *Front. Public Health* **2022**, *9*, 779654. [CrossRef] [PubMed]
25. Azazz, A.M.S.; Elshaer, I.A. Amid the COVID-19 Pandemic, Social Media Usage and Food Waste Intention: The Role of Excessive Buying Behavior and Religiosity. *Sustainability* **2022**, *14*, 6786. [CrossRef]
26. Saidi, A.; Bouhid, L.; Napoleone, C.; El Hadad-Gauthier, F.; Moussalim, S.; Alj, A. The Sustainability of the Fruit and Vegetable Supply Chain Tested by COVID-19: Case of Meknes City, Morocco. *Dev. Durable Territ.* **2022**, *13*, e21266.
27. Saleh, H.; Al-Kahlidi, M.; Abulridha, H.; Banoon, S.; Abdelzaher, M. Current Situation and Future Prospects for Plastic Waste in Maysan Governorate: Effects and Treatment During the COVID-19 Pandemic. *Egypt J. Chem.* **2021**, *64*, 4449–4460. [CrossRef]
28. Hoteit, M.; Ibrahim, C.; Saadeh, D.; Al-Jaafari, M.; Atwi, M.; Alasmar, S.; Najm, J.; Sacre, Y.; Hanna-Wakim, L.; Al-Jawaldeh, A. Correlates of Sub-Optimal Feeding Practices among under-5 Children amid Escalating Crises in Lebanon: A National Representative Cross-Sectional Study. *Children* **2022**, *9*, 817. [CrossRef]
29. ESCWA. The Innovation Landscape in Arab Countries a Critical Analysis. Available online: https://www.unescwa.org/publications/innovation-landscape-arab-countries-critical-analysis (accessed on 2 November 2020).
30. Efron, S.; Fromm, C.; Gelfeld, B.; Nataraj, S.; Sova, C. Food Security in the Gulf Cooperation Council. Available online: www.rand.org/cmepp (accessed on 12 July 2020).
31. The Economist Intelligence Unit. Global Food Security Index 2022. Available online: https://impact.economist.com/sustainability/project/food-security-index/resource-library (accessed on 3 May 2023).
32. World Food Programme. Economic and Food Security Implications of the COVID-19 Outbreak 1 an Update with Insights from Different Regions. Available online: https://reliefweb.int/report/world/economic-and-food-security-implications-covid-19-outbreak-update-insights-different (accessed on 25 June 2020).
33. de Carvalho, C.A.; Viola, P.C.D.A.F.; Sperandio, N. How Is Brazil Facing the Crisis of Food and Nutrition Security during the COVID-19 Pandemic. *Public Health Nutr.* **2020**, *24*, 561–564. [CrossRef]
34. Capone, R.; El Bilali, H.; Debs, D.; Bottalico, F.; Cardone, G.; Berjan, S.; Elmenofi, G.A.G.; Aboubdillah, A.; Charbel, L.; Ali Arous, S. Bread and Bakery Products Waste in Selected Mediterranean Arab Countries. *Am. J. Food Nutr.* **2016**, *4*, 40–50.
35. Berjan, S.; Capone, R.; Debs, P.; El Bilali, H. Food Losses and Waste: A Global Overview with a Focus on Near East and North Africa Region. *Int. J. Agric. Manag. Dev.* **2018**, *8*, 1–16.
36. FAO. *Regional Overview of Food Insecurity—Near East and North Africa: Strengthening Regional Collaboration to Build Resilience for Food Security and Nutrition*; FAO: Cairo, Egypt, 2015.
37. FAO. Regional Strategic Framework—Reducing Food Losses and Waste in the Near East & North Africa Region. Available online: https://www.fao.org/policy-support/tools-and-publications/resources-details/en/c/1300339/ (accessed on 14 June 2022).
38. Standing Committee for Economic and Commercial Cooperation of the Organization of Islamic Cooperation. *Reducing Food Waste in the OIC Countries*; COMCEC: Ankara, Turkey, 2017.
39. Baig, M.B.M.B.; Gorski, I.; Neff, R.A.R.A. Understanding and Addressing Waste of Food in the Kingdom of Saudi Arabia. *Saudi J. Biol. Sci.* **2019**, *26*, 1633–1648. [CrossRef]
40. El Bilali, H.; Ben Hassen, T. Food Waste in the Countries of the Gulf Cooperation Council: A Systematic Review. *Foods* **2020**, *9*, 463. [CrossRef] [PubMed]
41. Anríquez, G.; Foster, W.; Rocha, S.; Ortega, J.; Smolak, J.; Jansen, S. *Reducing Food Loss and Waste in the Near East and North Africa—Producers, Intermediaries and Consumers as Key Decision-Makers*; FAO: Cairo, Egypt, 2023.
42. FAO. FAO and UNEP Join Hands to Prevent Food Waste in the Arab Region. Available online: https://www.fao.org/neareast/news/view/en/c/1397462/ (accessed on 13 June 2022).
43. FAO. *Reducing Food Loss and Waste in the Near East and North Africa*; FAO: Cairo, Egypt, 2014.
44. FAO. *Rapport de Synthèse Sur La Réducňon Des Pertes Post-Récolte Des Produits Alimentaires Au Maroc*; FAO: Ribat, Morocco, 2016.
45. FAO. *Report of the Expert Consultation Meeting on Food Losses and Waste Reduction in the Near East Region: Towards a Regional Comprehensive Strategy*; FAO: Cairo, Egypt, 2013.
46. Baig, M.B.M.B.; Al-Zahrani, K.H.K.H.; Schneider, F.; Straquadine, G.S.G.S.; Mourad, M. Food Waste Posing a Serious Threat to Sustainability in the Kingdom of Saudi Arabia—A Systematic Review. *Saudi J. Biol. Sci.* **2019**, *26*, 1743–1752. [CrossRef]
47. Sassi, K.; Capone, R.; Abid, G.; Debs, P.; El Bilali, H.; Daaloul Bouacha, O.; Bottalico, F.; Driouech, N.; Sfayhi Terras, D. Food Wastage by Tunisian Households. *Int. J. AgroFor* **2016**, *1*, 172–181. [CrossRef]
48. Elmenofi, G.; Capone, R.; Waked, S.; Debs, P.; Bottalico, F.; El Bilali, H. An Exploratory Survey on Household Food Waste in Egypt. In Proceedings of the VI International Scientific Agriculture Symposium "Agrosym 2015", Jahorina, Bosnia and Herzegovina, 15–18 October 2015; pp. 1298–1304.

49. Ali Arous, S.; Capone, R.; Debs, P.; Haddadi, Y.; El Bilali, H.; Bottalico, F.; Hamidouche, M. Exploring Household Food Waste Issue in Algeria. *AgroFor Int. J.* **2017**, *2*, 55–67. [CrossRef]
50. Abouabdillah, A.; Capone, R.; El Youssfi, L.; Debs, P.; Harraq, A.; El Bilali, H.; El Amrani, M.; Bottalico, F.; Driouech, N. Household Food Waste in Morocco: An Exploratory Survey. In Proceedings of the Sixth International Scientific Agricultural Symposium "Agrosym 2015", Jahorina, Bosnia and Herzegovina, 15–18 October 2015; University of East Sarajevo: Lukavica, Bosnia and Herzegovina, 2015; pp. 1353–1360.
51. Ernst & Young; HSBC. Food for the Future: Sustainable Agriculture Sector in Egypt, Saudi Arabia and the UAE. Available online: https://www.sustainablefinance.hsbc.com/-/media/gbm/sustainable/attachments/food-for-the-future.pdf (accessed on 15 June 2022).
52. Brixi, H.; El-Gammal, Y. Il Est Temps Que Le Monde Arabe Investisse Dans Sa Population Plutôt Que Dans Des Subventions. Available online: https://blogs.worldbank.org/fr/arabvoices/investir-dans-la-population-et-non-les-subventions (accessed on 14 June 2022).
53. Ministry of Supply and Internal Trade. Results of the Tamween Program in 2019. Available online: http://www.msit.gov.eg/details.html?topicID=574 (accessed on 19 January 2023).
54. Negm, A.M.; Shareef, N. Introduction to the "Waste Management in MENA Regions". In *Waste Management in MENA Regions*; Negm, A.M., Shareef, N., Eds.; Springer: Cham, Switzerland, 2020; pp. 1–11.
55. Kumar, V.; Brancoli, P.; Narisetty, V.; Wallace, S.; Charalampopoulos, D.; Kumar Dubey, B.; Kumar, G.; Bhatnagar, A.; Kant Bhatia, S.; Taherzadeh, M.J. Bread Waste—A Potential Feedstock for Sustainable Circular Biorefineries. *Bioresour. Technol.* **2023**, *369*, 128449. [CrossRef]
56. WRAP. Reducing Household Bakery Waste. Available online: https://wrap.org.uk/resources/report/reducing-household-bakery-waste (accessed on 2 February 2024).
57. Brancoli, P.; Lundin, M.; Bolton, K.; Eriksson, M. Bread Loss Rates at the Supplier-Retailer Interface—Analysis of Risk Factors to Support Waste Prevention Measures. *Resour. Conserv. Recycl.* **2019**, *147*, 128–136. [CrossRef]
58. Jung, J.-M.; Kim, J.Y.; Kim, J.-H.; Kim, S.M.; Jung, S.; Song, H.; Kwon, E.E.; Choi, Y.-E. Zero-Waste Strategy by Means of Valorization of Bread Waste. *J. Clean. Prod.* **2022**, *365*, 132795. [CrossRef]
59. Sharma, H.B.; Vanapalli, K.R.; Cheela, V.S.; Ranjan, V.P.; Jaglan, A.K.; Dubey, B.; Goel, S.; Bhattacharya, J. Challenges, Opportunities, and Innovations for Effective Solid Waste Management during and Post COVID-19 Pandemic. *Resour. Conserv. Recycl.* **2020**, *162*, 105052. [CrossRef] [PubMed]
60. Laborde, D.; Martin, W.; Swinnen, J.; Vos, R. COVID-19 Risks to Global Food Security. *Science* **2020**, *369*, 500–502. [CrossRef] [PubMed]
61. Di Marcantonio, F.; Twum, E.K.; Russo, C. COVID-19 Pandemic and Food Waste: An Empirical Analysis. *Agronomy* **2021**, *11*, 1063. [CrossRef]
62. Wageningen University & Research. Rapid Country Assessment: Bangladesh. Available online: https://www.wur.nl/en/Research-Results/Research-Institutes/centre-for-development-innovation/Our-Value-Propositions/Guiding-Sector-Transformation/The-effects-of-COVID-19-on-food-systems-rapid-assessments/Rapid-Country-Assessment-Bangladesh.htm (accessed on 16 August 2020).
63. Galanakis, C.M. The Food Systems in the Era of the Coronavirus (COVID-19) Pandemic Crisis. *Foods* **2020**, *9*, 523. [CrossRef] [PubMed]
64. FAO; WFP; IFAD. Food Security in Iraq—Impact of COVID-19 (June–August 2020). Available online: https://reliefweb.int/report/iraq/food-security-iraq-impact-covid-19-june-august-2020-enar (accessed on 25 April 2022).
65. FAO; ESCWA. Arab Food Security: Vulnerabilities and Pathways. Available online: https://reliefweb.int/sites/reliefweb.int/files/resources/arab-regional-food-security-vulnerabilities-resilience-covid-19-crisis-english.pdf (accessed on 25 April 2022).
66. Rodgers, R.F.; Lombardo, C.; Cerolini, S.; Franko, D.L.; Omori, M.; Linardon, J.; Guillaume, S.; Fischer, L.; Tyszkiewicz, M.F. "Waste Not and Stay at Home" Evidence of Decreased Food Waste during the COVID-19 Pandemic from the U.S. and Italy. *Appetite* **2021**, *160*, 105110. [CrossRef]
67. CIHEAM. The COVID-19 Pandemic: Threats on Food Security in the Mediterranean Region. Available online: https://www.ciheam.org/wp-content/uploads/2020/07/COVID-rapport-FINAL-1.pdf (accessed on 15 August 2020).
68. FAO. COVID-19 and Its Impact on Food Security in the Near East and North Africa: How to Respond? Available online: http://www.fao.org/3/ca8778en/CA8778EN.pdf (accessed on 6 September 2020).
69. Lehberger, M.; Kleih, A.-K.; Sparke, K. Panic Buying in Times of Coronavirus (COVID-19): Extending the Theory of Planned Behavior to Understand the Stockpiling of Nonperishable Food in Germany. *Appetite* **2021**, *161*, 105118. [CrossRef] [PubMed]
70. Messner, W.; Payson, S.E. Effects of National Culture on the Extent of Panic Buying during the COVID-19 Outbreak. *J. Int. Consum. Mark.* **2021**, *34*, 235–254. [CrossRef]
71. Tsao, Y.C.; Raj, P.V.R.P.; Yu, V. Product Substitution in Different Weights and Brands Considering Customer Segmentation and Panic Buying Behavior. *Ind. Mark. Manag.* **2019**, *77*, 209–220. [CrossRef]
72. El Bilali, H.; Ben Hassen, T.; Baya Chatti, C.; Abouabdillah, A.; Alaoui, S.B. Exploring Household Food Dynamics During the COVID-19 Pandemic in Morocco. *Front. Nutr.* **2021**, *8*, 724803. [CrossRef]

73. Omar, N.A.; Nazri, M.A.; Ali, M.H.; Alam, S.S. The Panic Buying Behavior of Consumers during the COVID-19 Pandemic: Examining the Influences of Uncertainty, Perceptions of Severity, Perceptions of Scarcity, and Anxiety. *J. Retail. Consum. Serv.* **2021**, *62*, 102600. [CrossRef]
74. Naja, F.; Hamadeh, R. Nutrition amid the COVID-19 Pandemic: A Multi-Level Framework for Action. *Eur. J. Clin. Nutr.* **2020**, *74*, 1117–1121. [CrossRef]
75. Wesseler, J. Storage Policies: Stockpiling Versus Immediate Release. *J. Agric. Food Ind. Organ* **2020**, *18*, 20190055. [CrossRef]
76. Cranfield, J.A.L. Framing Consumer Food Demand Responses in a Viral Pandemic. *Can. J. Agric. Econ./Rev. Can. D'agroeconomie* **2020**, *68*, 151–156. [CrossRef]
77. Sarkis, J.; Cohen, M.J.; Dewick, P.; Schröder, P. A Brave New World: Lessons from the COVID-19 Pandemic for Transitioning to Sustainable Supply and Production. *Resour. Conserv. Recycl.* **2020**, *159*, 104894. [CrossRef]
78. Ben Hassen, T.; El Bilali, H.; Allahyari, M.S.; Charbel, L. Food Shopping, Preparation and Consumption Practices in Times of COVID-19: Case of Lebanon. *J. Agribus. Dev. Emerg. Econ.* **2021**. *ahead-of-print*. [CrossRef]
79. Ben Hassen, T.; Baya Chatti, C.; El Bilali, H. Impact of COVID-19 on Food Behavior and Diet in Qatar: A Cross-Sectional Survey on the Omicron Variant. *Nutr. Health* **2023**. Available online: https://journals.sagepub.com/doi/10.1177/02601060231189637 (accessed on 9 November 2023).
80. Khaleej Times. How Much Food UAE Residents Waste in a Year. Available online: https://www.khaleejtimes.com/news/general/how-much-food-uae-residents-waste-in-a-year (accessed on 13 June 2022).
81. Filimonau, V. The Prospects of Waste Management in the Hospitality Sector Post COVID-19. *Resour. Conserv. Recycl.* **2021**, *168*, 105272. [CrossRef] [PubMed]
82. Arab News. Will Fall in Food Waste in the Middle East Outlast the Coronavirus Pandemic? Available online: https://www.arabnews.com/node/1774936/middle-east (accessed on 13 June 2022).
83. UNEP. The State of Food Waste in West Asia. Available online: https://www.unep.org/resources/report/state-food-waste-west-asia (accessed on 6 November 2023).
84. Vargas-Lopez, A.; Cicatiello, C.; Principato, L.; Secondi, L. Consumer Expenditure, Elasticity and Value of Food Waste: A Quadratic Almost Ideal Demand System for Evaluating Changes in Mexico during COVID-19. *Socioecon. Plann. Sci.* **2021**, *82*, 101065. [CrossRef] [PubMed]
85. International Monetary Fund. World Economic Outlook Update, June 2020: A Crisis Like No Other, an Uncertain Recovery. Available online: https://www.imf.org/en/Publications/WEO/Issues/2020/06/24/WEOUpdateJune2020 (accessed on 31 July 2020).
86. Durante, K.M.; Laran, J. The Effect of Stress on Consumer Saving and Spending. *J. Mark. Res.* **2016**, *53*, 814–828. [CrossRef]
87. Fanelli, R.M.; Florio, A. Di Domestic Food Waste, Gap in Times of Crisis. *Ital. Rev. Agric. Econ.* **2016**, *71*, 111–125. [CrossRef]
88. Martinengo, M.C. Household Food Waste and Consumer Culture: Reflections on Italian Behaviour. *J. Nutr. Ecol. Food Res.* **2014**, *2*, 73–77. [CrossRef]
89. Hassan, H.F.; Rizk, Y.; Chalak, A.; Abiad, M.G.; Mattar, L. Household Food Waste Generation during COVID-19 Pandemic and Unprecedented Economic Crisis: The Case of Lebanon. *J. Agric. Food Res.* **2023**, *14*, 100749. [CrossRef]
90. Material Economics. The Circular Economy and COVID-19 Recovery: How Pursuing a Circular Future for Europe Fits with Recovery from the Economic Crisis. Available online: https://materialeconomics.com/material-economics-the-circular-economy-and-covid-19-recovery.pdf?cms_fileid=0704a908d9b4cecad7d9768bb1193fdc (accessed on 14 June 2022).
91. Al-Saidi, M.; Dehnavi, S. Toward a Circular Economy in the MENA Region: Insights from the Water-Food Nexus. In *Economic Development in the MENA Region*; Springer: Cham, Switzerland, 2021; pp. 139–159.
92. Geissdoerfer, M.; Morioka, S.N.; de Carvalho, M.M.; Evans, S. Business Models and Supply Chains for the Circular Economy. *J. Clean. Prod.* **2018**, *190*, 712–721. [CrossRef]
93. Korhonen, J.; Honkasalo, A.; Seppälä, J. Circular Economy: The Concept and Its Limitations. *Ecol. Econ.* **2018**, *143*, 37–46. [CrossRef]
94. ACTED. Circularity as a Lifeline for MENA Economies in Distress. Available online: https://www.acted.org/wp-content/uploads/2021/03/circularity-as-a-lifeline-for-mena-economies-in-distress-v3.pdf (accessed on 14 June 2022).
95. Italian Institute for International Political Studies. Circular Approaches for the Middle East Sustainable Development. Available online: https://med.ispionline.it/agenda/circular-approaches-for-the-middle-east-sustainable-development/ (accessed on 14 June 2022).
96. Emirates News Agency. Mohammed Bin Rashid Chairs First UAE Cabinet Meeting in 2021. Available online: https://wam.ae/en/details/1395302903978 (accessed on 14 June 2022).
97. The Government of the United Arab Emirates. UAE Circular Economy Policy 2021–2031. Available online: https://u.ae/en/about-the-uae/economy/circular-economy (accessed on 14 June 2022).
98. The Peninsula Qatar. Qatar Adopts Strategic Plan to Reduce Food Waste: Official. Available online: https://thepeninsulaqatar.com/article/14/08/2021/Qatar-adopts-strategic-plan-to-reduce-food-waste-Official (accessed on 14 June 2022).
99. Egypt Today. Egypt's Parliament Considers Bill Regulating Food Waste. Available online: https://www.egypttoday.com/Article/1/115471/Egypt%E2%80%99s-parliament-considers-bill-regulating-food-waste (accessed on 14 June 2022).
100. Food Tank. 12 Apps Preventing Household Food Waste and Protecting the Planet. Available online: https://foodtank.com/news/2021/09/apps-preventing-household-food-waste-and-protecting-the-planet/ (accessed on 14 June 2022).

101. KAWA News. 4 Startups Fighting against Food Waste in Mena. Available online: https://kawa-news.com/en/4-startups-fighting-against-food-waste-in-mena/ (accessed on 14 June 2022).
102. Khaleej Times. Innovations Key to Cutting Food Waste. Available online: https://www.khaleejtimes.com/opinion/innovations-key-to-cutting-food-waste (accessed on 17 June 2022).
103. GIZ. Assessment Report—The Circular Economy Ecosystem in the MENA Region. Available online: https://greentechknowledgehub.de/publications/assessment-report-circular-economy-ecosystem-mena-region (accessed on 3 February 2024).
104. Abis, S.; Bertin, A. How the War in Ukraine Exacerbates Food Insecurity in the MENA Region. Available online: https://www.ispionline.it/en/pubblicazione/how-war-ukraine-exacerbates-food-insecurity-mena-region-34722 (accessed on 17 January 2023).
105. Berkhout, P.; Bergevoet, R.; van Berkum, S. A Brief Analysis of the Impact of the War in Ukraine on Food Security. Available online: https://library.wur.nl/WebQuery/wurpubs/596254 (accessed on 6 May 2022).
106. Welsh, C. The Russia-Ukraine War and Global Food Security: A Seven-Week Assessment, and the Way Forward for Policymakers. Available online: https://www.csis.org/analysis/russia-ukraine-war-and-global-food-security-seven-week-assessment-and-way-forward (accessed on 6 May 2022).
107. Benton, T.; Froggatt, A.; Wellesley, L.; Grafham, O.; King, R.; Morisetti, N.; Nixey, J.; Schröder, P. The Ukraine War and Threats to Food and Energy Security: Cascading Risks from Rising Prices and Supply Disruptions. Available online: https://chathamhouse.soutron.net/Portal/Public/en-GB/RecordView/Index/191102 (accessed on 8 May 2022).
108. FAO. Impact of the Ukraine-Russia Conflict on Global Food Security and Related Matters under the Mandate of the Food and Agriculture Organization of the United Nations (FAO). Available online: https://www.fao.org/3/ni734en/ni734en.pdf (accessed on 11 May 2022).
109. World Bank. Middle East & North Africa Climate Roadmap (2021–2025). Available online: https://thedocs.worldbank.org/en/doc/6f868d4a875db3ef23ef1dc747fcf2ca-0280012022/original/MENA-Roadmap-Final-01-20.pdf (accessed on 15 July 2023).

sustainability

MDPI

Review

Food Security Challenges in Europe in the Context of the Prolonged Russian–Ukrainian Conflict

Mohammad Fazle Rabbi [1,*], Tarek Ben Hassen [2], Hamid El Bilali [3], Dele Raheem [4] and António Raposo [5]

1 Ihrig Károly Doctoral School of Management and Business, University of Debrecen, 4032 Debrecen, Hungary
2 Program of Policy, Planning, and Development, Department of International Affairs, College of Arts and Sciences, Qatar University, Doha 2713, Qatar
3 International Centre for Advanced Mediterranean Agronomic Studies (CIHEAM-Bari), Via Ceglie 9, 70010 Valenzano, Italy
4 Northern Institute for Environmental and Minority Law (NIEM), Arctic Centre, University of Lapland, 96101 Rovaniemi, Finland
5 CBIOS (Research Center for Biosciences and Health Technologies), Universidade Lusófona de Humanidades e Tecnologias, Campo Grande 376, 1749-024 Lisboa, Portugal
* Correspondence: drrabbikhan@gmail.com

Abstract: The ongoing conflict between Russia and Ukraine, two major agricultural powers, has numerous severe socio-economic consequences that are presently being felt worldwide and that are undermining the functioning of the global food system. The war has also had a profound impact on the European food system. Accordingly, this paper examines the implications of the ongoing conflict on food security pillars (viz. availability, access, use, stability) in European countries and considers potential strategies for addressing and mitigating these effects. The paper highlights that the food supply in Europe does not seem to be jeopardized since most European countries are generally self-sufficient in many products. Nonetheless, the conflict might impact food access and production costs. Indeed, the European agricultural industry is a net importer of several commodities, such as inputs and animal feed. This vulnerability, combined with the high costs of inputs such as fertilizers and energy, creates production difficulties for farmers and threatens to drive up food prices, affecting food affordability and access. Higher input prices increase production costs and, ultimately, inflation. This may affect food security and increase (food) poverty. The paper concludes that increasing food aid, ensuring a stable fertilizer supply, imposing an energy price cap, initiating a farmer support package, switching to renewable energy sources for cultivation, changing individual food behaviors, lifting trade restrictions, and political stability can safeguard food security pillars and strengthen the resilience of the European food system.

Keywords: food security; food security pillars; food supply; food; energy; conflict; Russia; Ukraine; war

Citation: Rabbi, M.F.; Ben Hassen, T.; El Bilali, H.; Raheem, D.; Raposo, A. Food Security Challenges in Europe in the Context of the Prolonged Russian–Ukrainian Conflict. *Sustainability* **2023**, *15*, 4745. https://doi.org/10.3390/su15064745

Academic Editor: Marian Rizov

Received: 24 January 2023
Revised: 5 March 2023
Accepted: 6 March 2023
Published: 7 March 2023

1. Introduction

During the past decades, the global food system has faced several crises, including climate change and the COVID-19 pandemic, causing market and supply chain disruption and raising concerns about food security. Consequently, food prices have been increasing since the middle of 2021 due to supply chain disruptions brought on by the pandemic [1], rising global demand, and poor harvests in several countries [2,3]. Fuel, fertilizer, and pesticide prices have also increased to nearly record levels [4,5]. Further, the FAO Food Price Index (FFPI) surpassed a new record in February 2022, rising by 2.2% from the previous peak in February 2011 and by 21% in the year prior [6,7]. Since most European countries depend on imports to meet their energy demand, the continent has seen skyrocketing costs beginning in the summer of 2021. The rise in energy prices hit many of the inputs used by European farmers, such as feed and fertilizers. Hence, annual inflation in the European

Union (EU) reached 5.2% in November 2021 (4.9% in the Euro area), 27.5% in the energy sector, and 2.2% in the food, alcohol, and tobacco sector [5].

In the early hours of 24 February 2022, Russia began a full-scale military invasion of Ukraine, resulting in civilian casualties and the destruction of vital infrastructure. In addition to significant human fatalities and devastation, the war has jeopardized global food security by disrupting agriculture production and trade in one of the world's most significant food-exporting regions [8–12]. It has significantly contributed to rapidly rising global food prices, aggravating existing food system vulnerabilities already worsened by climate change and the COVID-19 pandemic [13,14]. A year into the conflict, its final military implications and outcomes are unknown [15]. However, its impacts on agricultural production and food security are clear [11,12,16,17]. It has caused a severe drop in both countries' exports and production of essential commodities (e.g., cereals). Their price has soared worldwide, threatening to force millions into famine and poverty, especially in Low-Income Food-Deficit Countries (LIFDCs) [11,12,16,17]. The European Commission [17] predicted that up to 25 million tons of wheat would need to be substituted to meet global food demands for the current and upcoming seasons.

While Russia and Ukraine contribute just about 2% of the global Gross Domestic Product (GDP), they are both global breadbaskets, producing and exporting essential agricultural commodities, minerals, fertilizers, and energy [18–20]. These countries supply about 30% of globally traded wheat, 20% corn, and 70% sunflower oil. Hence, in 2021, they were among the top three global wheat and corn exporters, accounting for more than 50% and 25% of all sunflower oil sold worldwide [7]. Overall, Russia and Ukraine export around 12% of the global total caloric trade [4]. Furthermore, before the conflict, Russia was the world's largest supplier of fertilizers (such as nitrogen, potassium, and phosphorus) and one of the leading oil and natural gas exporters, owing to its vast reserves [10,21–23].

Accordingly, the conflict dealt a considerable blow to commodity markets, particularly food, fertilizers, and energy, impacting global trade, production, and consumption patterns in ways that will keep prices at historic highs until the end of 2024, jeopardizing global food security [11,12]. Higher energy, input, and food prices might considerably impact global food security, particularly in vulnerable countries. Because of the interdependence inherent in international trade, the broader repercussions are felt throughout the globe in today's hyper-connected global economy with its deep trade ties [24]. According to the World Bank [24], in January 2023, maize and wheat prices were 27% and 13% higher, respectively, than in January 2021, while rice price was 10% lower. Therefore, between September and December 2022, 94.1% of low-income nations, 92.9% of lower-middle-income countries, and 89% of upper-middle-income countries had inflation exceeding 5%, with several having double-digit inflation [25]. High inflation is also prevalent in high-income countries, including some in Europe, with around 85.5% suffering high food price inflation [26].

The conflict has also significantly affected the European food system, which was already dealing with interrupted supply lines due to the COVID-19 outbreak [27]. The food supply in the EU is not jeopardized, since most European countries benefit from well-developed agricultural production and are mostly self-sufficient in many products. However, the European agricultural sector is a net importer of specific products, such as animal feed. This vulnerability, combined with the high costs of inputs such as fertilizers and energy, creates production difficulties for farmers and threatens to drive up food prices, affecting food availability and access [28]. Indeed, the substantial dependence of some European nations on the Russian energy supply makes it hard to avoid price increases on essential items such as food [29]. This increases producer costs and affects food prices, raising worries over consumer purchasing power and producer income. Inflation affects the price of basic commodities, particularly for low-income households, for whom the affordability of nutritious meals was already a challenge before the start of the conflict [29]. The conflict highlighted the European food system's vulnerabilities, such as its dependence on imported energy, fertilizer, and animal feed [18]. In 2019, Russia supplied the European Union with over 40% of its natural gas, 25% of its oil, and almost 50% of its coal [30].

After decades of low inflation, the EU faces new economic, political, and social challenges from increasing consumer prices. Rising energy and food prices are already generating high societal costs in terms of decreased buying power. They are also anticipated to exacerbate material deprivation, poverty, and social exclusion throughout the EU [31]. The next several months will be among the most challenging in modern history for the European and global agri-food sectors [10]. Although futures prices have gone down and international markets have adjusted and adapted, there is a possibility of a short-term inflation increase due to the delayed transmission of previous food and energy price increases from global commodity markets to consumer prices. For instance, the IMF [31] predicts that global inflation will climb from 4.7% in 2021 to 8.8% in 2022 before falling to 6.5% in 2023 and 4.1% in 2024. In Europe, the effects are compounded by the significant impact of war-related energy shocks [31].

In this context, this paper aims to assess the possible impacts of the war between Russia and Ukraine on food security in European countries. It aims to address these two questions: Firstly, what were the principal consequences of the conflict on food security in European countries, and how significant were they? Secondly, how did the war affect the food security condition of European populations?

Several scholars, government representatives, and media outlets have examined the implications of the Russia–Ukraine conflict on food security. However, to the best of our knowledge, this study is the first to specifically examine the impact of the Russia–Ukraine conflict on food security in Europe. Despite the numerous studies conducted on the topic, none have expressly focused on this region and the possible repercussions it may face due to the ongoing conflict. Most of the existing research focused on the impact of the conflict on global food security [11,12,30,32–35], energy security [16,36], or its economic implications [37,38]. Accordingly, this research aims to fill that gap by providing a comprehensive examination of the impact of the Russia–Ukraine conflict on food security in Europe, including the potential risks and challenges that may arise, as well as potential strategies for mitigating those risks. By providing this information, we hope to contribute to a better understanding of the complex relationship between conflicts and food security in Europe and beyond.

While food security is only one aspect of the consequences of the war, it is a critical one that affects the well-being of millions worldwide. Therefore, the focus on the impact of the war on food security is vital because it highlights the urgent need for measures to address these issues. It is also worth noting that food security is interconnected with other aspects of the war's consequences, such as inflation, poverty, and social instability. Therefore, by addressing food security, it is possible to have positive ripple effects on other aspects of the conflict's consequences.

The impacts of the war exhibit regional variability and may even differ among countries within the same region. Other regions of the world that may be more seriously affected by the impact of the war on food security, such as the Middle East and the North Africa (MENA) region [39], might have different dynamics and factors at play that require different policy interventions. To better grasp the far-reading and multifaceted effects of the war on the global food system, it is paramount to have analyses relating to developing and developed countries (e.g., the European Union). By focusing specifically on the impact of the Russian–Ukrainian conflict on food security in Europe, the paper provides targeted policy recommendations tailored to the region's specific context and challenges. In the context of the conflict, it is crucial to consider the unique dynamics and factors in each area to develop effective solutions.

In the following sections, we will introduce the research methodology (Section 2), followed by the presentation of the study findings in Sections 3 and 4. Next, we will examine and discuss these findings before presenting the major conclusions.

2. Materials and Methods

A specific search strategy and an article selection criterion are incorporated into the methodology (Figure 1). The article draws upon both the scholarly literature and the grey literature. In both cases, strict and well-defined inclusion criteria were used so that only documents that deal with the war in Ukraine and its impacts on food security (and its different pillars) were considered eligible and included in the present review. As for the scholarly literature, we used forward and backward searches on the most important databases, namely Scopus, Web of Science, and Google Scholar, which is the most effective way to find peer-reviewed literature (individually or Boolean combined). Figure 1 contains the search string used, focusing primarily on "food security", Ukraine, war, and Europe. For instance, in the case of the Web of Science, the search returned 18 documents [12,17,23,40–54]. The terms were chosen to capture the broadest range of the literature relevant to our research question. Using multiple databases and a combination of search terms ensured that we identified a comprehensive and diverse range of the literature on the topic, which was then carefully evaluated for relevance, eligibility, and quality. This approach enabled us to identify the most relevant and recent literature on the impact of the Russia–Ukraine conflict on food security in Europe.

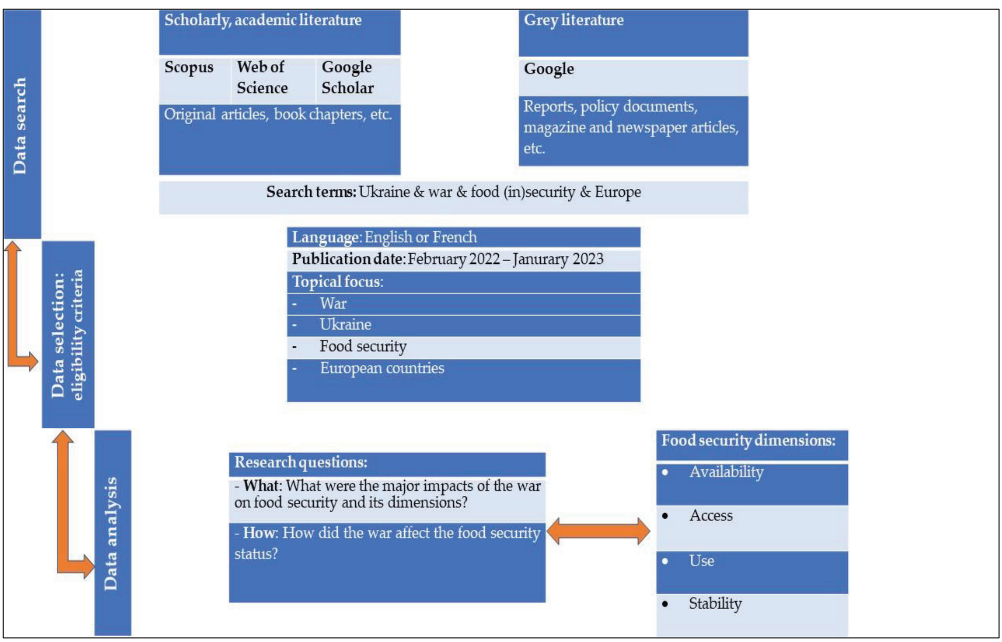

Figure 1. Data search, selection, and analysis. Source: authors' elaboration.

The grey literature was located using Google and included reports, policy documents, magazine and newspaper articles, and technical and working papers produced by regional and international organizations (e.g., Food and Agriculture Organization of the United Nations (FAO), World Food Program (WFP), World Bank, Organization for Economic Cooperation and Development (OECD), World Economic Forum (WEF), European Commission, European Council, European Committee of the Regions, European Parliament (EP), European Investment Bank), Agricultural Market Information System (AMIS), Food Security Portal, consulting firms (e.g., McKinsey, Boston Consulting Group, KPMG, etc.), and international newspapers and news platforms (e.g., Food Business News, Geneva Environment Network, Bloomberg, Deutsche Welle, Euronews, Financial Times, The Guardian).

This method enabled us to collect a broad range of information from various sources, including government reports, news articles, and other pertinent documents that give a thorough knowledge of the effect of the Russia–Ukraine conflict on food security in Europe.

In accordance with the definition of food security, the analytical approach adopted in this research considers all four dimensions: availability, access, use, and stability [55]. The study aims to comprehensively analyze how the conflict has affected food security in Europe by assessing the various factors contributing to food insecurity. This includes evaluating the impact on food production, distribution, and consumption, as well as the stability of the food supply chain. Additionally, the research also examines the various strategies that have been implemented to mitigate the effects of the conflict on food security and assesses their effectiveness. Overall, the analytical approach adopted in this research aims to provide a comprehensive understanding of the impact of the Ukrainian conflict on food security in European countries.

3. Results and Discussion

In this section, we first analyze the threats posed by the war in Ukraine and other disruptions to food security and its pillars (viz. availability, access, utilization, and stability) before analyzing how the European Union can reshape and reconfigure its food system in order to ensure food security for its population amid the war crisis.

3.1. Threats Posed by War and Other Disruptions to Food Security

The conflict between Russia and Ukraine has undermined important food security tenets. Wars and military conflicts put countries at risk of international trade disruptions, particularly those that depend on imports of critical commodities such as oil and food [16]. Armed conflicts may negatively impact food security by generating shortages of upstream and downstream outputs, hurting food production, commercialization, and stock management [56]. War and violence continue to be the primary cause of hunger, with 60% of the world's hungry population residing in regions affected by conflict. Further, in today's globalized world, military conflicts may exacerbate food insecurity in regions beyond the battlefield [35]. Due to wars, a country's agricultural production can be drastically reduced if crops cannot be planted, weeded, or harvested [57].

Farmers in Ukraine's conflict-prone areas lost livestock, food supplies, and other assets, disrupting food market supply in these and other surrounding regions and neighboring countries. The destruction of civil infrastructure and the presence of mines and Unexploded Ordnances (UXOs) coupled with limitations on the movement of people and goods have made it difficult for farmers to tend to their fields, harvest their crops, and sell their livestock products [58]. Additionally, with conscription and population displacement, there was a significant labor shortage. Fertilizers and other critical agricultural inputs are becoming more limited, exacerbating the situation [15]. Further, the conflict-affected regions, such as Kherson and Zaporizhzhia, account for a significant portion of Ukraine's pre-war output, with 25% of barley, 16% of sunflower seed, 20% of rapeseed, and 20% of wheat [59]. According to assessments, the conflict would cost farmers and agricultural corporations USD 28.3 billion this year in lost income, damage to farming machinery, equipment, storage facilities, livestock, and crops, and increased transportation costs [60].

The conflict's effects on global issues are too early to be determined, but it is evident they will be multifaceted [61]. The conflict has prompted widespread international concern over a global food crisis and its potential effects on food security (Figure 2). Indeed, a growing body of the literature shows that the war has affected food security at different levels and scales [12,17,23,40–54], especially in developing countries that rely on food imports [12,42,44,45,51] and for some commodities such as wheat [47,52,53]. However, it seems that the impacts of the war have not been alike on the four pillars of food security. Furthermore, the extent of the war's impact on the food security pillars will be determined by its length and the outcomes of the different scenarios.

Figure 2. Ukrainian–Russian conflict and its consequences on food security pillars. Source: developed by the authors.

3.1.1. Availability

First and foremost, food security requires a sufficient amount of food needs to be available regularly. It focuses on determining what calories are available nationally or at the individual level (e.g., cereals or animal proteins), including the adequate supply of nutritional foods [55].

Ukraine has long been renowned as "Europe's breadbasket" because of its abundance of "Chernozem", or black soil, considered the most fertile farmland in the world, and has a high producing potential. Ukraine's agricultural land area totals 41 million hectares, with 33 million hectares being arable, the equivalent of one-third of the EU's total arable land area [62]. A significant fall in agricultural production and supply followed the collapse of the Soviet Union in the early 1990s and Russia and Ukraine became net importers of food [63]. However, Russian and Ukrainian agro-food output and exports have expanded considerably during the last three decades due to intense modernization and automation, making the region the world's breadbasket [19]. In 2021, Russia and Ukraine exported nearly 12% of the food calories traded globally, making them essential actors in the global agri-food sector [23]. They are significant producers of staple agro-commodities such as wheat, corn, and sunflower oil and Russia is the largest exporter of fertilizers in the world. Further, Ukraine is one of the top three grain exporters, leading the world in soybean and sunflower oil exports. Ukraine controls 52.2% of the global sunflower oil market. Ukrainian agricultural exports have acquired a rising reputation in China, Egypt, India, Turkey, and the European Union [64].

Figure 3 shows that in 2021, Ukraine and Russia combined trade accounts for over 34% of world wheat, 17% of corn, 27% of barley, and over 80% and 55% of sunflower cake and oil, respectively. The global trade in vegetable oils and food calories amounts to 10% and 11.80%, respectively. Furthermore, Russia exports 16% of fish (Alaska pollock), 13% of mineral fertilizers such as ammonia, phosphate rock, sulfur, and 16% of finished fertilizers [4].

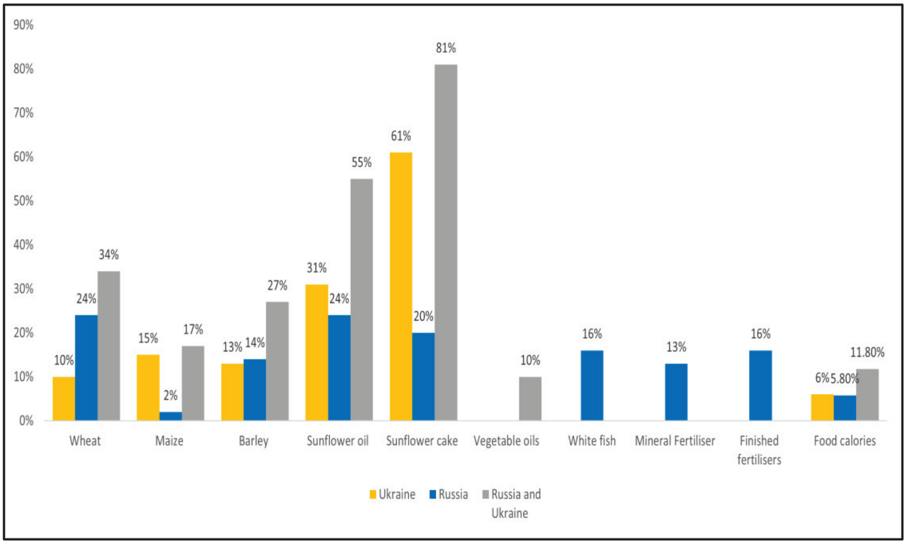

Figure 3. The proportion of Ukraine and Russia's combined global exports in 2021. Source: authors' estimations based on FAO [18] and AMIS market monitor data [65].

As a result of Russia's invasion of Ukraine, global markets were disrupted. Short-term disruptions in global grain supply and long-term effects on natural gas and fertilizer markets negatively impacted producers during the planting season. This disruption might exacerbate already high food price inflation, posing a significant threat to low-income net food importers, many of whom have suffered a rise in malnutrition rates due to the pandemic disruptions [4].

The European Commission [17] predicted that up to 25 million tons of wheat would need to be substituted to meet global food demands for the current and upcoming seasons. The Black Sea Grain Initiative's inception and renewal, as well as measures to enhance export capacity through non-marine channels, have assisted in easing Ukraine's strict export restrictions brought on by the shutdown of Black Sea ports at the onset of the conflict [23]. Over 9.3 million metric tons of grains, oilseeds, and other products have been shipped under the deal as of 28 October 2022. The agreement enables Ukraine to quadruple its exports above the pre-deal level, albeit it still functions at 50% of its pre-war 2021 level. Even while the deal did not completely address the problems with food exports from the conflict zone, it significantly relieved the strain on the existing markets and Ukrainian farmers who were unable to transport their commodities [66]. Consequently, Ukraine is expected to export 39.5 million tons of grain and oilseeds in 2022–23, while the country's entire export potential is between 55 and 60 million tons [59]. Ukraine's exports and grain production decreased by around 40% and 30% in 2022 compared with 2021. The decline in the wheat, maize, and sunflower harvests is estimated to be approximately 40–50%, 25%, and 35%, respectively, compared with 2021 [67].

Further, some issues will impact the 2023 harvest due to rising seed, transport, and fuel costs combined with low grain selling prices [68]. For instance, the transportation costs to ports have increased by over 100%, and the substitute option, which involves truck transport to Romania, costs nearly four times as much [69]. Accordingly, the sowing of winter wheat has decreased by 17% compared with the harvested area of 2022, while the estimated area for maize cultivation is reduced by 30% to 35% [67]. As a result, in 2023, Ukraine's grain production and exports are anticipated to diminish by 20% and 15% compared with 2022. The grain exports may decline even more to 15 MT during the 2023/2024 season, a significant drop from the 54.9 MT recorded in 2019–2020 and 44.9 MT in 2020–2021 [67]. Additionally, despite reports that Russian food exports have persisted, there are fears that access to banking services required to execute foreign transactions may have hindered exports [23].

Furthermore, as was evident during the 2007–2008 food crisis and the COVID-19 pandemic, many nations imposed export bans to ensure the availability of local foods and to reduce inflation (e.g., India for wheat; Serbia for grains and vegetable oils; Indonesia for palm oil), which exacerbates the situation [70]. Indeed, growing protectionism exacerbates the war's impact on global food markets. Around 17% of total global food and feed exports (on a caloric basis) were impacted by export restrictions at their height in late May 2022. After May, many nations relaxed the restrictions to some degree: midway through July, it dropped to 7.3% of total trade being impacted and stayed relatively constant for the remainder of 2022. According to IFPRI's Food and Fertilizer Export Restrictions Tracker, 32 countries implemented a total of 77 export restrictions in 2022. These limits included export license requirements, export taxes or duties, outright bans, or some combination of measures [71]. As of December 2022, 19 countries had imposed 23 food export bans, while 8 had adopted 12 export restriction measures [25]. These actions can potentially have severe unintended consequences for vulnerable populations in food-importing countries, boosting prices and deepening food insecurity issues already aggravated by the COVID-19 pandemic [40,72]. Export limitations exacerbated severe deficits during the food crisis of 2007–2008, which led to riots across Asia and Africa [73].

In Europe, the food supply is not jeopardized since most European countries benefit from well-developed agricultural production. Except for tropical items (such as fruit, coffee, and tea), oilseeds (particularly soya), and natural fats and oils (including palm oil), the EU is self-sufficient in most food products [74]. The EU is generally self-sufficient in essential agricultural crops, including wheat and barley (which it is a net exporter of), maize, and sugar. The EU is also self-sufficient in a variety of animal products, including dairy and meat products, as well as fruits and vegetables [5]. Although Russia's Ukraine conflict and climate change affect output, the EU's food system remains robust and reliable. However, essential goods, such as animal feed, are net imported by the European agricultural industry. Due to this vulnerability and the high input costs, such as those for energy and fertilizers, farmers face productivity challenges and risk having food prices rise. This would reduce access to and availability of food [28]. Indeed, the substantial dependence of some European nations on the Russian energy supply makes it hard to avoid price increases on essential items such as food [29]. Ukraine was a key exporter of corn to Euro countries before the start of the conflict, accounting for 42% of EU grain imports in 2019, 30.5% in 2020, and 29.1% in 2021. Vegetable fat and oil imports from Ukraine were also significant, making up about 24% of EU imports between 2019 and 2021 before the crisis. Meanwhile, before the conflict, Russia accounted for approximately one-fifth of EU inorganic fertilizer imports. With the extensive usage of fertilizers in the EU, this may be destabilizing [29].

Some countries, such as Spain, are more vulnerable than others due to their high dependence on imports from Ukraine. The Spanish agricultural industry was already dealing with a significant increase in energy and other input costs, as well as a lengthy period of drought. The invasion of Ukraine is causing challenges in industries such as animal husbandry, the food industry, and food retailing. Indeed, Spain is a significant global pork exporter (China's largest pig meat supplier), but pigs need a large quantity of grain and oilseed to reach marketable weight. However, it also has a structural shortage of grains [75]. Accordingly, Spain is a net importer of cereals, with Ukraine accounting for a significant portion of its imports. Ukraine is one of Spain's most important agricultural trading partners, accounting for over 30% of its corn imports and 70% of its sunflower oil imports in 2021 [29]. In the same year, Spain bought 18.4% of its total cereals purchased on foreign markets from Ukraine, valued at EUR 545 million. This makes Ukraine its second biggest trade partner after Brazil. In the case of corn, an essential item for animal feed, Ukraine accounted for more than 30% of total imports, accounting for 2.4 million tons worth EUR 510 million [75].

3.1.2. Accessibility

This pillar comprises variables that measure infrastructures for bringing food to market, individual indicators of people's access to calories, and affordability of purchasing nutritional food. Accordingly, market disruption and rising inflation may put the food accessibility pillar in jeopardy [55]. Due to the Ukraine–Russia war, it will become even more difficult for some European low-income households to afford food.

As explained above, the food supply in the EU is not jeopardized since most European countries benefit from well-developed agricultural production. Indeed, the EU is a significant producer of agri-food products—it was the world's largest trader in 2021—and, although Russia's conflict in Ukraine and climate change affect output, the EU's food system remains robust and reliable. However, inflation and increased food prices affect EU citizens [76]. The steep rise in energy prices following the conflict impacts agriculture, an energy-intensive industry. Additionally, despite the recent price drops, the cost of fertilizers and other energy-intensive goods has remained high due to the war. Increased input costs translate into higher production expenses, thus raising food prices [23]. Accordingly, accessibility and affordability are the main consequences of the conflict on food security, especially for low-income and vulnerable populations that are disproportionately impacted [76].

On average, Europeans face lower rates of undernourishment, hunger, and food insecurity than the rest of the world [77]. However, in 2021, 7.3% of the EU's total population and more than one-sixth of the poor could not afford a meal containing meat, fish, or a vegetarian equivalent every other day. This proportion varied from 22.4% in Bulgaria to less than 2.0% in Cyprus (0.4%), Ireland (1.6%), Sweden (1.6%), and the Netherlands (1.8%). Among those at risk of poverty, the share was 17.4% [78].

According to Eurostat [79], the European Union's statistics agency, annual inflation in the Eurozone is predicted to be 9.2% in December 2022, down from 10.1% in November. When it comes to the main components of eurozone inflation, energy is expected to have the highest annual rate in December (25.7% compared with 34.9% in November), followed by food, alcohol, and tobacco (13.8% compared with 13.6% in November), and non-energy industrial goods (6.4% compared with 6.1% in November). It dipped slightly lower for the first time since June 2021. However, it remains in the double digits as increasing food costs and hefty energy bills continue to strain budgets. They will continue to have an impact on European consumers' purchasing power.

Since November 2021, energy and food have been the primary contributors to consistently high monthly inflation. Since the Spring of 2022, the situation has deteriorated due to market interruptions caused by the conflict in Ukraine. The Baltic countries continue to be the most affected. For instance, in November 2022, inflation in Latvia was at 21.7% compared with 7.4% a year ago, making it the highest rate in the Eurozone. Inflation in the UK unexpectedly climbed to 11.1% in October 2022, the highest level since 1981. Despite a government cap, the cost of energy and gas increased by 24% year over year, while the price of food increased by 16.4%, contributing significantly to the overall rise [80]. Even though inflation affects countries differently throughout the EU, lower-income families are the most impacted in all member states. According to the European Parliament's Eurobarometer study [81], the major concern for European citizens is "increasing living costs" (93%), followed by "poverty and social exclusion" (82%).

Moreover, inflation caused by the conflict might cut private consumption by 1.1% in the European Union in 2022. However, the effect would vary by country. The impact will be felt more acutely in nations where consumption is more sensitive to energy and food costs and where a sizable proportion of the population is vulnerable to poverty. Central and south-eastern European countries are disproportionately impacted [82]. Europeans continuously feel the strain of the rise in food prices and the high inflation rate. As a result, many European citizens are losing buying power of necessary commodities. For instance, even Germany, which has solid domestic production and does not rely much on Ukrainian exports, is very susceptible to escalating inflation, driven mainly by the rising cost of Russian energy and fertilizer [29]. In November 2022, Germany's consumer price index (CPI) year-over-year change was 10.0%. This was a modest decrease in the inflation rate from the +10.4% seen in October 2022. In November 2022, food prices increased by 21.1% compared with November 2021. This inflation rate is more than twice as high as the rate of general price inflation. The annual rate of inflation for food has been steadily climbing since January (October 2022: +20.3%). In November of 2022, prices increased across the board for all types of food. Edible fats and oils had the most significant price increase at 41.5%; dairy products and eggs increased by 34.0%; bread and cereals increased by 21.1%; vegetables increased by 21.1% [83] (Figure 4).

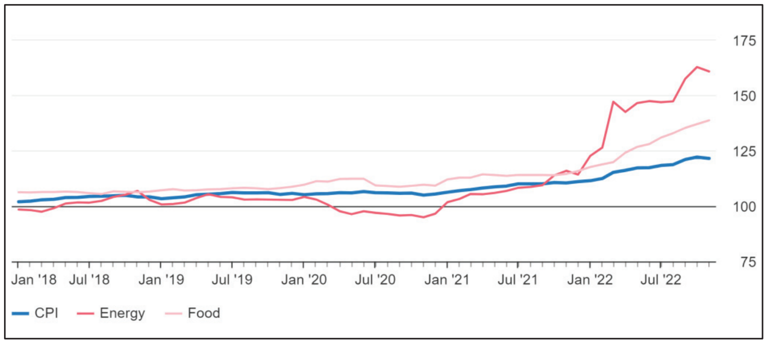

Figure 4. Consumer price indices in Germany (2015 = 100). Source: German Federal Statistical Office [83].

In Spain, cereals and animal feed supply shortages from Ukraine directly impact producer pricing as the production of pigs is heavily reliant on grains and corn supplied from Ukraine. In this industry, inflation is also harming livestock farmers' profitability. Although producers attempt to agree with shops to decrease finished items' prices, meat prices will undoubtedly rise due to import constraints of wheat and corn finished items' prices and meat prices will undoubtedly rise due to import constraints of wheat and corn [29].

For instance, Hungary is emerging as a new inflation hotspot due to the highest food price hikes among the EU's member states [84]. Despite producing most of the grain supplies it needs domestically, Hungary imports little wheat from Russia or Ukraine. However, the disruption in global value chains is reflected in increased food prices. Further, similar to other EU nations, Hungary is impacted by fertilizer supply problems caused by halted exports from Russia, the world's largest supplier. This situation is exacerbated by businesses' difficulties in sustaining their production capabilities as energy costs climb [29]. Accordingly, during November 2022, food price increases were 40% more than the EU average. Bread, cheese, and eggs have all seen price increases of over 90% from the same time in 2021, with egg costs increasing by over 92%. Consequently, the government has indicated it would add eggs and potatoes to the list of five items for which price controls will be implemented [84].

The persistent and significant uncertainty surrounding the ongoing high inflation raises the question of how these affect European households' finances, purchasing power, and socio-economic situation. Rising energy and food prices are already generating high societal costs in terms of decreased buying power and are anticipated to exacerbate material deprivation, poverty, and social exclusion throughout the EU [31]. It is estimated that in 2021, 95.4 million people in the EU (21.7% of the population) were vulnerable to poverty or social exclusion (livelihood poverty, extreme material and social deprivation, or living in a household with low labor intensity) [85]. The ongoing inflation imposes significant welfare and social costs on European society. The socio-economic ramifications of the current situation are notably unequal throughout the EU, owing to considerable disparities in price trends and spending patterns among member states and demographic divisions. Prospects are especially bleak in several central and eastern European nations, where low-income families and vulnerable groups (such as large households, rural populations, children, and the elderly) face heightened financial difficulty and social exclusion risks. At the EU level, inflation has raised the cost of living for median families by around 10%, the incidence of material and social deprivation by approximately 2%, and the rate of energy poverty and absolute monetary poverty by about 5%. The related welfare consequences are predicted to be several times greater in selected member states and among vulnerable populations, presumably widening existing inequalities in poverty and social exclusion throughout the EU [31].

Consequently, food bank use is rising throughout Europe, as the region's poorest, who spend a more significant percentage of their income on energy and food, are struck the hardest by the region's most tremendous inflation in a generation. Charities from Spain to Latvia estimate a 20% to 30% rise in demand over last year, with a further increase expected this winter. People accessing the national food bank in Bulgaria, one of the poorest nations in the EU, increased by three-quarters between September and October 2022 [86]. However, in many countries, the organizations that manage the food banks face increased operational expenses, which endangers their operations. For instance, food banks in Germany are busier than ever, with empty shelves, high pricing, and more people in need. There is also a scarcity of donations and volunteers [87]. In the UK, donations to food banks are declining due to rising living costs, but demand increases as inflation continues to increase and people have difficulty buying vital food products. Amid a cost-of-living crisis, when more than a quarter of all UK households report struggling financially, families' priorities are saving money for food shopping needs. Contrarily, more than half of food bank donations have dropped [88,89]. Furthermore, people oppose cost-of-living raises using various means, including street protests and strikes, in several nations [90].

3.1.3. Utilization

This pillar tracks anthropometric and other measures of people's ability to use calories; related measures include wasting, stunting, and low weight among children. Russia's war in Ukraine harmed the food utilization pillar, resulting in a lack of nutritional variety and malnutrition.

In addition to the 780 to 811 million people who experienced chronic hunger in 2020, FAO predicts that, in 2022 and 2023, there will be an additional 7.6 million to 13.1 million undernourished people due to Russia's war in Ukraine [18]. The nutritional variety substantially impacts EU citizens' health [26]. Since healthy variety or dietary diversity is a fundamental requirement for people to obtain all essential nutrients, it can be used as one of the core indicators for examining food habits and the productivity of people. Hence, chronic hunger in the EU is associated with undernourishment, indicative of a productivity decline.

3.1.4. Stability

When the previous three pillars are in order, this pillar ensures the stability of supply and access over time [91]. The main issues impeding the stability pillar of food security are higher energy prices, rising interest rates, and political turmoil. As a result of higher food and energy prices, farmers from competing nations, such as the United States and Brazil, may cover any supply shortages created by the war in Ukraine. However, higher energy prices make some food products, mainly corn, sugar, and oilseeds/vegetable oils, more appealing for bioenergy production, such as ethanol or biodiesel. This could raise food prices to their energy parity equivalents [23].

Meanwhile, the increased costs and shortages will significantly impact food assistance for vulnerable nations. According to estimates from the World Food Program (WFP) [92], 45% of the population in Ukraine is already concerned about having enough to eat. Furthermore, higher and unstable energy prices were also observed, particularly for natural gas, which is essential for fertilizer production [93]. Due to several factors, including weather-related interruptions to the supply of coal and renewable energy, prices have been increasing significantly since 2021 [7].

Since the outbreak of the Ukrainian conflict, Europe's economic growth forecasts have been lowered downward, while inflation forecasts have risen. Most current predictions, which account for increased uncertainty and commodity price shocks, indicate that real GDP growth in the European Union might fall far below 3% in 2022, a drop of more than 1.3 percentage points from pre-war expectations. Additional supply chain disruptions and economic penalties are expected to send the European economy into a recession [82]. There has already been a substantial economic impact on European consumers due to Russia's invasion of Ukraine, posing political risks to incumbent governments. Rising inflation, higher food prices, and food insecurity result in protests and strikes across Europe, underscoring growing discontent with skyrocketing living costs and threatening political turmoil.

As of January 2023, the slowdown in the global economy and fears of a worldwide recession have contributed to a general lowering of commodity prices. Nevertheless, commodity prices remain high relative to historical averages, extending the challenges connected with food security. Lower input costs, especially for fertilizers, are expected to contribute to a 5% drop in agricultural prices in 2023. Despite these forecasts, prices are projected to stay higher than pre-pandemic levels. As a result, global inflation will remain high in 2023 at 5.2% before decreasing to 3.2% in 2024. Although inflation is expected to decline gradually during 2023, underlying inflationary pressures may become more persistent [25]. According to the International Monetary Fund [94], global food prices are anticipated to stay high due to conflict, energy costs, and weather events, despite interest rate rises marginally easing pricing pressures.

Although the European Central Bank has increased interest rates to combat inflation, it also anticipates that consumer prices will rise further. Additionally, the depreciation of the euro and the pound versus the US dollar has placed further pressure on manufacturers and merchants who must pay their suppliers in US dollars and numerous nations are now facing a possible recession [90].

3.2. Reshaping EU Food Security Amid the War Crisis

In response to Russia's invasion of Ukraine, the European Parliament adopted a comprehensive resolution on 24 March 2022, endorsing many of the initiatives included in the European Commission's package and calling for an urgent EU action plan to secure food security both inside and outside the EU [95]. EU leaders endorsed short-term and medium-term measures at the state levels to protect food security and strengthen the resilience of food systems. Most actions may be carried out using the Common Agriculture Policy (CAP). The EU members emphasized the importance of maintaining food supply security and took some immediate actions (Box 1).

Box 1. Prompt action from the European Union to maintain food safety and build a resilient food system [96–99].

- EU farmers support a package worth EUR 500 million to safeguard food security and strengthen the resilience of food systems.
- Reduction of energy import dependency and price shocks through REPowerEU plans.
- Maintaining the EU single market by avoiding restrictions and bans on exports.
- The Fund for European Aid to the Most Deprived (FEAD) provides food and essential material support worth EUR 3.8 billion.
- Using the new CAP strategic plans to decrease reliance on gas, fuel, and inputs such as pesticides and fertilizers.
- A unique and temporary exception to enable the cultivation of any crops for food and feed on fallow land while farmers retain the full amount of the greening payment.
- Specific temporary exemptions from current animal feed import regulations.

Sources: [96–99]

The conflict is pushing food security challenges to the brink of a global crisis. As the war continues, several scenarios could affect food security in the EU. The EU food system is typically vulnerable due to fertilizer import dependency, unreliable grain markets, and high energy prices. In addition, these factors further exacerbated food insecurity during the war [100].

Further strategies are needed to safeguard food security and bring resilience to the food system. The war has exposed the global food system's fragility, emphasizing the significance of rebuilding the food system to strengthen resilience to future shocks, crises, and stressors [101]. As shown in Figure 5, several approaches are required, such as increasing food aid, ensuring fertilizer supply, imposing an energy price cap, initiating a farmer support package, switching to renewable energy sources for cultivation, changing individual food behaviors, lifting a trade ban, and political stability.

Figure 5. Actions for ensuring food security and strengthening food system resilience. Source: developed by authors.

The food availability pillar has been jeopardized during Russia's armed confrontation with Ukraine. As a result, the EU needs enough fertilizer at a reasonable price to make agricultural production more efficient to safeguard the food availability pillar. Maintaining equity in fertilizer access is a powerful lever for reducing food insecurity concerns in the short term. In the longer term, fair fertilizer usage must be supplemented with efforts to guarantee sustainable fertilizer use, ecosystem protection, and emission reductions [102]. However, export restrictions and bans must be avoided to preserve the EU single market. This will allow the EU and vulnerable countries to maintain a secure food supply.

Food insecurity is the inability to consistently obtain adequate food to maintain an active and healthy lifestyle. On the contrary, food security can be established only through easy access to food, which the war has already impacted. The EU member states should impose a price cap on food to prevent adverse effects from market anomalies. Consequently, food would be more affordable and accessible to the EU people. In addition, the government needs to increase food aid to support the most vulnerable citizens in the EU. Furthermore, price caps can reduce inflation rates in the EU, which can promote food accessibility.

Several measures can be taken to ensure food utilization, including minimizing food waste and loss, eating a healthy diet, or recycling food. Foods derived from plants are transformed into culinary creations that satisfy hunger, provide nutrients, and alleviate obesity. Indeed, adopting plant-based diets across Europe may boost food resilience in the face of the Russia–Ukraine war [27].

Households must always have access to adequate food to be food secure. In case of a sudden shock, such as a climatic or economic crisis or a war, they should not risk losing access to food. The armed conflict involving Russia in Ukraine impacts food stability in the EU and beyond. This situation requires a reduction in the interest rate to reduce food import prices and a reduction in Value-Added Tax (VAT), which is an alternative solution. Energy price caps protect consumers who default on basic energy tariffs from their suppliers. Putting a cap on energy prices ensures that businesses and individuals will pay a fair price, limiting food inflation, import costs, and retail prices.

The significant trade-related impact of the war causes an increase in commodity prices. Indeed, energy, food products, and metals are three major commodities impacted by the war. Consequently, the significant price hike affects global markets and supply chains. Furthermore, commodity price hikes coupled with higher inflation rates on a global scale could result in changes in demand because people are unable or unwilling to make the usual food purchases.

In the context of the Russia–Ukraine war, to enhance the resilience of food systems against future crises, we have outlined five key initiatives that will help global policymakers, governments, and researchers to minimize the impact of food insecurity in the EU:

1. Food prices will rise due to higher energy costs since fertilizers and transportation costs will also increase. As a result, renewable energy sources must be adopted by EU farmers to lower the cost of agricultural output.
2. The governments in the EU should impose an energy price cap to stagnate price volatility. For instance, the Hungarian government has set energy and food price caps amid soaring inflation.
3. Monetary policy should remain on track to restore price stability, while fiscal policy should strive to reduce cost-of-living pressures while remaining appropriately restrictive in line with monetary policy [31].
4. The war might also cause further disruptions to global supply chains, making international trade even more challenging. Export restrictions and bans should be avoided to preserve the EU single market.
5. The war may have political repercussions as well. For instance, increased energy costs could result in instability and violence in society and politics. Therefore, EU leaders must provide adequate food aid to their citizens.

Furthermore, in the short term, measures aimed at preserving and expanding trade routes from Ukraine, enabling greater food production in vulnerable countries, and reducing harmful consumption in the EU are most adapted to addressing the present issues. Although, the food crisis causes immediate concerns, it also highlights systemic issues in the European and global food systems. As highlighted by Galanakis [14] "The pressing challenges induced by climate change, global warming, the COVID-19 pandemic, and the Russian-Ukrainian war merge to conclude that the food sector needs an urgent transformation toward sustainability and resilience."

While short-term solutions may mitigate the crisis' negative effect, a long-term and systemic approach is required to strengthen its resilience [102]. As the European Commission [103] outlined, improving resilience through minimizing European agriculture's reliance on energy, energy-intensive imports, and feed imports is more critical than ever. Resilience necessitates diverse import sources and market outlets through a solid global and bilateral trade strategy. Consequently, the Commission has asked member states to consider revising their Common Agricultural Policy (CAP) strategic plans to boost the sector's resilience, increase renewable energy output, and decrease reliance on synthetic fertilizers via more sustainable production methods [103]. Overall, addressing food security challenges in Europe requires a comprehensive approach that involves improving domestic food production, reducing dependence on food imports, reducing food waste, shifting to more sustainable diets, and increasing international cooperation while diversifying trade partnerships.

4. Conclusions

Food systems in Europe are facing several environmental, economic, social, and health issues. Research that straddles disciplines and innovates at their intersections is required to effectively address them. This paper aimed to assess the possible impacts of the war between Russia and Ukraine on food security in European countries. The review suggests that the implications of war varied among the food security pillars. However, the prolonged repercussions of the Russian–Ukraine conflict on fertilizer prices will influence domestic food production by making fertilizers less available and more expensive. As energy costs and interest rates in the EU continue to climb, food importers will find it considerably more challenging to fund the cost of food imports, affecting domestic food prices and, consequently, food accessibility and affordability across the EU. The impacts on food availability and accessibility can have long-term implications regarding food use (e.g., dietary diversity) and food system stability and resilience. Indeed, high inflation, trade restrictions, food price hikes, shortages of fertilizer, and political turmoil can directly impact the EU's food security pillars.

The paper contributed to the literature on food security and the war effect by shedding light on the following facts: (1) lack of fertilizer supplies (determining their price increases), higher energy prices, trade restrictions, and bans, as well as rising inflation rates increase food prices and affect the availability and accessibility of food; (2) increasing food price caps and food aid and limiting the inflation rate can improve food accessibility; (3) it is possible to protect the food utilization pillar by eating a nutritious diet, diversifying diet, and promoting food recovery and distribution; (4) social and political unrest and turmoil can be controlled by lowering interest rates and imposing energy price caps, which secure food stability pillar.

Further, by adopting a comprehensive analytical approach that considers all four dimensions of food security, this research has provided a thorough understanding of how the prolonged Russian–Ukrainian conflict has affected food security in Europe. By assessing the various drivers and factors contributing to food insecurity, the study has identified the key challenges facing the food systems in Europe. Furthermore, addressing these complex challenges requires innovative interdisciplinary research that straddles the boundaries of different disciplines and innovates at their intersections. This approach can lead to new knowledge, solutions, and strategies that can help to ensure the sustainability, resilience, and inclusivity of the food systems in Europe. Moreover, the impact of the conflict on food security may vary across different regions and countries in Europe, depending on their level of dependence on agricultural imports, their capacity to produce food locally, and their vulnerability to food price shocks. This variability adds to the uncertainty in predicting the impact of the conflict on food security in Europe.

Furthermore, the study highlights the importance of developing effective and efficient policy solutions based on a shared understanding of the complex and interconnected nature of Europe's food security concerns in the context of the war. This might include adopting a unified strategy for data collection, analysis, and sharing, as well as enacting policy actions adapted to the individual requirements of the impacted regions and individuals. This study contributes to the theoretical development of policies that promote sustainable and resilient food systems, especially in the face of prolonged wars and other geopolitical issues, by emphasizing the need for inter-European collaboration.

This paper does have some limitations. One of the main limitations is the high level of uncertainty, since the impacts of the war depend not only on the evolution of the conflict but also on the responses of the EU and single member states. Russia's current approach to the conflict in Ukraine will likely prolong the war over the next few years and Europe's ability to survive a food crisis will be pushed to its limits. The EU will have a more robust long-term stance toward Russia if it can continue to be united and successfully coordinated. Although we have suggested risk-reduction methods, resolving the situation would necessitate a thorough re-assessment of the EU's food security and agri-food systems over the following years.

Author Contributions: Conceptualization, M.F.R. and T.B.H.; methodology, M.F.R., T.B.H., H.E.B. and A.R.; validation, M.F.R.; formal analysis, M.F.R., H.E.B. and A.R.; writing—original draft preparation, M.F.R., T.B.H. and H.E.B.; writing—review and editing, M.F.R., T.B.H., H.E.B., A.R. and D.R.; visualization, M.F.R.; supervision, H.E.B. and A.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Vos, R.; Glauber, J.; Hernández, M.; Laborde, D. COVID-19 and Rising Global Food Prices: What's Really Happening? Available online: https://www.ifpri.org/blog/covid-19-and-rising-global-food-prices-whats-really-happening (accessed on 8 December 2022).
2. Rice, B.; Hernández, M.A.; Glauber, J.; Vos, R. The Russia-Ukraine War Is Exacerbating International Food Price Volatility. Available online: https://www.ifpri.org/blog/russia-ukraine-war-exacerbating-international-food-price-volatility (accessed on 10 May 2022).
3. NASA. Brazil Battered by Drought. Available online: https://earthobservatory.nasa.gov/images/148468/brazil-battered-by-drought (accessed on 24 January 2023).
4. Glauber, J.; Laborde, D. How Will Russia's Invasion of Ukraine Affect Global Food Security? Available online: https://www.ifpri.org/blog/how-will-russias-invasion-ukraine-affect-global-food-security (accessed on 8 May 2022).
5. European Parliament Question Time: Food Price Inflation in Europe. Available online: https://www.europarl.europa.eu/RegData/etudes/ATAG/2023/739298/EPRS_ATA(2023)739298_EN.pdf (accessed on 21 January 2023).
6. FAO. Impact of the Ukraine-Russia Conflict on Global Food Security and Related Matters under the Mandate of the Food and Agriculture Organization of the United Nations (FAO). Available online: https://www.fao.org/3/ni734en/ni734en.pdf (accessed on 11 May 2022).
7. Pereira, P.; Zhao, W.; Symochko, L.; Inacio, M.; Bogunovic, I.; Barcelo, D. The Russian-Ukrainian Armed Conflict Will Push Back the Sustainable Development Goals. *Geogr. Sustain.* **2022**, *3*, 277–287. [CrossRef]
8. Boston Consulting Group. The War in Ukraine and the Rush to Feed the World. Available online: https://www.bcg.com/publications/2022/how-the-war-in-ukraine-is-affecting-global-food-systems (accessed on 16 December 2022).
9. KPMG. Ukraine-Russia Sector Considerations: Agriculture. Available online: https://home.kpmg/xx/en/home/insights/2022/05/ukraine-russia-sector-considerations-agriculture.html (accessed on 16 December 2022).
10. Jagtap, S.; Trollman, H.; Trollman, F.; Garcia-Garcia, G.; Parra-López, C.; Duong, L.; Martindale, W.; Munekata, P.E.S.; Lorenzo, J.M.; Hdaifeh, A.; et al. The Russia-Ukraine Conflict: Its Implications for the Global Food Supply Chains. *Foods* **2022**, *11*, 2098. [CrossRef] [PubMed]
11. Ben Hassen, T.; el Bilali, H. Impacts of the Russia-Ukraine War on Global Food Security: Towards More Sustainable and Resilient Food Systems? *Foods* **2022**, *11*, 2301. [CrossRef] [PubMed]
12. Bloem, J.R.; Farris, J. The COVID-19 Pandemic and Food Security in Low- and Middle-Income Countries: A Review. *Agric. Food Secur.* **2022**, *11*, 55. [CrossRef] [PubMed]
13. Galanakis, C.M. The "Vertigo" of the Food Sector within the Triangle of Climate Change, the Post-Pandemic World, and the Russian-Ukrainian War. *Foods* **2023**, *12*, 721. [CrossRef]
14. Foreign Affairs No One Would Win a Long War in Ukraine. Available online: https://www.foreignaffairs.com/ukraine/no-one-would-win-long-war-ukraine (accessed on 18 January 2023).
15. Allam, Z.; Bibri, S.E.; Sharpe, S.A. The Rising Impacts of the COVID-19 Pandemic and the Russia–Ukraine War: Energy Transition, Climate Justice, Global Inequality, and Supply Chain Disruption. *Resources* **2022**, *11*, 99. [CrossRef]

16. Zhou, X.-Y.; Lu, G.; Xu, Z.; Yan, X.; Khu, S.-T.; Yang, J.; Zhao, J. Influence of Russia-Ukraine War on the Global Energy and Food Security. *Resour. Conserv. Recycl.* **2023**, *188*, 106657. [CrossRef]
17. European Commission. *Safeguarding Food Security and Reinforcing the Resilience of Food Systems*; Publications Office of the European Union: Brussels, Belgium, 2022.
18. FAO. The Importance of Ukraine and the Russian Federation for Global Agricultural Markets and the Risks Associated with the Current Conflict. Available online: https://www.fao.org/3/cb9013en/cb9013en.pdf (accessed on 7 May 2022).
19. OECD. Economic and Social Impacts and Policy Implications of the War in Ukraine. Available online: https://www.oecd-ilibrary.org/sites/4181d61b-en/index.html?itemId=/content/publication/4181d61b-en (accessed on 11 May 2022).
20. Rabobank. The Russia-Ukraine War's Impact on Global Fertilizer Markets. Available online: https://research.rabobank.com/far/en/sectors/farm-inputs/the-russia-ukraine-war-impact-on-global-fertilizer-markets.html (accessed on 8 May 2022).
21. Benton, T.; Froggatt, A.; Wellesley, L.; Grafham, O.; King, R.; Morisetti, N.; Nixey, J.; Schröder, P. The Ukraine War and Threats to Food and Energy Security: Cascading Risks from Rising Prices and Supply Disruptions. Available online: https://chathamhouse.soutron.net/Portal/Public/en-GB/RecordView/Index/191102 (accessed on 8 May 2022).
22. FAO. The Importance of Ukraine and the Russian Federation for Global Agricultural Markets and the Risks Associated with the War in Ukraine. *December 2022.* Available online: https://www.fao.org/3/cc3317en/cc3317en.pdf (accessed on 10 December 2022).
23. Hellegers, P. Food Security Vulnerability Due to Trade Dependencies on Russia and Ukraine. *Food Secur.* **2022**, *14*, 1503–1510. [CrossRef]
24. World Bank Food Security Update. January 2023. Available online: https://www.worldbank.org/en/topic/agriculture/brief/food-security-update (accessed on 18 January 2023).
25. World Bank Food Security Update. December 2022. Available online: https://www.worldbank.org/en/topic/agriculture/brief/food-security-update?cid=ECR_LI_worldbank_EN_EXT (accessed on 8 December 2022).
26. Sun, Z.; Scherer, L.; Zhang, Q.; Behrens, P. Adoption of Plant-Based Diets across Europe Can Improve Food Resilience against the Russia–Ukraine Conflict. *Nat. Food.* **2022**, *3*, 905–910. [CrossRef]
27. European Commission Commission. Acts for Global Food Security and for Supporting EU Farmers and Consumers. Available online: https://ec.europa.eu/commission/presscorner/detail/en/ip_22_1963 (accessed on 13 December 2022).
28. European Committee of the Regions Repercussions of the Agri-Food Crisis at Local and Regional Level. Available online: http://www.cor.europa.eu (accessed on 8 December 2022).
29. Tollefson, J. What the War in Ukraine Means for Energy, Climate and Food. *Nature* **2022**, *604*, 232–233. [CrossRef]
30. Menyhert, B. *The Effect of Rising Energy and Consumer Prices on Household Finances, Poverty and Social Exclusion in the EU*; Publications Office of the European Union: Luxembourg, 2022.
31. IMF. World Economic Outlook, October 2022: Countering the Cost-of-Living Crisis. Available online: https://www.imf.org/en/Publications/WEO/Issues/2022/10/11/world-economic-outlook-october-2022 (accessed on 24 February 2023).
32. Lang, T.; McKee, M. The Reinvasion of Ukraine Threatens Global Food Supplies. *BMJ* **2022**, *376*, o676. [CrossRef] [PubMed]
33. Osendarp, S.; Verburg, G.; Bhutta, Z.; Black, R.E.; de Pee, S.; Fabrizio, C.; Headey, D.; Heidkamp, R.; Laborde, D.; Ruel, M.T. Act Now before Ukraine War Plunges Millions into Malnutrition. *Nature* **2022**, *604*, 620–624. [CrossRef] [PubMed]
34. Nóia Júnior, R.d.S.; Ewert, F.; Webber, H.; Martre, P.; Hertel, T.W.; van Ittersum, M.K.; Asseng, S. Needed Global Wheat Stock and Crop Management in Response to the War in Ukraine. *Glob. Food Sec.* **2022**, *35*, 100662. [CrossRef]
35. Lin, F.; Li, X.; Jia, N.; Feng, F.; Huang, H.; Huang, J.; Fan, S.; Ciais, P.; Song, X.-P. The Impact of Russia-Ukraine Conflict on Global Food Security. *Glob. Food Sec.* **2023**, *36*, 100661. [CrossRef]
36. Żuk, P.; Żuk, P. National Energy Security or Acceleration of Transition? Energy Policy after the War in Ukraine. *Joule* **2022**, *6*, 709–712. [CrossRef]
37. Mbah, R.E.; Wasum, D. Russian-Ukraine 2022 War: A Review of the Economic Impact of Russian-Ukraine Crisis on the USA, UK, Canada, and Europe. *Adv. Soc. Sci. Res. J.* **2022**, *9*, 144–153. [CrossRef]
38. Yousaf, I.; Patel, R.; Yarovaya, L. The Reaction of G20+ Stock Markets to the Russia–Ukraine Conflict "Black-Swan" Event: Evidence from Event Study Approach. *J. Behav. Exp. Financ.* **2022**, *35*, 100723. [CrossRef]
39. Al-Saidi, M. Caught off Guard and Beaten: The Ukraine War and Food Security in the Middle East. *Front. Nutr.* **2023**, *10*. [CrossRef]
40. Nchasi, G.; Mwasha, C.; Shaban, M.M.; Rwegasira, R.; Mallilah, B.; Chesco, J.; Volkova, A.; Mahmoud, A. Ukraine's Triple Emergency: Food Crisis amid Conflicts and COVID-19 Pandemic. *Health Sci. Rep.* **2022**, *5*, e862. [CrossRef]
41. Lopes, H.; Martin-Moreno, J. ASPHER Statement: 5 + 5 + 5 Points for Improving Food Security in the Context of the Russia-Ukraine War. An Opportunity Arising from the Disaster? *Public Health Rev.* **2022**, *43*. [CrossRef]
42. von Cramon-Taubadel, S. Krieg Produziert Hunger. *Osteuropa* **2022**, *72*, 13. [CrossRef]
43. Hall, D. Russia's Invasion of Ukraine and Critical Agrarian Studies. *J. Peasant Stud.* **2023**, *50*, 26–46. [CrossRef]
44. Hatab, A.A. Africa's Food Security under the Shadow of the Russia-Ukraine Conflict. *Strateg. Rev. South. Afr.* **2022**, *44*. [CrossRef]
45. Gross, M. Global Food Security Hit by War. *Curr. Biol.* **2022**, *32*, R341–R343. [CrossRef]
46. Behnassi, M.; el Haiba, M. Implications of the Russia–Ukraine War for Global Food Security. *Nat. Hum. Behav.* **2022**, *6*, 754–755. [CrossRef] [PubMed]
47. von Cramon-Taubadel, S. Russia's Invasion of Ukraine–Implications for Grain Markets and Food Security. *Ger. J. Agric. Econ.* **2022**, *71*, 1–13. [CrossRef]
48. Ma, Y.; Lyu, D.; Sun, K.; Li, S.; Zhu, B.; Zhao, R.; Zheng, M.; Song, K. Spatiotemporal Analysis and War Impact Assessment of Agricultural Land in Ukraine Using RS and GIS Technology. *Land* **2022**, *11*, 1810. [CrossRef]

49. Martinho, V.J.P.D. Impacts of the COVID-19 Pandemic and the Russia–Ukraine Conflict on Land Use across the World. *Land* **2022**, *11*, 1614. [CrossRef]
50. Nasir, M.A.; Nugroho, A.D.; Lakner, Z. Impact of the Russian–Ukrainian Conflict on Global Food Crops. *Foods* **2022**, *11*, 2979. [CrossRef]
51. Yazbeck, N.; Mansour, R.; Salame, H.; Chahine, N.B.; Hoteit, M. The Ukraine–Russia War Is Deepening Food Insecurity, Unhealthy Dietary Patterns and the Lack of Dietary Diversity in Lebanon: Prevalence, Correlates and Findings from a National Cross-Sectional Study. *Nutrients* **2022**, *14*, 3504. [CrossRef]
52. Bentley, A.R.; Donovan, J.; Sonder, K.; Baudron, F.; Lewis, J.M.; Voss, R.; Rutsaert, P.; Poole, N.; Kamoun, S.; Saunders, D.G.O.; et al. Near- to Long-Term Measures to Stabilize Global Wheat Supplies and Food Security. *Nat. Food* **2022**, *3*, 483–486. [CrossRef]
53. Carriquiry, M.; Dumortier, J.; Elobeid, A. Trade Scenarios Compensating for Halted Wheat and Maize Exports from Russia and Ukraine Increase Carbon Emissions without Easing Food Insecurity. *Nat. Food* **2022**, *3*, 847–850. [CrossRef]
54. Pereira, P.; Bašić, F.; Bogunovic, I.; Barcelo, D. Russian-Ukrainian War Impacts the Total Environment. *Sci. Total Environ.* **2022**, *837*, 155865. [CrossRef] [PubMed]
55. UN High Level Task Force on Global Food Security. *Food and Nutrition Security: Comprehensive Framework for Action. Summary of the Updated Comprehensive Framework for Action (UCFA)*; FAO: Rome, Italy, 2011.
56. de Paulo Gewehr, L.L.; de Andrade Guerra, J.B.S.O. Geopolitics of Hunger: Geopolitics, Human Security and Fragile States. *Geoforum* **2022**, *137*, 88–93. [CrossRef]
57. Martin-Shields, C.P.; Stojetz, W. Food Security and Conflict: Empirical Challenges and Future Opportunities for Research and Policy Making on Food Security and Conflict. *World Dev.* **2019**, *119*, 150–164. [CrossRef]
58. FAO. Ukraine: Strategic Priorities for 2023. Available online: https://www.fao.org/documents/card/fr/c/CC3385EN/ (accessed on 23 January 2023).
59. USDA. Ukraine, Moldova and Belarus–Crop Production Maps. Available online: https://ipad.fas.usda.gov/rssiws/al/up_cropprod.aspx (accessed on 18 January 2023).
60. The New York Times. Mines, Fires, Rockets: The Ravages of War Bedevil Ukraine's Farmers. Available online: https://www.nytimes.com/2022/08/04/world/europe/ukraine-russia-farms-farming-wheat-barley.html (accessed on 18 January 2023).
61. Bin-Nashwan, S.A.; Hassan, M.K.; Muneeza, A. Russia–Ukraine Conflict: 2030 Agenda for SDGs Hangs in the Balance. *Int. J. Ethics. Syst.* **2022**. ahead of print. [CrossRef]
62. FAO FAOSTAT. Ukraine. Available online: https://www.fao.org/faostat/en/#country/230 (accessed on 23 February 2023).
63. Bokusheva, R.; Hockmann, H.; Kumbhakar, S.C. Dynamics of Productivity and Technical Efficiency in Russian Agriculture. *Eur. Rev. Agric. Econ.* **2012**, *39*, 611–637. [CrossRef]
64. Leshchenko, R. Ukraine Can Feed the World. Available online: https://www.atlanticcouncil.org/blogs/ukrainealert/ukraine-can-feed-the-world/ (accessed on 28 November 2022).
65. AMIS. Market Monitor May 2022. Available online: http://www.amis-outlook.org/fileadmin/user_upload/amis/docs/Market_monitor/AMIS_Market_Monitor_current.pdf (accessed on 10 May 2022).
66. Laborde, D.; Glauber, J. Suspension of the Black Sea Grain Initiative: What Has the Deal Achieved, and What Happens Now? Available online: https://www.ifpri.org/blog/suspension-black-sea-grain-initiative-what-has-deal-achieved-and-what-happens-now (accessed on 10 December 2022).
67. Knowledge Centre for Global Food and Nutrition Security. The Impact of Russia's War against Ukraine on Global Food Security-Impact on Global Agricultural Production and Exports Impact on Ukrainian Production and Exports. Available online: https://knowledge4policy.ec.europa.eu/sites/default/files/Impact%20of%20Russia%20war%20against%20Ukraine%20on%20global%20food%20security_knowledge%20review%206_final.pdf (accessed on 23 February 2023).
68. Reuters Ukraine Farmers May Cut Winter Grain Sowing by at Least 30%–Union. Available online: https://www.reuters.com/article/ukraine-crisis-grain-sowing-idAFL1N30J0CL (accessed on 19 January 2023).
69. The New York Times. How Russia's War on Ukraine Is Worsening Global Starvation. Available online: https://www.nytimes.com/2023/01/02/us/politics/russia-ukraine-food-crisis.html (accessed on 23 February 2023).
70. Glauber, J.; Laborde, D.; Mamun, A. From Bad to Worse: How Russia-Ukraine War-Related Export Restrictions Exacerbate Global Food Insecurity. Available online: https://www.ifpri.org/blog/bad-worse-how-export-restrictions-exacerbate-global-food-security (accessed on 10 May 2022).
71. Glauber, J.; Laborde, D.; Mamun, A. Food Export Restrictions Have Eased as the Russia-Ukraine War Continues, but Concerns Remain for Key Commodities. Available online: https://www.ifpri.org/blog/food-export-restrictions-have-eased-russia-ukraine-war-continues-concerns-remain-key (accessed on 21 February 2023).
72. Food Security Portal Food and Fertilizer Export Restrictions Tracker. Available online: https://www.foodsecurityportal.org/tools/COVID-19-food-trade-policy-tracker (accessed on 10 May 2022).
73. Soffiantini, G. Food Insecurity and Political Instability during the Arab Spring. *Glob. Food Sec.* **2020**, *26*, 100400. [CrossRef]
74. Berkhout, P.; Bergevoet, R.; van Berkum, S. A Brief Analysis of the Impact of the War in Ukraine on Food Security. Available online: https://library.wur.nl/WebQuery/wurpubs/596254 (accessed on 6 May 2022).
75. Agroberichten Buitenland. Ukraine Is a Key Supplier of Some Commodities to Spain. Available online: https://www.agroberichtenbuitenland.nl/actueel/nieuws/2022/03/15/ukraine-is-a-key-supplier-of-some-commodities-to-spain (accessed on 13 December 2022).

76. European Council Food Security and Affordability. Available online: https://www.consilium.europa.eu/en/policies/food-security-and-affordability/ (accessed on 10 December 2022).
77. FAO. *Europe and Central Asia–Regional Overview of Food Security and Nutrition 2021*; FAO: Rome, Italy, 2021.
78. Eurostat Living Conditions in Europe–Material Deprivation and Economic Strain. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Living_conditions_in_Europe_-_material_deprivation_and_economic_strain#Key_findings (accessed on 10 December 2022).
79. Eurostat Euro Area Annual Inflation Down to 9.2%. Available online: https://ec.europa.eu/eurostat/documents/2995521/15725146/2-06012023-AP-EN.pdf/885ac2bb-b676-0f0d-b8b1-dc78f2b34735 (accessed on 21 January 2023).
80. Euronews Eurozone Inflation Is Easing but Remains Painful. Which Countries in Europe Are Being Worst Hit? Available online: https://www.euronews.com/next/2022/11/30/record-inflation-which-country-in-europe-has-been-worst-hit-and-how-do-they-compare (accessed on 10 December 2022).
81. European Parliament EP Autumn 2022 Survey: Parlemeter. Available online: https://europa.eu/eurobarometer/surveys/detail/2932 (accessed on 21 January 2023).
82. European Investment Bank. How Bad Is the Ukraine War for the European Recovery? Available online: www.eib.org/economics (accessed on 10 December 2022).
83. German Federal Statistical Office Inflation Rate at +10.0% in November 2022. Available online: https://www.destatis.de/EN/Press/2022/12/PE22_529_611.html (accessed on 13 December 2022).
84. Bloomberg Hungary Becomes EU's New Inflation Hotspot as Food Prices Spiral. Available online: https://www.bloomberg.com/news/articles/2022-11-08/hungary-becomes-eu-s-new-inflation-hotspot-as-food-prices-spiral?leadSource=uverify%20wall (accessed on 10 December 2022).
85. Eurostat Over 1 in 5 at Risk of Poverty or Social Exclusion. Available online: https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20220915-1 (accessed on 13 December 2022).
86. Financial Times on the Breadline: Inflation Overwhelms Europe's Food Banks. Available online: https://www.ft.com/content/bb098ccd-c74b-4c7e-8baa-e90546030fa5 (accessed on 10 December 2022).
87. Deutsche Welle Niemcy: Bankom Żywności Kończą Się Zapasy. Available online: https://www.dw.com/pl/niemcy-bankom-%C5%BCywno%C5%9Bci-ko%C5%84cz%C4%85-si%C4%99-zapasy/a-61712630 (accessed on 13 December 2022).
88. Grocery Gazette Special Report: How the Cost-of-Living Crisis Is Affecting Supermarket Food Bank Donations. Available online: https://www.grocerygazette.co.uk/2022/12/12/supermarket-food-bank-donation/ (accessed on 13 December 2022).
89. The Guardian Food Bank Britain: Five Months on the Frontline of the New Emergency Service. Available online: https://www.theguardian.com/society/2022/dec/03/food-bank-britain-five-months-on-the-frontline-of-the-new-emergency-service (accessed on 13 December 2022).
90. McKinsey & Company. How Retailers in Europe Can Navigate Rising Inflation. Available online: https://www.mckinsey.com/industries/retail/our-insights/how-retailers-in-europe-can-navigate-rising-inflation (accessed on 10 December 2022).
91. Aborisade, B.; Bach, C. Assessing the Pillars of Sustainable Food Security. *Eur. Int. J. Sci. Technol.* **2014**, *3*, 117–125.
92. WFP. WFP Reaches One Million People with Life-Saving Food Support in Conflict-Stricken Ukraine. Available online: https://www.wfp.org/news/wfp-reaches-one-million-people-life-saving-food-support-conflict-stricken-ukraine (accessed on 28 November 2022).
93. Rabbi, M.F.; Popp, J.; Máté, D.; Kovács, S. Energy Security and Energy Transition to Achieve Carbon Neutrality. *Energy* **2022**, *15*, 8126. [CrossRef]
94. IMF. Global Food Prices to Remain Elevated Amid War, Costly Energy, La Niña. Available online: https://www.imf.org/en/Blogs/Articles/2022/12/09/global-food-prices-to-remain-elevated-amid-war-costly-energy-la-nina (accessed on 18 January 2023).
95. European Parliament Need for an Urgent EU Action Plan to Ensure Food Security inside and Outside the EU in Light of the Russian Invasion of Ukraine. Available online: https://www.europarl.europa.eu/doceo/document/TA-9-2022-0099_EN.html (accessed on 28 November 2022).
96. European Commission Increased Support for EU Farmers through Rural Development Funds. Available online: https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3170 (accessed on 28 November 2022).
97. European Commission REPowerEU: Affordable, Secure and Sustainable Energy for Europe. Available online: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en (accessed on 10 December 2022).
98. European Commission Diverse Approaches to Supporting Europe's Most Deprived: FEAD Case Studies 2021. Available online: https://ec.europa.eu/european-social-fund-plus/en/publications/2021-fead-network-case-study-catalogue (accessed on 28 November 2022).
99. European Commission CAP Strategic Plans and Commission Observations. Available online: https://agriculture.ec.europa.eu/cap-my-country/cap-strategic-plans_en (accessed on 28 November 2022).
100. McKinsey & Company. A Reflection on Global Food Security Challenges Amid the War in Ukraine and the Early Impact of Climate Change. Available online: https://www.mckinsey.com/industries/agriculture/our-insights/a-reflection-on-global-food-security-challenges-amid-the-war-in-ukraine-and-the-early-impact-of-climate-change (accessed on 10 December 2022).
101. Dyson, E.; Helbig, R.; Avermaete, T.; Halliwell, K.; Calder, P.C.; Brown, L.R.; Ingram, J.; Popping, B.; Verhagen, H.; Boobis, A.R.; et al. Impacts of the Ukraine–Russia Conflict on the Global Food Supply Chain and Building Future Resilience. *EuroChoices* **2023**. [CrossRef]

102. Zachmann, G.; Weil, P.; von Cramon-Taubadel, S. A European Policy Mix to Address Food Insecurity Linked to Russia's War. Available online: https://www.bruegel.org/policy-brief/european-policy-mix-address-food-insecurity-linked-russias-war#toc-2-2-effects-on-prices (accessed on 17 January 2023).
103. European Commission. New Common Agricultural Policy: Set for 1 January 2023. Available online: https://ec.europa.eu/commission/presscorner/detail/en/ip_22_7639 (accessed on 21 January 2023).

sustainability

MDPI

Systematic Review

Conceptualizing Agrifood Systems for a Healthy, Sustainable, and Just Transformation: A Systematic Scoping Review

Sydney Pryor *, Trevor Casey and William H. Dietz

Milken Institute School of Public Health, The George Washington University, Washington, DC 20037, USA; info@trevorcasey.io (T.C.); bdietz@gwu.edu (W.H.D.)
* Correspondence: sydneypryor@gwu.edu

Abstract: Human and planetary health are interconnected through food and agriculture. Food production and consumption patterns continue to drive the global burden of malnutrition, diet-related disease, climate change, and environmental degradation. There is an urgent need to identify pathways for transforming agrifood systems to be increasingly healthy, sustainable, and just, but conceptual frameworks necessary for visualizing these complex relationships are limited. This systematic scoping review identified existing frameworks for analyzing human and environmental outcomes of agrifood systems and evaluated their inclusion of policy and governance. Frameworks have evolved to increasingly consider the food supply chain activities and actors, the drivers that shape them, and the outcomes of these interactions. The findings of the review were used to develop a conceptual framework specific to modern industrialized agrifood systems where policy landscape is an explicit component. The framework is tailored to researchers and policymakers with the intention of providing a foundation for analyzing and communicating agrifood system issues, including identifying facilitators and barriers to effective policy, places to intervene in the system, and windows of opportunity for successful transformation.

Keywords: sustainable agrifood systems; sustainable diets; climate change; nutrition; food policy; food governance; systems approach

Citation: Pryor, S.; Casey, T.; Dietz, W.H. Conceptualizing Agrifood Systems for a Healthy, Sustainable, and Just Transformation: A Systematic Scoping Review. *Sustainability* **2024**, *16*, 9862. https://doi.org/10.3390/su16229862

Academic Editors: Tarek Ben Hassen, Hamid El Bilali and Carola Strassner

Received: 26 September 2024
Revised: 1 November 2024
Accepted: 9 November 2024
Published: 12 November 2024

1. Introduction

The agrifood system's ability to produce healthy diets for a projected population of 9.7 billion people by 2050 is a pressing societal challenge. An even greater challenge is doing so without irreversible environmental damage. Agrifood systems encompass all actors involved in food production, processing, distribution, purchasing, consumption, and disposal [1–5]. The interconnections between these activities and actors are shaped by social, economic, political, and environmental factors. Over time, modern industrialized agrifood systems have accomplished great feats of innovation to increase productivity, efficiency, affordability, nutrient content, safety, taste, and more, but at what cost [6,7]? Agrifood systems account for approximately one-third of greenhouse gas (GHG) emissions globally [8]. High production and consumption of animal-source foods in particular are a key contributor to the climate crisis [8–10]. Without climate action in food and agriculture, experts suggest global warming will go beyond 1.5 degrees Celsius above pre-industrial levels, which is the threshold set by the Intergovernmental Panel on Climate Change (IPCC) [11,12]. Surpassing this threshold will lead to more intense and frequent climate and weather events, including heat waves, severe drought, and heavy precipitation, with disproportionate impacts on the most vulnerable communities [11,12]. Significant loss in the quality and availability of natural resources will impact the productivity of agrifood systems and the safety and stability of the food supply [13–15]. Furthermore, a heating climate and related weather extremes will directly threaten the health and safety of the agricultural workforce and local communities [14–16]. Current diets are also driving the global burden of diet-related disease through malnutrition in the form of both undernutrition and overnutrition [13,17,18].

The Call for an Agrifood System Transformation

Defined by Burlingame, sustainable diets "protect and respect biodiversity and ecosystems, are culturally acceptable, accessible, economically fair, and affordable, nutritionally adequate, safe and healthy, while optimizing natural and human resources" [17,19–21]. Researchers and advocates continue to call for a global shift to healthy and sustainable diets as a strategy to meet climate change mitigation targets, such as the Paris Climate Agreement, an international treaty to limit warming below the 1.5 degree Celsius threshold [22]. The EAT-Lancet Commission on Food, Planet, Health has referred to healthy and sustainable diets as a "win–win" climate and health strategy [10,17,23,24]. Given the scale, complexity, and heterogeneity of agrifood systems, a global shift to "win–win" diets has been referred to as an agrifood system transformation [17].

To begin to conceptualize the complexity of agrifood systems, the relationships between components, and their impact on human and planetary health, Ericksen in 2008 developed a food systems framework (Figure 1) to analyze food security and global environmental change [4]. Ericksen proposed the need to expand 'food systems' to represent more than just the activities from production to consumption; the framework included these activities, their socioeconomic and environmental drivers, related outcomes, and the feedback among them as the key components of agrifood systems [4]. Drivers are characterized as changes in the natural and human environments and their interactions that influence agrifood system activities. The activities include the sectors of the food supply chain from production to consumption. Production represents all of the activities involved in the production, growing, and harvesting of raw food materials, including both plant and animal production [4]. Processing, manufacturing, and packaging represent the various transformations that raw food material (vegetables, fruit, animals) undergo to "add value" to the raw product [4]. Distribution and retail are the processes through which food products move between production and processing to their final retail destination and the ways in which they are marketed. Consumption represents the process of preparing, eating, and digesting food products [4]. The food system outcomes in Ericksen's framework include food security, environmental security, and social welfare, with a focus on food security and its determinants, such as food utilization, food availability, and food access. Feedback represents the eventual impact of these activities and outcomes on the environmental and socioeconomic drivers, such as impacts on natural resource quality, greenhouse gas emissions, and livelihoods [4,25].

In addition to visualizing the complex interactions underlying food systems, Ericksen and others have highlighted the ability to identify potential trade-offs and synergies between agrifood system outcomes as another strength of a more holistic systems approach to food systems research [4,5,26]. A systems thinking approach to agrifood system research, often referred to as a food systems approach (FSA), has been growing [26]. Prior research has concluded that FSAs must be "useful to decision makers, which requires more explicit depiction of the interactions and dynamics of agrifood systems and the pathways through which they could change" [26,27].

Policy and governance structures and the relationships between diverse actors in the agrifood system are necessary dynamics to understand, particularly given the urgency of mitigating the agrifood system's double burden on human and planetary health and the need to identify effective pathways for agrifood system transformation. However, there is a paucity of policy-oriented frameworks. Ericksen highlighted food system governance as an area in need of further analysis, and although attention to governance in food systems research has increased, it is still unclear to what extent more recent conceptual frameworks have considered policy or governance structures [4,28]. Thus, our primary research question is 'How do policy and governance structures influence the complex relationships between agrifood systems and human and environmental outcomes?' The aim of this paper is to synthesize the key components of existing frameworks and identify gaps in their applicability to policy decision-making to develop an updated conceptual framework for agrifood systems transformation research that is grounded in the literature and explicitly policy-oriented. This paper presents a systematic scoping review that was conducted to understand to what extent existing frameworks for analyzing human and environmental outcomes of agrifood systems have conceptualized the role of policy and governance in upholding current systems and as potential levers for change.

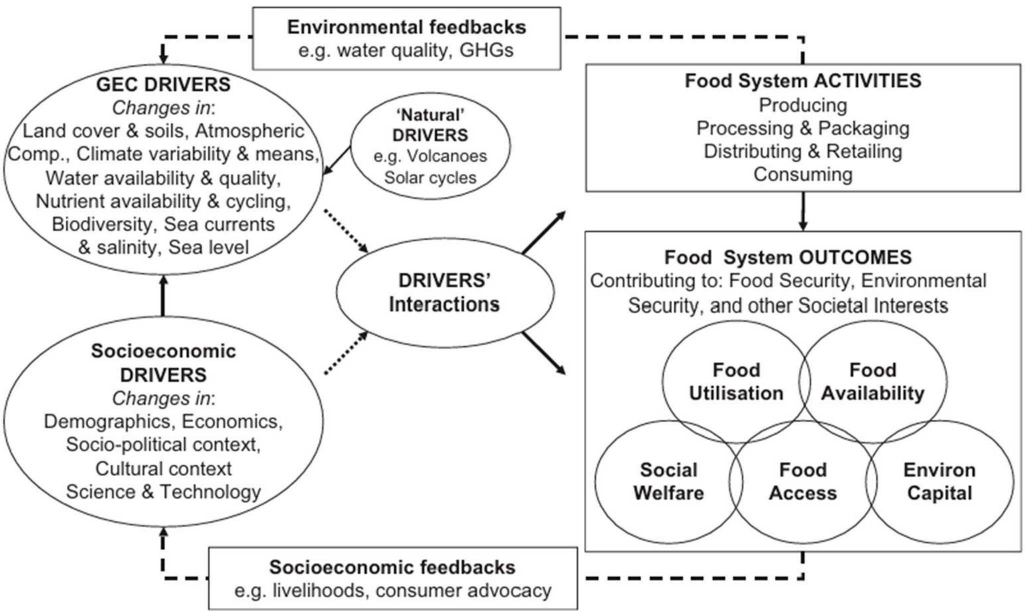

Figure 1. Ericksen's Food Systems Conceptual Framework. The figure presents a conceptual framework of food systems, including global environmental change (GEC) drivers, socioeconomic drivers, food system activities, food system outcomes, and feedback (environmental and socioeconomic) [4].

2. Methods

A systematic scoping review of academic and grey literature was conducted to identify conceptual frameworks for analyzing human and environmental outcomes of agrifood systems published between 2008 and 2023, with a focus on research from both industrialized and developing nations. Scoping reviews are particularly useful for complex and interdisciplinary research topics and are commonly used to clarify conceptual boundaries of a field, accompanied by the limitations of a broad rather than narrow research scope [29,30]. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) standards were followed and documented using the PRISMA-ScR Checklist [31] to maintain transparency in the research process. Using the methodological framework of Arksey and O'Malley, and recommendations from Levac et al. and Currie et al., we completed this review in 5 steps [32–34].

Step 1. Identify research questions considering the purpose of the scoping review is to understand to what extent existing frameworks for analyzing human and environmental outcomes of agrifood systems have conceptualized the role of policy and governance in upholding current systems and as potential levers for change.

1. What are the research objectives, context, application, and policy relevance of existing agrifood system frameworks that address human and planetary health outcomes?
2. What are the key components and interactions (drivers, activities, outcomes, feedback) underlying the complex relationships between agrifood systems and human and planetary health outcomes?
3. How have policy and governance structures been included in conceptualizations of agrifood systems?

Step 2. Identify relevant studies

A systematic scoping review protocol was developed in collaboration with a research librarian to guide this review. A systematic search of the literature was conducted using PubMed, Scopus, and Google Scholar to identify relevant journal articles and grey literature. The search terms are detailed in Table 1. The title, abstract, and full-text of identified studies were compiled using Covidence to prepare for the following screening and data extraction processes.

Table 1. Search Strategy and Terms.

Database	Search Terms
PubMed	("food"[mesh] OR "food supply"[mesh] OR "food systems" OR "agricultural systems") AND ("policy"[mesh] OR "policy making"[mesh] OR "models, theoretical"[mesh] OR "systems analysis"[mesh]) AND framework
Scopus	(INDEXTERMS (food) OR INDEXTERMS ("food supply") OR "food systems" OR "agricultural systems") AND (INDEXTERMS ("policy") OR INDEXTERMS ("policy making")) AND framework AND conceptual
Google Scholar	("food systems" OR "agrifood systems") AND ("policy" OR "policy making" OR "theoretical models" OR "systems analysis") AND framework AND concept

Step 3. Study Selection

The identified studies were screened following predetermined inclusion and exclusion criteria (Table 2). Publications were limited to the English language and the years 2008 to 2023. 2008 represents the publication year of Ericksen's framework, which acts as a foundation for many of the frameworks that followed and for this research [4,5,35,36]. Publications after this year also increasingly acknowledge the drivers of agrifood systems and there is a growing focus on sustainable agrifood systems, reflected by a steady increase in the number of publications related to food system policy and governance over the 2007–2014 period [28,37–39].

Table 2. Screening inclusion and exclusion criteria.

	Inclusion	Exclusion
Language	English	Not English
Research Methods	Empirical or theoretical; qualitative and quantitative	
Time Frame	2008+	Prior to 2008
Content High-level analysis of agrifood systems, including both human health and environmental outcomes	Yes	No
Conceptual Framework Included: Visually conceptualizes agrifood system drivers, activities, outcomes, and feedback	Yes	No

Two reviewers (SP and TC) independently screened the titles and abstracts of publications using the eligibility criteria. The publication content had to include a high-level analysis of agrifood systems that considered both human health and environmental outcomes. Studies focused specifically on one supply chain, one policy or sector of the food system, or a particular set of outcomes that did not encompass both human and environmental impacts were excluded. Further assessment of publications in the full-text screening was completed to confirm the content was aligned with the research question. A framework that visually conceptualized agrifood system drivers, activities, outcomes, and feedback was also required for inclusion in the review. Disagreement between reviewers was resolved through consensus.

Step 4. Charting the data

Relevant publications containing conceptual frameworks that matched the inclusion criteria were then evaluated relative to the research questions. We extracted relevant data points including general publication characteristics (Table 3) and specific characteristics of the included conceptual frameworks (Table 4), including framework context and application, agrifood system components organized by Ericksen's framework—(1) drivers, (2) activities, (3) outcomes, and (4) feedback—and documented how the publications included policy and governance in their conceptual frameworks [4].

Table 3. General characteristics of included publications.

Publication year
Publication type (journal/research article, reports)
Research objective(s)
Research approach
Policy relevance

Table 4. Specific characteristics of included frameworks.

Framework context/application: 1. Scale: multi-scale, global, international, national, regional, local 2. Context-specific: yes/no 3. Intended end-user: policymaker, researcher 4. Specified agrifood system/policy goal of interest
Agrifood system component details following Ericksen: [4] Drivers: changes in the natural and human environments and their interactions that influence the agrifood system activities. Activities: processes of the food supply chain from production to consumption, including production, processing and packaging, distribution and retail, and consumption. Outcomes: the multiple health, social, environmental, and economic effects of the activities, such as food security, environmental security, and social welfare, with a focus on food security and its determinants (food utilization, food availability, and food access). Feedback: the eventual impact of these activities and outcomes on the environmental and socioeconomic drivers, such as impacts on natural resource quality, greenhouse gas emissions, and livelihoods [4,25].
Policy/Governance inclusion (within framework)

Step 5. Summarizing and reporting the results

The extracted data for each included publication and conceptual framework are summarized in Tables S1 and S2 and in narrative format. The data were analyzed in the context of the research questions to synthesize how frameworks conceptualize agrifood systems, their similarities and differences in drivers, activities, outcomes, and feedback included over time, and the extent to which policy and governance are a part of these dynamics. Further inductive analysis was used to identify strengths in existing frameworks' ability to conceptualize complex interactions between agrifood systems and human and planetary health outcomes and to identify gaps in the applicability of existing agrifood system frameworks for effective policy decision-making.

3. Results

The process and results of the study identification, screening, and selection were documented using the PRISMA flowchart for scoping reviews (Figure 2) [31]. Research publications including high-level frameworks conceptualizing agrifood system components and their interrelationships with human and planetary health outcomes (N = 8) were identified, reviewed, and summarized based on their objectives, application to food systems research, and relevance for policy decision-making (Table S1). As specified in the inclusion criteria, all publications framed agrifood systems as influential for both human and planetary health outcomes.

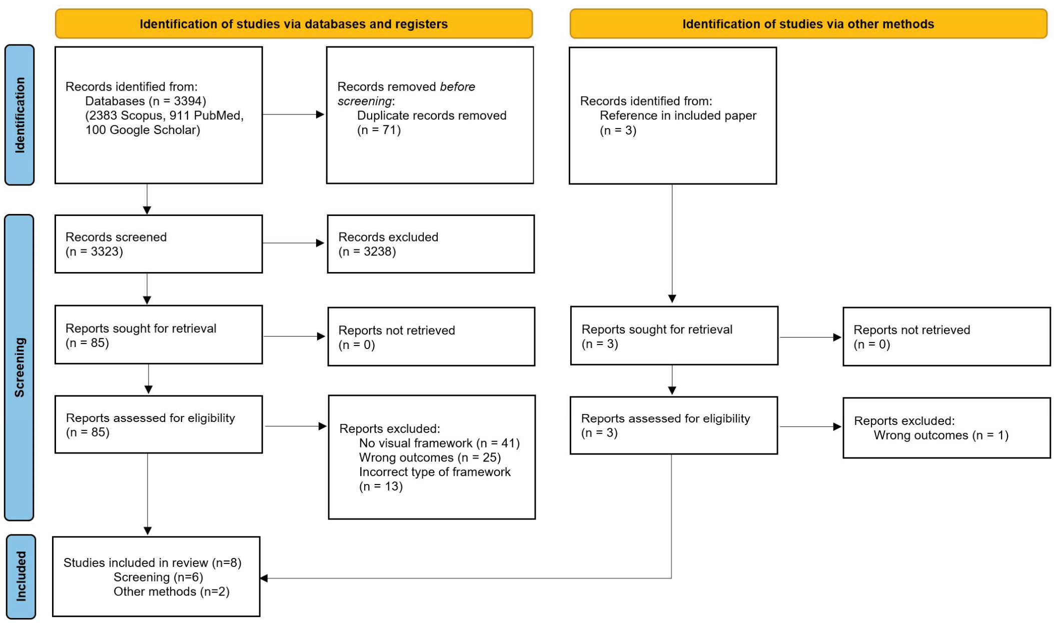

Figure 2. PRISMA 2020 flow diagram for new systematic reviews (databases/registers, other sources).

3.1. Overview of Included Conceptual Frameworks

All publications discussed the benefit of applying a food systems approach to improve understanding of the complex influence of food system activities and actors on various outcomes, as well as the overarching drivers and non-linear feedback loops throughout the system. Researchers applied a variety of methods to developing conceptual frameworks, including literature reviews and syntheses and consensus-based development. All included frameworks are multi-scale, suggesting their generalizability across one or more scales (i.e., global, national, subnational), and only two are considered context-specific. Van Berkum et al. and Zurek et al. focused specifically on agrifood systems in the context of the Netherlands and the European Union (EU), respectively [38,40]. While the majority of reviewed frameworks suggest they are generalizable to agrifood systems at various scales, the components and characteristics included are more closely aligned to industrialized agrifood systems and Western diets. Individuals in these frameworks are represented as actors across several highly coordinated and technical food system sectors that operate at scale. The industrialized perspective of these frameworks is also reflected in their representation of policy and governments as the organized process and entity through which changes to the food system can be made. Researchers, policymakers, and public health practitioners were all named as potential end users of these frameworks.

Publications were evaluated by the content included in their conceptual frameworks, organized by drivers, activities, outcomes, feedback, and policy/governance as described previously (Table S2) [4]. All publications included in the review referenced Ericksen in their description of how food systems are conceptualized, and their conceptual frameworks largely build on each other. Over time, researchers have made significant additions to food system frameworks for evaluating multiple food system outcomes. These updates aim to increase end users' ability to adequately understand the interconnectedness of agrifood system drivers, agrifood system activities, and multiple related outcomes. The evolution of these conceptual frameworks over time reflects growing attention to the interrelationships between agrifood systems and human and planetary health. This attention also reflects an increasing acceptance of systems approaches and the inherent complexity and interconnectedness of various elements within agrifood systems.

3.2. Components of Included Conceptual Frameworks

Pinstrup-Andersen and Watson conceptualize food systems as the biophysical (natural), socioeconomic, political, and demographic environments that drive the food supply chain activities and related actors from production through consumption and ultimately the environmental, socioeconomic, and health and nutrition outcomes that feedback to change the drivers [41]. Their framework also highlights the bidirectional relationship between the food supply chain components and system agent behavior, representing how actors and their decisions influence and are influenced by the system [41]. Lawrence et al. connect the food system to the environment and public health nutrition, representing the feedback between food supply chain activities (the same as introduced by Ericksen) and human health and environmental outcomes [36]. Lawrence et al. also expand on the interconnectedness of food system activities themselves by including multiple arrows between production, processing and packaging, distribution and retail, and consumption, rather than presenting a traditional linear food supply chain with no feedback. Meybeck and Gitz later conceptualized food systems with a specific focus on the contribution of diets and consumer behavior to the environmental, economic, and social sustainability of food systems [42]. Their conceptual framework drew specific attention to the influence of attitudes and lifestyle (as cultural drivers) on food choice behavior and ultimately diets, in addition to the environmental, economic, and social drivers of agrifood system activities.

In 2017, the High Level Panel of Experts on Food Security and Nutrition (HLPE) classified drivers of agrifood systems into five primary categories: biophysical and environmental drivers, innovation and technological drivers, political and economic drivers, social and cultural drivers, and demographic drivers, building on the work of Pinstrup-Andersen and Watson [39,41]. Food system researchers have continued to apply these categories of drivers in their approaches and conceptual frameworks [38,43].

Biophysical and environmental drivers include natural resources, ecological systems, and climate change.

Innovation, technology, and infrastructure drivers include new technologies and growing infrastructure that can influence the efficiency or sustainability of food system activities.

Political and economic drivers include specific food, agriculture, and nutrition policies, trade policies, and governance structures that function as the underlying mechanics of each sector of the food supply chain. Political and economic drivers also influence the market structure related to food and agriculture and changes in supply and demand of certain products and services over time [2].

Sociocultural drivers include the subjective components of food, social norms, and culturally relevant factors influencing behavior.

Demographic drivers include population changes in size, age composition, and geographic distribution.

Like Meybeck and Gitz, the HLPE framework centered on the role of diets, which are influenced by consumer behavior, in linking food systems, human health and nutrition outcomes, and other social, economic, and environmental impacts [39,42]. Consumer behavior was defined as the "choices and decisions made by consumers, at the household or individual level, on what foods to acquire, store, prepare, cook and eat, and on the allocation of food within the household" and is influenced by personal preferences (taste, convenience, values, traditions, culture, beliefs) and the food environment [39]. Consumer behavior along with food supply chains (including actors) and food environments represent the three distinct, but interrelated activities of the agrifood system in the HLPE framework and act as points of intervention for nutrition.

The inclusion of food environments distinguishes the HLPE framework from previous conceptualizations. Food environments are defined as "factors that mediate the acquisition of foods by people within the wider food system", including availability and physical access (proximity), economic access (affordability), promotion, advertising and information, and food quality and safety [39,44].

Van Berkum et al. build heavily on the HLPE framework and other international reports to conceptualize the food system impact of environmental change on food security with the goal of identifying policies to improve food and nutrition security within environmental limits in the Netherlands [38]. Like Ericksen, Van Berkum et al. include socio-economic and environmental drivers of food systems, and food security, socioeconomic, and environmental outcomes of food systems [4,38]. Van Berkum et al. also add 'enabling environment', or the factors that create the conditions within which the system functions, as a food system activity. The factors of an enabling environment include transport networks, regulations, institutional arrangements, and research infrastructure [38]. Zurek et al. conceptual framework focuses on assessing food and nutrition security and sustainability in the EU food system and highlights the need to consider equity in food system conditions and outcomes [40]. Zurek et al. highlight indirect food system drivers, similar to HLPE, as well as direct drivers of actors within the food system [39,40]. Unique to Zurek et al. is that the food system activities in the framework are highly interconnected and include disposal/reuse.

Bene et al. developed a conceptual framework based on a literature review to formally define 'food system driver' as it had not been previously defined, and identified key drivers supported by the literature based on this definition [37]. Bene et al. defined three necessary characteristics of a food system driver: (1) durably affects the actors and/or activities of the system; (2) does not replicate another driver; and (3) their origin (external or internal) and the nature of their impact (intentional or unintentional) is clear [37]. Using this updated definition, they identified 12 key drivers and categorized them into 3 categories (production/supply, distribution/trade, and consumption/demand) to facilitate the understanding of each driver's influence along the food supply chain [37].

"Production and supply drivers include technological innovations, intensification and homogenization of agriculture, infrastructure, and policies, such as farm, labor, and trade. Production and supply also depend on natural resource availability (land, water, minerals, air, and forests), which are adversely affected by climate change and environmental degradation. Climate change and environmental degradation also exist as outcomes of agricultural production. Impacts to the biophysical environment feed back as inputs to the system as the natural resource base.

Distribution and trade drivers include trade policies, internationalization of private investments, and growing concerns for food safety.

Consumption and demand drivers include urbanization and related lifestyle changes, population growth, consumer sociodemographic characteristics, such as income, culture, preferences, such as taste, and concerns such as food safety" [37].

Although not specified in their framework, Bene et al. are the first to distinguish between intentional and unintentional agrifood system drivers, such as policy and climate change [37].

With respect to policy and governance, two publications did not include policy within their visual conceptual framework [36,42]. Lawrence et al. explicitly identified their framework as part of a policy formulation tool to promote healthy and sustainable diets [36]. However, policies are not represented within the conceptual framework itself, but rather in an 'Orders of Food System Change' schema. Pinstrup-Andersen and Watson's framework included governance along with institutions and policies to represent the political environment as a driver of food system activities and decisions [41]. The other frameworks presented policies, most often trade policy, as one of the many drivers of agrifood system activities [37,38]. HLPE presented political, program, and institutional actions as influencing the drivers, which included the food supply chain, food environment, and consumer behavior, and being influenced by the health, social, environmental, and economic impacts of the agrifood system [39]. Institutional arrangements and regulations were also depicted in van Berkum et al.'s framework within the enabling environment [38]. Zurek et al. addressed policy and governance by depicting EU and national policymakers and other food system influencers, such as NGOs, as the pathway through which EU policy goals for sustainable food and nutrition security are realized and included these policy goals within the framework [40].

3.3. Significant Additions to Conceptual Framework Components over Time

Significant additions and revisions have been made to these food system frameworks over their evolution that have strengthened their ability to address complex agrifood system research questions. These updates are outlined in chronological order by publication date in Table 5, organized by food system component (drivers, activities, outcomes, feedback, and policy/governance). The evolution of these frameworks was largely centered around expanding the concept of food system activities to better understand how they influence the food system outcomes. Frameworks progressed from a linear representation of a food supply chain to an interconnected set of activities and actions that include the food supply chain as well as the food environment within which individuals make their food choices. The inclusion of the food environment and food choices reflects researchers' shift in focus to understanding consumer behavior as a driver of diets and the agrifood systems' impact on human and planetary health. Recognizing the role of consumers as a decision-maker within the broader system is critical to understanding and changing problematic trends and improving outcomes.

Table 5. Strengths and significant additions and revisions to agrifood system frameworks.

Food System Component	Strengths/Significant Additions and Revisions
Drivers	**Pinstrup-Andersen and Watson [41]:** 4 environments influencing food system activities (biophysical, socioeconomic, political, demographic) **HLPE [39]:** 5 categories of drivers (and the influence of these drivers over various food system activities) **Zurek et al. [40]:** indirect drivers of food system and direct drivers of food system actors (exogenous and endogenous drivers of change) **Bene et al. [37]:** 3 categories of key drivers (production/supply, distribution/trade, consumption/demand) and typology of food system drivers (internal/endogenous vs. external/exogenous; intended/controllable vs. unintended/accidental)
Activities	**Pinstrup-Andersen and Watson [41]:** Imports and exports as components of food system activities that influence and are influenced by other food systems **HLPE [39]:** 3 components of food system activities (food supply chain including actors, food environments, consumer behavior) **Zurek et al. [40]:** interrelationships within food supply chain activities (adds disposal/reuse) and between actors (trade, money) **Bene et al. [37]:** nested approach to food system activities (consumer food choice influenced by food environment, which is influenced by food system supply actors and activities) that collectively influence outcomes
Outcomes	**Zurek et al. [40]:** 4 outcomes that are context-specific and related to the EU food system goals (diets and consumption patterns; productivity, profit, and competitiveness; environmental conditions; fair and just social conditions for food system actors) **Bene et al. [37]:** 4 outcomes and interactions between them capture trade-offs and synergies (environment; nutrition and health; economic; social)

Table 5. *Cont.*

Food System Component	Strengths/Significant Additions and Revisions
Feedback	**Pinstrup-Andersen and Watson [41]:** Bidirectional feedback between system agent behavior (decisions of actors in the system) and food system activities **Lawrence et al./Meybeck and Gitz/Zurek et al. [36,40,42]:** Bidirectional feedback within food supply chain activities **HLPE [39]:** Demonstrates significant feedback between and within food system components (drivers, activities, outcomes), including consumer behavior feeding back to influence food supply chains and food environments **Van Berkum et al./Bene et al. [37,38]:** feedback and interactions between drivers and throughout the system
Policy/Governance	**Pinstrup-Andersen and Watson [41]:** Political environment as a driver of food system activities and decisions (governance, institutions, policies); agents as decision-makers in the system **HLPE [39]:** Political, program, and institutional actions as drivers and outcomes of agrifood systems with potential to intervene through food supply chains, food environments, and consumer behavior. **Van Berkum et al. [38]:** Enabling environment, which includes regulations, included as a food system activity that influences the food supply chain. **Zurek et al. [40]:** Specific EU policy goals are included in the framework and shown to influence policymakers and other food system influencers. Regulatory environment is included as a direct driver of food system actors, as determined by agriculture and trade policies. **Bene et al. [37]:** Political economy as part of the general context. Classifies policies as intended/controllable drivers.

Following Ericksen's framework, researchers have consistently considered the environmental, socioeconomic, and nutritional outcomes of food systems in their conceptualizations. Later frameworks more explicitly address the interactions between these outcomes in the form of trade-offs and synergies. They also include the distribution of these effects between actors as part of the outcomes. The feedback between these outcomes and the drivers of food systems in these frameworks have become more nuanced over time as well, solidifying the idea of the food system as a complex and adaptive system over time. Ericksen's environmental and socioeconomic drivers of agrifood system change have been added to and adapted over time. However, less attention was given to food system drivers relative to the food system activities until later frameworks, particularly when Bene et al. formalized the concept as described [37]. In general, frameworks progressively included more nuanced feedback between and within components.

With respect to policy and governance, frameworks followed less of a trend in their evolution compared to the other components. Building on Ericksen's call to prioritize governance in food system frameworks, all included publications discussed the implications of a food systems framework for policy decision-making, with some attention to the ability to identify leverage points to change the system and to evaluate 'tradeoffs and synergies' between policies and across outcomes [4]. However, the explicit inclusion of policy and governance structures within frameworks was limited and differed significantly between frameworks. The earliest and only publication that explicitly included governance in the framework was that of Pinstrup-Andersen and Watson in 2011 [41]. Later frameworks included political and institutional actions in their conceptual frameworks but varied in how they conceptualized the relationships between these factors and the activities and actors within the food system. Without specific analysis of these relationships, the influence of these policy or regulatory variables over the activities or outcomes of the system remained unclear.

3.4. Gaps for Policy Decision-Making in Included Frameworks

The review of existing frameworks identified two gaps that limit their applicability for policy decision-making and solutions-oriented insights. These include the frameworks' generalizability despite heterogeneity across contexts, and limited attention to analyzing political economy.

The burdens and inequities of food systems and the challenges of changing them to be healthy, sustainable, and just differ between regional and country contexts. Accordingly, the impact of various drivers and policies is highly dependent on the type of food system being discussed [2,39]. HLPE distinguished between three broad types of food systems (traditional, mixed, and modern) and highlighted the heterogeneity of food supply chains and food environments between different food system types [39]. The diverse components and structures of food systems between contexts suggest the need for context-specific solutions. Thus, a conceptual framework that is specific to a certain typology may lend itself to an increased understanding of the food system components and their interrelationships, and how they collectively contribute to and are impacted by food system outcomes.

The actual applicability of the existing frameworks for effective policy decision-making is also unclear. HLPE and Van Berkum et al. demonstrated how their framework can be used to trace policies through the agrifood system activities to outcomes, which is helpful to visualize feedback throughout the system [38,39]. However, how agrifood systems change is not solely driven by policies and policymakers, but more broadly by actors throughout the system representing diverse, often disparate, and even conflicting, interests. The authors of the existing frameworks acknowledge the importance of multiple decisions made by multiple actors/stakeholder groups throughout food supply chains, but these dynamics and relationships are not addressed within the conceptual frameworks or further analyzed. Without the additional analysis of political economy, researchers cannot adequately identify policy trade-offs and synergies [27,45,46]. Political economy is included in the Bene et al. framework as part of the general context within which food systems operate, but they do not specify an approach to analyze the role of various actors and their decisions in the political process [37]. Relatedly, Zurek et al. concluded that effective governance requires that decision-makers understand how complex food system components interact to influence outcomes, and also understand the effect of policies or other innovations on different actors [40].

3.5. A Conceptual Framework for Modern Industrialized Agrifood Systems

To address these gaps, we developed an agrifood system conceptual framework (Figure 3) that integrates components of existing food system frameworks with two specific additions. First, to improve the agrifood system framework's ability to generate practical, relevant, and solutions-oriented insights, our framework is specific to 'modern and industrialized food systems', classified by Marshall et al. as part of a typology to account for heterogeneity between food system types [39,47,48]. This heterogeneity provides the rationale for specifying the development of a new framework specific to modern industrialized agrifood systems, particularly as the production-oriented industrialized system dominates at the expense of health and well-being globally with disproportionate impacts on developing countries [49]. Moreover, prior frameworks suggested their generalizability, but largely reflected the components and structure of modern industrialized agrifood systems. Modern industrialized food systems are associated with increased agricultural productivity, supermarket availability, dietary diversity, and urbanization [48]. They are also typically characterized by several actors with various roles throughout the system, significant processing and packaging of foods, reliable storage and transport infrastructure, high monitoring of food safety, increased food-related information for consumers, and differential access to and availability of foods by income level [32]. The cost of staple goods is lower relative to animal-source foods; perishable foods and specialty foods such as those produced locally or organically are more expensive [39]. The U.S. is an example of an industrialized agrifood system and will be used as a simple example to apply the conceptual framework. Second, our framework will make explicit the endogenous and exogenous role of policies and governance structures in agrifood systems, including actors and their relationships to one another in influencing agrifood system activities and outcomes, and related policies. This addition provides a political economy lens to understand how the interests and ideas of relevant agrifood system actors and institutions interact to influence policy development and decision-making processes [46,50].

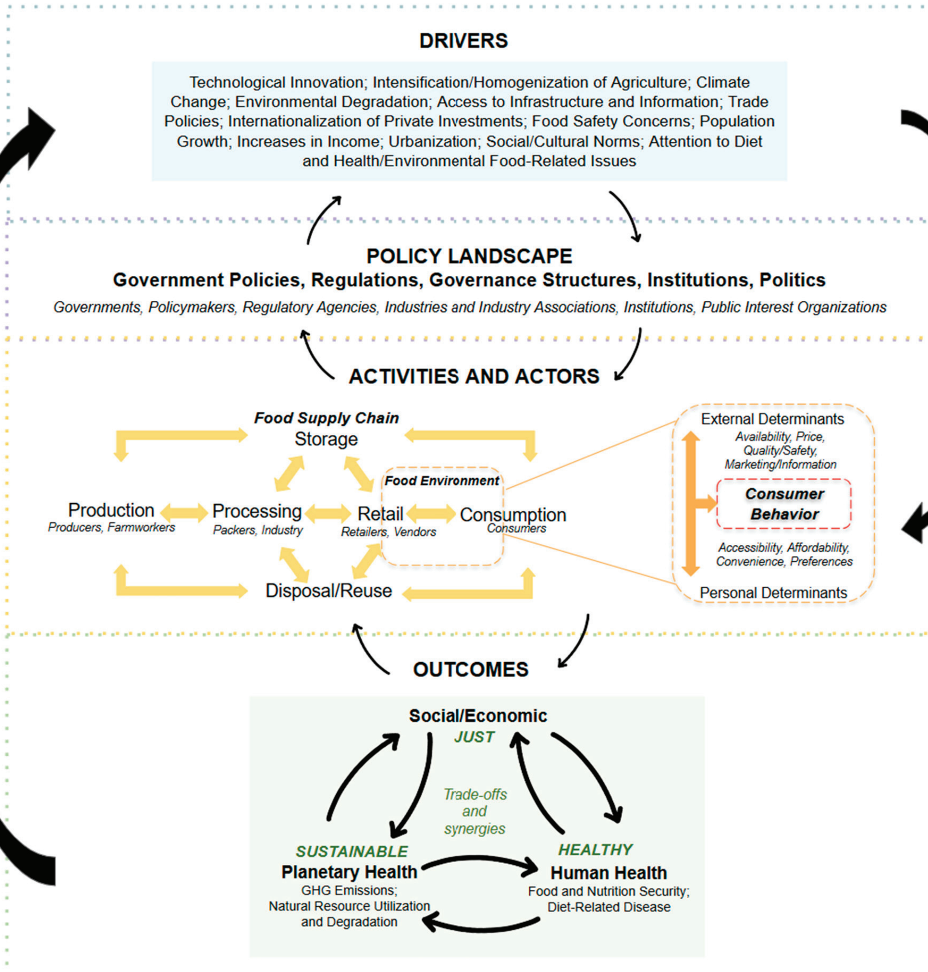

Figure 3. Policy-Oriented Conceptual Framework for Modern Industrialized Agrifood Systems.

3.6. A Conceptual Framework for Modern Industrialized Agrifood Systems: The Components

The updated conceptual framework (Figure 3) maintains drivers, activities, outcomes, and feedback as the primary components of agrifood systems and proposes *policy landscape* as a fifth key component. Researchers and policymakers can apply this framework to understand these components and their interactions in the context of their specific research or policy questions. Importantly, feedback is represented broadly throughout the framework as bidirectional arrows and feedback loops within and between each of the agrifood system components. The dotted lines between components also represent the constant interaction and shifting dynamics of modern industrial agrifood systems over time. The visual framework and the following descriptions of the framework components are not intended to be exhaustive or prescriptive but rather to provide a lens through which issues related to industrialized agrifood systems can be analyzed. For example, the framework provides an opportunity to analyze cultural norms as a driver of agrifood system activities, organic farming, and food miles as part of these activities, biodiversity as an environmental outcome as well as a driver, and food security and related inequities as components of consumer behavior and as outcomes relevant to both human health and socioeconomics.

3.6.1. Drivers

Our framework includes 14 drivers derived from Bene et al.'s recent systematic review, as described previously [37]. In addition to the 12 key drivers Bene et al. identified that influence the supply and demand of agrifood systems, we include cultural and social norms and attention to the environmental impacts of diets as two additional drivers of modern industrialized agrifood systems [37]. Users can conceptualize drivers as intentional or unintentional depending on the context of their research or policy issue; this may be a subjective exercise, but useful for understanding potential places to intervene. Cultural and social norms influence the acceptability, desirability, and thus demand for certain foods [51]. This driver captures the often-overlooked recognition that consumers themselves, through various motivations, can generate social movements and shift food-related norms [52–55]. Attention to the environmental impacts of diet is also included based on the growing focus on this relationship over time in the literature and by consumers [56–58]. The arrows between drivers and the policy landscape depict the role of historical and future policies in shaping these trends, and conversely, the role of these trends in shaping actors' personal and policy interests.

3.6.2. Activities and Actors

Our framework utilizes the components of agrifood system activities identified and defined in HLPE, including food supply chains, food environments, and consumer behavior. In our framework, agrifood system activities explicitly include relevant actors to account for the relationship between actors, their decisions, and agrifood system activities [41]. Food supply chain subcomponents include production, processing and packaging, storage and distribution, retail, and consumption as well as disposal/reuse, as included by Zurek et al. [4,39,40]. In modern industrialized food systems, production includes a wide variety of foods produced at farms of various sizes, significantly characterized by large-scale industrialization and productivity. Processing refers to the transformation of raw foods and ingredients into new products. Processing is conducted predominantly by large industries to generate processed and ultra-processed packaged foods that often lack nutrient density, but are developed to be safe, cheap, widely available, hyperpalatable, and have a long shelf life [59]. Storage and distribution reflect the transport and storage of foods between food supply chain actors and modern industrialized food systems. These are characterized by substantial infrastructure that increases the feasibility of these processes as well as the distance between consumers and where their food was produced [60]. Retail refers to the several destinations where food can be marketed and acquired, including supermarkets, farmers and specialty markets, corner stores, full-service, fast-casual, and fast-food restaurants, food trucks, and street vendors [39]. Consumption reflects the process of preparing, eating, and digesting food products, and modern food systems trend toward overconsumption, particularly of animal-source foods [4,47]. Finally, disposal and reuse refer to food that is lost or wasted, which contributes significantly to the environmental burden of modern industrialized food systems [61,62]. Agrifood system actors within the food supply chain include, but are not limited to, producers, laborers, processors and packers, distributors, retailers, food service providers, and consumers [2,28,63].

Food supply chain subcomponents influence each other and act as determinants of the food environment, consumer behavior, and ultimately human health, environmental, and socioeconomic outcomes, and the inequitable distribution of these effects. The food environment refers to the physical, economic, political, and sociocultural conditions that shape dietary preferences, choice, and consumption [64,65]. Food environments are influenced by availability and physical access (proximity), economic access (affordability), promotion, advertising, and marketing, and food quality and safety [39,44]. Although it was not included in our review because it did not meet our inclusion criteria, Raza et al. developed a framework to analyze children's and adolescents' diets that added nuance to previous frameworks by dividing the food environment into external and personal domains, based on the work of Turner et al. [43,64]. External food environments are "the retail and commercial markets, schools, and informal vendors where consumers interface with food, and reflect aspects of availability, food price, marketing and advertising, and vendor and product properties" and personal food environments are "the individual and household-level factors that consumers bring to the food environment, such as purchasing power, access, convenience, desirability, and informs why people choose to procure the foods that they do" [64]. This differentiation is highly relevant for modern industrialized food systems and is included in the updated framework as external and personal determinants of the food environment. Just as the food supply chains, food environments, and consumer behavior are highlighted as entry and exit points for nutrition in HLPE, we argue that they are also entry and exit points for sustainability and equity, and represent points of intervention for policymakers and practitioners in modern industrialized food systems [39].

3.6.3. Outcomes

The outcomes of modern industrialized food systems in the conceptual framework include human health outcomes (food and nutrition security, diet-related chronic disease), planetary health outcomes (greenhouse gas emissions, natural resource utilization, and degradation), and social and economic outcomes (income, livelihoods, distribution of effects). These outcomes are influenced by the food system activities and the actions of various actors. Changes in these outcomes, or the distribution of these outcomes across populations, will feed back to influence the food system activities and actors, primarily as consumers, as well as influence various food system drivers over time. The outcomes of modern industrialized agrifood systems do not exist in isolation. The framework depicts feedback loops between each of the types of outcomes to highlight their interconnectedness. These relationships create trade-offs and synergies between outcomes that decision-makers must consider in attempting to achieve healthy, sustainable, and just agrifood systems [4,37].

3.6.4. Policy Landscape

Healthy, sustainable, and just agrifood system transformations require action from governments and institutions, which have been explicitly included in the conceptual framework [17]. This addition to agrifood system frameworks is labeled as the *policy landscape* to reflect the existing policies, regulations, governance structures, institutions and politics that interact with the agrifood system components [38,39,41]. Policy and governance structures can directly shape how activities and actors operate within the agrifood system (endogenous) or indirectly through actions from outside the agrifood system (exogenous) that change outcomes or aspects of the policy process [38,39,41].

Governments, policymakers, regulatory agencies, industries and industry associations, institutions, and public interest organizations are actors within the policy landscape that interact with the activities and outcomes of modern industrialized agrifood systems [2,66]. These actors hold different interests depending on the food system issue being analyzed, the context, and their relationship to one another and the other actors in the food supply chain [5,67]. Food policies are influenced by the interests and power imbalances that exist between these actors [28,66]. As a result, food policies in modern industrialized agrifood systems are often fragmented across sectors and production-oriented to prioritize economic interests, while failing to adequately account for public health and environmental implications [28,68–70]. A combination of strategies should be considered to improve healthy and sustainable consumption [71,72].

4. Discussion

The scoping review provided a foundation and guidance for the development of an updated policy-oriented conceptual framework for modern industrialized agrifood systems. The updated framework provides a conceptual tool for policymakers and researchers to understand the linkages between activities and actors within modern industrialized agrifood systems and human health, environmental, social, and economic outcomes, and the endogenous and exogenous policy and governance structures that contribute to these relationships. Importantly, our framework highlights how policies contribute to the current system structure and provide opportunities to influence the system. Collectively these insights can facilitate the identification of places to intervene in the system and windows of opportunity for change.

4.1. Research Contributions

Our integrated agrifood system framework for political economy analysis addresses gaps in prior food systems research and improves the applicability of a food systems approach for both research and policy analysis and decision-making. The updated framework is grounded in the literature on food systems and their impact on human and planetary health. The framework can bolster an understanding of the complex dynamics between the food system drivers, activities, and actors that generate outcomes in modern industrialized food systems. The framework does so by providing a simplified conceptual structure that is relevant to the complexities of modern industrialized agrifood systems, but also adaptable to the context-dependent factors that shape where change might be possible, through who, and how it might influence humans and the environment.

The framework also outlines several potential places to intervene in the system. Depending on the research question, users can apply the framework as a conceptual tool to identify activities throughout the supply chain or actors in the supply chain that offer opportunities for transformation. The agrifood system drivers can facilitate or inhibit the feasibility or effectiveness of intervention targets. Likewise, the framework facilitates the analysis of how an existing policy landscape can support or inhibit new policy action in relevant settings. The systems insights generated from applying the integrated framework can inform the identification, development, and implementation of policy strategies for a healthy, sustainable, and just agrifood system transformation in modern industrialized agrifood systems.

4.2. Practical Application

Our framework can be used by researchers and policymakers to analyze various agrifood system goals and policies through the lens of system transformation. First, users should determine their policy or agrifood system goals of interest specific to a particular context. Examples for a modern industrialized food system include (1) increasing the availability and accessibility of healthy and sustainable diets in the US, particularly for marginalized populations; and (2) decreasing the climate and environmental footprint of US diets. The next step is to identify possible policy objectives, or specific strategies, that can be implemented to achieve these goals [73]. This can be undertaken by identifying where the policy goal fits within the agrifood system components and tracing it downstream and upstream through the conceptual framework to find places to intervene. Alternatively, researchers and policymakers may want to explore the feasibility of specific policy interventions.

For example, one potential policy strategy to improve population and planetary health in the US is to shift federal food procurement standards to procure less beef and more minimally processed plant proteins for federal food programs. After policy strategies are identified, the framework can be used to conduct a more nuanced analysis of factors that may facilitate or inhibit the success of the identified policy strategy. This analysis can determine if a window of opportunity exists for change or if other factors need to change before a policy is practical. The policy landscape component of the agrifood system framework is used to identify actors with a direct interest in the policy process. The food supply chain component also outlines potential actors with direct or indirect interest in the implications of the policy. The interests of all of these actors should be documented and analyzed; if a policy to reduce beef consumption were to be enacted, who wins, who loses, and by how much? Synthesizing actors' interests relative to one another can assess power imbalances among actors as well as potential unintended consequences or trade-offs that will require attention. As a brief example, if U.S. federal food procurement policy shifted to include more plant-based foods and less beef, cattle ranchers, the beef-packing industry, and policymakers who receive political donations from the cattle industry would likely oppose this shift. An unintended consequence of enacting a new procurement policy may be loss of livelihood for cattle ranchers, which would be offset by increased profits for plant-based producers, increased sustainability of federally procured food, and improved health for those who consume it. Potential synergies may be found while considering trade-offs; for example, this new procurement strategy could be coupled with incentives for producers to transition to regenerative farming or to the production of less resource-intensive crops. Framework users can also assess the context and role of institutions related to the policy issue and proposed strategy. For example, there are strong social norms around beef consumption in the US. These norms may lead policymakers or government agencies, like the US Department of Agriculture, to oppose policies to reduce beef consumption in favor of an alternative policy that is less polarizing and likely less effective, reflecting internal conflicts between the economic success of US agriculture and its human and environmental impact.

4.3. Limitations and Future Research

Despite the ability of a food systems approach to handle complexity, a limitation of this research is the inability to capture all variables and relationships relevant to modern industrialized agrifood systems within a single conceptual framework. Even with our scoping systematic review of the drivers, activities, outcomes, and feedback used to conceptualize agrifood systems and their influence on and by human and planetary health, fully integrating all components, subcomponents, and interactions within each framework was not feasible. Therefore, variables and relationships may have been omitted in the updated framework with the objective of developing a framework that is simple and relevant to the modern industrialized context. Additionally, the scoping systematic review was focused on food system frameworks with specific characteristics and outcomes of interest. Existing frameworks that did not meet our inclusion criteria (i.e., focused on nutrition without environmental considerations) may have been omitted despite containing relevant insights. The inclusion criteria were developed specific to our research question, but future research may benefit from less stringent criteria that allow for the inclusion of frameworks for analyzing agrifood systems of various typologies and with non-specific outcomes.

Alternatives to modern industrialized agrifood systems exist, including rural and traditional, informal and expanding, and emerging and diversifying, as outlined by Marshall et al. [48]. Aspects of non-industrialized systems, including local, traditional, and Indigenous food systems offer opportunities for improving the health and sustainability of agrifood systems globally as well as benefits for social equity and economic well-being [74]. Modern industrialized agrifood systems can and should learn from more traditional systems. The deepest leverage point in a system is the ability to change the values and goals that shape it [75,76]. Users of this framework must consider how agrifood system transformation in industrialized systems may require reorienting the goals and, thus, the overall structure of the system. Likewise, future research should assess how these agrifood system types interact and the implications for human and planetary health.

Future research should prioritize applying the integrated framework to problematic trends or policy goals in modern industrialized food system contexts to demonstrate its applicability for policy decision-making and identify meaningful policy insights. The framework can also be used to map the state of the literature on a given agrifood system issue to identify areas of focus for future research as well as serve as a foundation for a system dynamics (SD) approach. SD is both a qualitative and quantitative modeling approach for understanding dynamic problems within complex systems, identifying places to intervene in the system, and comparing policy options against several outcomes, and may enable several further analyses utilizing this framework.

5. Conclusions

Strategies for achieving healthy, sustainable, and just agrifood system transformations require immediate attention. An integrated conceptual framework for modern industrialized agrifood systems offers a foundation for research and policy analysis. Researchers and policymakers should leverage the use of policy-oriented conceptual frameworks to facilitate political economy analyses and gain a nuanced understanding of issues in the context of modern industrialized agrifood systems. Exploring interconnections between system components, power imbalances between actors, and trade-offs between outcomes can enhance decision-making around existing or proposed policy interventions. Collectively, system insights enable decision-makers to identify and prioritize places to intervene for agrifood system change.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16229862/s1, Table S1: General characteristics of included publications; Table S2: Specific characteristics of included frameworks.

Author Contributions: Conceptualization, S.P. and W.H.D.; formal analysis, S.P. and T.C.; methodology, S.P. and W.H.D.; investigation, S.P. and W.H.D. data curation, S.P. and T.C.; writing—original draft preparation, S.P.; writing—review and editing, S.P., T.C., and W.H.D.; visualization, S.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Rogers, A.; Castree, N.; Kitchin, R. Agro-food system. In *A Dictionary of Human Geography*; Oxford University Press: Oxford, UK, 2013.
2. IOM (Institute of Medicine) and NRC (National Research Council). *A Framework for Assessing Effects of the Food System*; The National Academies Press: Washington, DC, USA, 2015.
3. Vermeulen, S.J.; Campbell, B.M.; Ingram, J.S.I. Climate change and food systems. *Annu. Rev. Environ. Resour.* **2012**, *37*, 195–222. [CrossRef]
4. Ericksen, P.J. Conceptualizing food systems for global environmental change research. *Glob. Environ. Change* **2008**, *18*, 234–245. [CrossRef]
5. Ingram, J. A food systems approach to researching food security and its interactions with global environmental change. *Food Secur.* **2011**, *3*, 417–431. [CrossRef]
6. Pretty, J.; Bharucha, Z.P. Sustainable intensification in agricultural systems. *Ann. Bot.* **2014**, *114*, 1571–1596. [CrossRef]
7. FoodPrint. The Industrial Food System. Available online: https://foodprint.org/the-total-footprint-of-our-food-system/issues/the-industrial-food-system/ (accessed on 1 June 2024).
8. Crippa, M.; Solazzo, E.; Guizzardi, D.; Monforti-Ferrario, F.; Tubiello, F.N.; Leip, A. Food systems are responsible for a third of global anthropogenic GHG emissions. *Nat. Food* **2021**, *2*, 198–209. [CrossRef]
9. Springmann, M.; Godfray, H.C.; Rayner, M.; Scarborough, P. Analysis and valuation of the health and climate change cobenefits of dietary change. *Proc. Natl. Acad. Sci. USA* **2016**, *113*, 4146–4151. [CrossRef]
10. Tilman, D.; Clark, M. Global diets link environmental sustainability and human health. *Nature* **2014**, *515*, 518–522. [CrossRef] [PubMed]
11. Clark, M.A.; Domingo, N.G.G.; Colgan, K.; Thakrar, S.K.; Tilman, D.; Lynch, J.; Azevedo, I.L.; Hill, J.D. Global food system emissions could preclude achieving the 1.5 °C and 2 °C climate change targets. *Science* **2020**, *370*, 705–708. [CrossRef]
12. Pörtner, H.-O.; Roberts, D.; Tignor, M.; Poloczanska, E.; Mintenbeck, K.; Alegría, A.; Craig, M.; Langsdorf, S.; Löschke, S.; Möller, V.; et al. *Climate Change 2022: Impacts, Adaptation and Vulnerability Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2022.
13. Clark, M.A.; Springmann, M.; Hill, J.; Tilman, D. Multiple health and environmental impacts of foods. *Proc. Natl. Acad. Sci. USA* **2019**, *116*, 23357–23362. [CrossRef]

14. IPCC (Intergovernmental Panel on Climate Change). *Climate Change 2023: AR6 Synthesis Report*; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2023.
15. Jägermeyr, J.; Müller, C.; Ruane, A.C.; Elliott, J.; Balkovic, J.; Castillo, O.; Faye, B.; Foster, I.; Folberth, C.; Franke, J.A.; et al. Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. *Nat. Food* **2021**, *2*, 873–885. [CrossRef]
16. El Khayat, M.; Halwani, D.A.; Hneiny, L.; Alameddine, I.; Haidar, M.A.; Habib, R.R. Impacts of climate change and heat stress on farmworkers' health: A scoping review. *Front. Public Health* **2022**, *10*, 782811. [CrossRef] [PubMed]
17. Willett, W.; Rockström, J.; Loken, B.; Springmann, M.; Lang, T.; Vermeulen, S.; Garnett, T.; Tilman, D.; DeClerck, F.; Wood, A.; et al. Food in the anthropocene: The EAT-Lancet commission on healthy diets from sustainable food systems. *Lancet* **2019**, *393*, 447–492. [CrossRef]
18. Swinburn, B.A.; Kraak, V.I.; Allender, S.; Atkins, V.J.; Baker, P.I.; Bogard, J.R.; Brinsden, H.; Calvillo, A.; De Schutter, O.; Devarajan, R.; et al. The global syndemic of obesity, undernutrition, and climate change: The lancet commission report. *Lancet* **2019**, *393*, 791–846. [CrossRef] [PubMed]
19. Burlingame, B.; Dernini, S. *Sustainable Diets and Biodiversity: Directions and Solutions for Policy, Research and Action. International Scientific Symposium, Biodiversity and Sustainable Diets United Against Hunger*; Food & Agriculture Organization of the UN (FAO) headquarters: Rome, Italy, 2012.
20. McGreevy, S.R.; Rupprecht, C.D.D.; Niles, D.; Wiek, A.; Carolan, M.; Kallis, G.; Kantamaturapoj, K.; Mangnus, A.; Jehlička, P.; Taherzadeh, O.; et al. Sustainable agrifood systems for a post-growth world. *Nat. Sustain.* **2022**, *5*, 1011–1017. [CrossRef]
21. Shannon, K.L.; Kim, B.F.; McKenzie, S.E.; Lawrence, R.S. Food system policy, public health, and human rights in the United States. *Annu. Rev. Public Health* **2015**, *36*, 151–173. [CrossRef]
22. Rockström, J.; Edenhofer, O.; Gaertner, J.; DeClerck, F. Planet-proofing the global food system. *Nat. Food* **2020**, *1*, 3–5. [CrossRef]
23. Clark, M.; Hill, J.; Tilman, D. The diet, health, and environment trilemma. *Annu. Rev. Environ. Resour.* **2018**, *43*, 109–134. [CrossRef]
24. Niles, M.T.; Ahuja, R.; Barker, T.; Esquivel, J.; Gutterman, S.; Heller, M.C.; Mango, N.; Portner, D.; Raimond, R.; Tirado, C.; et al. Climate change mitigation beyond agriculture: A review of food system opportunities and implications. *Renew. Agric. Food Syst.* **2018**, *33*, 297–308. [CrossRef]
25. FAO. *Climate Change and Food Security: A Framework Document*; Food & Agriculture Organization of the UN (FAO): Rome, Italy, 2008.
26. Hammond, R.A.; Dubé, L. A systems science perspective and transdisciplinary models for food and nutrition security. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 12356–12363. [CrossRef]
27. Brouwer, I.; McDermott, J.; Ruben, R. Food systems everywhere: Improving relevance in practice. *Glob. Food Secur.* **2020**, *26*, 100398. [CrossRef]
28. Hospes, O.; Brons, A. Food system governance: A systematic literature review. In *Food Systems Governance: Challenges for Justice, Equality and Human Rights, Kennedy, A., Liljeblad, J., Eds.*; Routledge: Abingdon, UK, 2016; pp. 13–42.
29. Peters, M.; Godfrey, C.; Khalil, H.; McInerney, P.; Parker, D.; Soares, C. Guidance for conducting systematic scoping reviews. *Int. J. Evid.-Based Healthc.* **2015**, *13*, 141–146. [CrossRef] [PubMed]
30. Davis, K.; Drey, N.; Gould, D. What are scoping studies? A review of the nursing literature. *Int. J. Nurs. Stud.* **2009**, *46*, 1386–1400. [CrossRef]
31. Tricco, A.C.; Lillie, E.; Zarin, W.; O'Brien, K.K.; Colquhoun, H.; Levac, D.; Moher, D.; Peters, M.D.J.; Horsley, T.; Weeks, L.; et al. PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation. *Ann. Intern. Med.* **2018**, *169*, 467–473. [CrossRef] [PubMed]
32. Arksey, H.; O'Malley, L. Scoping studies: Towards a methodological framework. *Int. J. Soc. Res. Methodol.* **2005**, *8*, 19–32. [CrossRef]
33. Levac, D.; Colquhoun, H.; O'Brien, K.K. Scoping studies: Advancing the methodology. *Implement. Sci.* **2010**, *5*, 69. [CrossRef]
34. Currie, D.J.; Smith, C.; Jagals, P. The application of system dynamics modelling to environmental health decision-making and policy—A scoping review. *BMC Public Health* **2018**, *18*, 402. [CrossRef]
35. Prosperi, P.; Allen, T.; Cogill, B.; Padilla, M.; Peri, I. Towards metrics of sustainable food systems: A review of the resilience and vulnerability literature. *Environ. Syst. Decis.* **2016**, *36*, 3–19. [CrossRef]
36. Lawrence, M.A.; Friel, S.; Wingrove, K.; James, S.W.; Candy, S. Formulating policy activities to promote healthy and sustainable diets. *Public Health Nutr.* **2015**, *18*, 2333–2340. [CrossRef]
37. Béné, C.; Prager, S.; Achicanoy, H.; Toro, P.; Lamotte, L.; Bonilla, C.; Mapes, B. Understanding food systems drivers: A critical review of the literature. *Glob. Food Secur.* **2019**, *23*, 149–159. [CrossRef]
38. Van Berkum, S.; Ruben, R. *The Food System Approach: Sustainable Solutions for a Sufficient Supply of Healthy Food*; The Hague: Wageningen Economic Research:: Den Haag, Holland, 2018.
39. HLPE. *Nutrition and Food Systems. A Report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security*; Food & Agriculture Organization of the UN (FAO): Rome, Italy, 2017.
40. Zurek, M.; Hebinck, A.; Leip, A.; Vervoort, J.; Kuiper, M.; Garrone, M.; Havlík, P.; Heckelei, T.; Hornborg, S.; Ingram, J.; et al. Assessing Sustainable Food and Nutrition Security of the EU Food System—An Integrated Approach. *Sustainability* **2018**, *10*, 4271. [CrossRef]

41. Pinstrup-Andersen, P.; Watson, D.D.; Frandsen, S.E.; Kuyvenhoven, A.; von Braun, J. *Food Policy for Developing Countries the Role of Government in Global, National, and Local Food Systems*; Cornell University Press: Ithaca, NY, USA, 2011.
42. Meybeck, A.; Gitz, V. Sustainable diets within sustainable food systems. *Proc. Nutr. Soc.* **2017**, *76*, 1–11. [CrossRef] [PubMed]
43. Raza, A.; Fox, E.L.; Morris, S.S.; Kupka, R.; Timmer, A.; Dalmiya, N.; Fanzo, J. Conceptual framework of food systems for children and adolescents. *Glob. Food Secur.* **2020**, *27*, 100436. [CrossRef]
44. Herforth, A.; Ahmed, S. The food environment, its effects on dietary consumption, and potential for measurement within agriculture-nutrition interventions. *Food Secur.* **2015**, *7*, 505–520. [CrossRef]
45. Ruben, R.; Verhagen, J.; Plaisier, C. The challenge of food systems research: What difference does it make? *Sustainability* **2018**, *11*, 171. [CrossRef]
46. Baker, P.; Lacy-Nichols, J.; Williams, O.; Labonté, R. The political economy of healthy and sustainable food systems: An introduction to a special issue. *Int. J. Health Policy Manag.* **2021**, *10*, 734–744. [CrossRef]
47. Ambikapathi, R.; Schneider, K.R.; Davis, B.; Herrero, M.; Winters, P.; Fanzo, J.C. Global food systems transitions have enabled affordable diets but had less favourable outcomes for nutrition, environmental health, inclusion and equity. *Nat. Food* **2022**, *3*, 764–779. [CrossRef]
48. Marshall, Q.; Fanzo, J.; Barrett, C.B.; Jones, A.D.; Herforth, A.; McLaren, R. Building a global food systems typology: A new tool for reducing complexity in food systems analysis. *Front. Sustain. Food Syst.* **2021**, *5*, 746512. [CrossRef]
49. Lähde, V.; Vadén, T.; Toivanen, T.; Järvensivu, P.; Eronen, J.T. The crises inherent in the success of the global food system. *Ecol. Soc.* **2023**, *28*, 16. [CrossRef]
50. Hall, P.A. The role of interests, institutions, and ideas in the comparative political economy of the industrialized nations. In *Comparative Politics: Rationality, Culture and Structure*; Lichbach, M.I., Zuckerman, A.S., Eds.; Cambridge University Press: Cambridge, UK, 1997; pp. 174–207.
51. Monterrosa, E.C.; Frongillo, E.A.; Drewnowski, A.; de Pee, S.; Vandevijvere, S. Sociocultural influences on food choices and implications for sustainable healthy diets. *Food Nutr. Bull.* **2020**, *41*, 59S–73S. [CrossRef]
52. Chaudhury, S.R.; Albinsson, P.A. Citizen-consumer oriented practices in naturalistic foodways:the case of the slow food movement. *J. Macromark.* **2015**, *35*, 36–52. [CrossRef]
53. Vermeulen, S.J.; Park, T.; Khoury, C.K.; Béné, C. Changing diets and the transformation of the global food system. *Ann. N. Y. Acad. Sci.* **2020**, *1478*, 3–17. [CrossRef] [PubMed]
54. Eker, S.; Reese, G.; Obersteiner, M. Modelling the drivers of a widespread shift to sustainable diets. *Nat. Sustain.* **2019**, *2*, 725–735. [CrossRef]
55. Lusk, J.L.; McCluskey, J.J. Understanding the impacts of food consumer choice and food policy outcomes. *Appl. Econ. Perspect. Policy* **2018**, *40*, 5–21. [CrossRef]
56. Petrescu, D.C.; Vermeir, I.; Petrescu-Mag, R.M. Consumer understanding of food quality, healthiness, and environmental impact: A cross-national perspective. *Int. J. Environ. Res. Public Health* **2019**, *17*, 169. [CrossRef] [PubMed]
57. Fanzo, J.; Bellows, A.L.; Spiker, M.L.; Thorne-Lyman, A.L.; Bloem, M.W. The importance of food systems and the environment for nutrition. *Am. J. Clin. Nutr.* **2021**, *113*, 7–16. [CrossRef]
58. Kenny, T.A.; Woodside, J.V.; Perry, I.J.; Harrington, J.M. Consumer attitudes and behaviors toward more sustainable diets: A scoping review. *Nutr. Rev.* **2023**, *81*, 1665–1679. [CrossRef]
59. Baker, P.; Machado, P.; Santos, T.; Sievert, K.; Backholer, K.; Hadjikakou, M.; Russell, C.; Huse, O.; Bell, A.; Scrinis, G.; et al. Ultra-processed foods and the nutrition transition: Global, regional and national trends, food systems transformations and political economy drivers. *Obes. Rev.* **2020**, *21*, e13126. [CrossRef]
60. Li, M.; Jia, N.; Lenzen, M.; Malik, A.; Wei, L.; Jin, Y.; Raubenheimer, D. Global food-miles account for nearly 20% of total food-systems emissions. *Nat. Food* **2022**, *3*, 445–453. [CrossRef]
61. Gustavsson, J.; Cederberg, C.; Sonesson, U.; Van Otterdijk, R.; Meybeck, A. *Global Food Losses and Food Waste*; Food & Agriculture Organization of the UN (FAO): Rome, Italy, 2011.
62. El-Hage Scialabba, N. *Food Wastage Footprint Full-Cost Accounting*; Report for Food & Agriculture Organization of the UN (FAO): Rome, Italy, 2014.
63. Pereira, L. *The Future of South Africa's Food System: What Is Research Telling Us*; Technical Report for Southern Africa Food Lab: Stellenbosch, South Africa, 2014.
64. Turner, C.; Aggarwal, A.; Walls, H.; Herforth, A.; Drewnowski, A.; Coates, J.; Kalamatianou, S.; Kadiyala, S. Concepts and critical perspectives for food environment research: A global framework with implications for action in low- and middle-income countries. *Glob. Food Secur.* **2018**, *18*, 93–101. [CrossRef]
65. Swinburn, B.; Sacks, G.; Vandevijvere, S.; Kumanyika, S.; Lobstein, T.; Neal, B.; Barquera, S.; Friel, S.; Hawkes, C.; Kelly, B.; et al. INFORMAS (International Network for Food and Obesity/non-communicable diseases Research, Monitoring and Action Support): Overview and key principles. *Obes. Rev.* **2013**, *14* (Suppl. 1), 1–12. [CrossRef]
66. Wilde, P. *Food Policy in the United States: An Introduction*, 2nd ed.; Routledge: London, UK, 2018.
67. Ngqangashe, Y.; Goldman, S.; Schram, A.; Friel, S. A narrative review of regulatory governance factors that shape food and nutrition policies. *Nutr. Rev.* **2021**, *80*, 200–214. [CrossRef] [PubMed]
68. Barling, D.; Lang, T.; Caraher, M. Joined-up food policy? the trials of governance, public policy and the food system. *Soc. Policy Adm.* **2002**, *36*, 556–574. [CrossRef]

69. Lang, T.; David, B.; Caraher, M. Food, social policy and the environment: Towards a new model. *Soc. Policy Adm.* **2002**, *35*, 538–558. [CrossRef]
70. Maxwell, S.; Slater, R. *Food Policy Old and New*; Development Policy Review; Wiley-Blackwell: Hoboken, NJ, USA, 2003. [CrossRef]
71. Reisch, L.; Eberle, U.; Lorek, S. Sustainable food consumption: An overview of contemporary issues and policies. *Sustain. Sci. Pract. Policy* **2013**, *9*, 7–25. [CrossRef]
72. Ammann, J.; Arbenz, A.; Mack, G.; Nemecek, T.; El Benni, N. A review on policy instruments for sustainable food consumption. *Sustain. Prod. Consum.* **2023**, *36*, 338–353. [CrossRef]
73. Magnusson, R.; Reeve, B. Food reformulation, responsive regulation, and "regulatory scaffolding": Strengthening performance of salt reduction programs in australia and the united kingdom. *Nutrients* **2015**, *7*, 5281–5308. [CrossRef]
74. Kanter, R.; Kennedy, G.; Boza, S. Editorial: Local, traditional and indigenous food systems in the 21st century to combat obesity, undernutrition and climate change. *Front. Sustain. Food Syst.* **2023**, *7*, 1195741. [CrossRef]
75. Abson, D.J.; Fischer, J.; Leventon, J.; Newig, J.; Schomerus, T.; Vilsmaier, U.; von Wehrden, H.; Abernethy, P.; Ives, C.D.; Jager, N.W.; et al. Leverage points for sustainability transformation. *Ambio* **2017**, *46*, 30–39. [CrossRef]
76. Meadows, D.H. *Leverage Points: Places to Intervene in a System*; Report for The Sustainability Institute: Hartland, VT, USA, 1999.

sustainability

MDPI

Review

Blue in Food and Beverages—A Review of Socio-Cultural, Economic, and Environmental Implications

Agnieszka Szmagara

Department of Chemistry, Institute of Biological Sciences, Faculty of Medicine, The John Paul II Catholic University of Lublin, Konstantynów 1J, 20-708 Lublin, Poland; agnieszka.szmagara@kul.pl; Tel.: +48-81-4545630

Abstract: The presented review concerns the cross-disciplinary approaches to the subject of blue food and blue colourants, the socio-cultural aspects of blue food and beverage consumption, human health effects, environmental impact, and economic aspects. Blue colour in relation to food is not only about improving visual appeal, to which the addition of food colouring is usually limited when the food is coloured in some way that does not encourage eating. It is also the rich and complex sociological side related to food, that is, not only the food itself but also the background, dishware, and light, depending on whether we want to encourage—to increase consumption—or discourage—to, for example, reduce the amount of food eaten for dietary purposes. The negative side of consuming and disposing of synthetic dyes and the health-promoting aspects of natural dyes are also mentioned, with the economic and environmental aspects of sourcing natural dyes being discussed. The food industry uses blue dyes not only for consumption, but also for food quality control, taking advantage of the pH-dependent colour change properties of the compound.

Keywords: sustainability; blue; food; drink; dyes and pigments; food colour; food quality; food decision-making; socio-cultural; economic; environmental implications

Citation: Szmagara, A. Blue in Food and Beverages—A Review of Socio-Cultural, Economic, and Environmental Implications. *Sustainability* **2024**, *16*, 8142. https://doi.org/10.3390/su16188142

Received: 9 July 2024
Revised: 4 September 2024
Accepted: 5 September 2024
Published: 18 September 2024

1. Introduction

Colour signals the edibility and nutritional value of food [1]. According to the FDA (U.S. Food and Drug Administration), a colour additive is "any dye, pigment or substance which when added or applied to a food, drug or cosmetics, or the human body, is capable (alone or through reactions with other substances) of imparting a colour". These may be preparations obtained from natural raw materials (vegetable, animal, mineral, or other source) by selective extraction, isolation, or otherwise derived, with or without an intermediate or final change in the identity of pigments [2]. Based on their use, two groups can be distinguished among food colourants:

- food colourants with a limited permissible daily intake, the maximum levels of which are contained in the relevant legislation (mainly synthetic colourants),
- colourants used in line with the quantum satis rule (comprising mainly colourants of natural origin), which have no defined maximum level of use and should be used at the lowest dose necessary to achieve the intended technological effect, applying the principles of good manufacturing practice.

Dyes are used in foods to improve visual appeal. The addition of colourants to foods is thought to have occurred in Egyptian cities, where confectionery manufacturers cca 1500 BC added natural extracts and wine to enhance the appearance of the product [3,4]. However, it is difficult to speak of such use in the case of the colour blue, where a colour different from the natural one is deliberately used.

The blue colour of food has always signified otherness, but over time the meaning, the sense of otherness, has changed. In the past, blue meant rotten—mouldy; later, with the development of the dye industry, it took on the meaning of 'artificial' [5]. Currently, it has its adherents, especially among young people; the distinctiveness of blue food is perceived positively as unique. Trends over the last few years have shown the increasing popularity of blue food. It seems that acceptance, however, only applies to a certain group of foods. Certain blue foods are already considered 'acceptable', like sweets, candies, cakes, and beverages, and receive significant attention from consumers who are delighted by the colour difference [5,6]. However, consumers still associate blue foods with artificial colouring [6,7].

It appears that determinants of food choice may be linked to affective memory and genetic factors [8,9]. For young people, the blue colour of food can be associated with messages passed down in childhood fairy tales and cartoons, in which blue berries, such as gummiberries (Gummi Bears) and Smurf berries (Smurfs), had magical properties. This fact is not entirely dissimilar to reality, as the intensely blue-coloured berries are characterised by a high content of anthocyanins, which have strong antioxidant effects and interesting properties. When deciding between using natural and synthetic food colourings, it is important to consider the complex benefit-loss balance. From the manufacturer's and retailer's point of view, colourants should, above all, be stable enough to avoid significant degradation during distribution and sale, both the ingredient and the food or beverage, which may include storage from days to years under refrigerated or ambient conditions.

General causes of degradation include heat, light, oxygen, acid, and oxidants like ascorbic acid or trace metals. Producers may have additional demands, such as water- or oil-solubility for defined applications [10].

The issues involved in an interdisciplinary approach to the links between economic, environmental, and social relationships are often complex, interrelated, and defined by the characteristics of each compound. Figure 1 presents the most important sustainable correlations between aspects of the use of natural blue food colourants, according to the main pillars of sustainability with the inclusion and attempted positioning of health aspects and properties (Figure 1). Before considering the socio-cultural, economic, and ecological contexts, a brief review of the current state of knowledge on the origin and properties of blue food dyes is necessary to explore aspects that will show us the turning points, which are also linked to health-promoting aspects. To increase the clarity of the work, Figure 2 illustrates a summary of the content of the review (Figure 2).

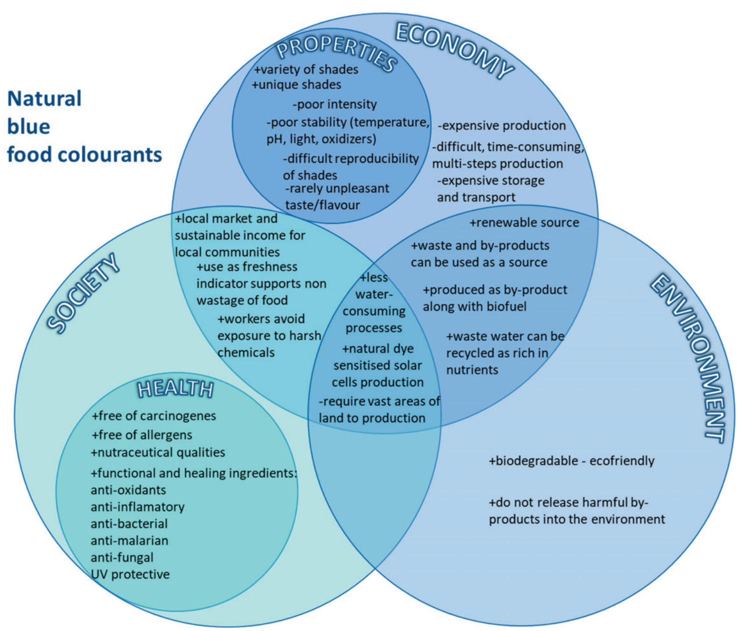

Figure 1. Correlations between sustainability aspects of natural blue food colourants, (+) advantages, (-) disadvantages.

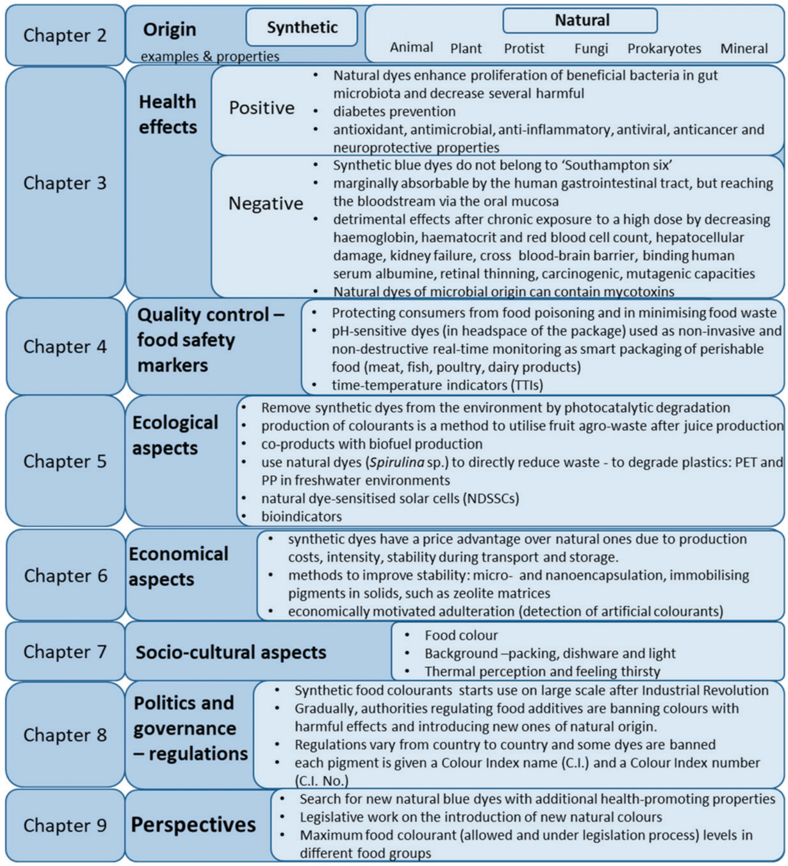

Figure 2. Summary of review content.

2. Origin of Blue Pigments—Food Colourants

Dyes can be of natural and synthetic origin, and blue colour is not always strictly determined by the presence of blue dye in a material. The colour perceived as blue in animals, plants, algae, fungi, and bacteria or as a result of human activities in the manipulation of natural products has two key sources: (i) structural colour caused by the reflection of blue light from nanoscale structures (iridescent phenomenon) and (ii) molecular colour due to red-light absorbers [11].

Nature offers a wide variety of colours [10], but blue is the last colour to appear in the natural world and the last to be developed and produced in the Anthropocene [11]. It is known that blue colours are infrequent in nature because the electronic configurations required for photon absorption at 560–700 nm are complex and rarely occur [12]. Colour systems utilised by liverworts (furanoflavylium), mosses and ferns (3-deoxyanthocyanins), and angiosperms (anthocyanins) are chemically identical, although only the anthocyanins are capable of producing the colour blue [11].

The food industry is seeking more and more colourings of natural origin. It is often the case that a pigment changes colour depending on the pH, as is the case with anthocyanins, whose shade is determined by structural changes that occur under the influence of pH. Under acidic conditions, anthocyanins appear pink or red, while in an alkaline environment, they become blue [13].

There also exist dyes that turn blue when the relevant reaction has occurred. Fruits of Genipa americana L. and Gardenia jasminoides Ellis contain the iridoid glycoside geniposide, which releases the aglycone genipin after enzymatic hydrolysis by β-glucosidase [14]. While genipin is colourless, when it reacts with primary amines and proteins in an aerobic environment, it forms a water-soluble blue pigment that is stable when exposed to light [15] and low pH (3.0–4.0) conditions [16].

Pigments can also turn blue after appropriate treatment, such as thermal degradation. An example of such a pigment is bikaverin, a red polyketide derived from the secondary metabolism of fungi, mainly of the genus Fusarium [17]. Similarly, chamazulene, a component of the volatile oil of chamomile (*Matricaria chamomilla* L.) and yarrow (*Achillea millefolium* L.), turns blue after the thermal degradation of its colourless precursor during distillation [6].

2.1. Synthetic Blue Pigments

The food industry makes extensive use of artificial dyes to restore the colour lost during food processing and storage, enhance the current colour, minimise colour differences in batches, and present the food more attractively to consumers [9,18]. To ensure food has an attractive appearance, food manufacturers use synthetic or natural dyes. Synthetic colours were first produced in the mid-19th century, and due to their low production cost, high heat resistance, and chemical stability, they rapidly became popular as food colourings [3,19,20]. Artificial dyes are divided into two main groups, azo and triphenylmethane [21]. Currently, three artificial colourants are used in the food industry (Figure 3, Table 1): blue dyes (E131 and E133), belonging to the triphenylmethane group, and indigo dye (E132) [9,22].

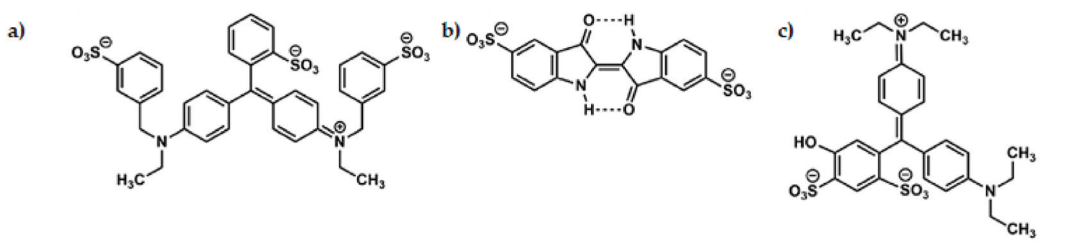

Figure 3. (**a**) Brilliant blue FCF, (**b**) indigo carmine, and (**c**) patent blue V.

Table 1. Synthetic dye properties [3,23,24].

Colourant	ε	λ_{max}	Properties
E131, INS 131 patent blue V	10,600	635	Excellent light and heat stability. Faded by acids and SO_2.
E132, INS 132 indigo carmine syn. Indigotin	7920	607	Poor light heat and acid stability. Poor oxidative and SO_2 stability. Faded by ascorbic acid.
E133, INS 133 brilliant blue	134,000	630	Fair light and acid stability. Poor oxidative stability.

where λ_{max}, wavelength of maximum absorption in nm, ε, molar extinction coefficient (or molar absorptivity) in M^{-1} cm^{-1}.

During the past century, these additives have most often been associated with toxicological risks to human health. Many substances have already been banned in some countries due to experimental confirmations of carcinogenic effects. Still, the food industry uses them as they are cheaper, more stable, and brighter than natural dyes [9,18].

Patent blue (INS 131, E131, Cl food blue 5) is a sky-blue synthetic food colourant with a triphenylmethane group. It is water soluble and slightly soluble in ethanol, in an aqueous solution, and pH-dependent: deep blue in alkaline to weak acidic media and yellow-orange in strong acidic media [23].

Indigo carmine (INS 132, E132) is a synthetic dye, soluble in water but sparingly soluble in ethanol. Originally extracted from a shrub species (*Indigofera tinctoria*), they are currently commonly obtained by chemical synthesis. It is very sensitive to light and oxidising agents such as bleach [23].

Brilliant blue (INS 133 or E133, Cl food blue 2, acid blue 9) is soluble in water and glycerol but only slightly soluble in ethanol. It is very sensitive to light and oxidising agents such as bleach [23].

All above-mentioned synthetic dyes are used in the food industry, especially in flavoured drinks, decorations and coatings for pastry products, pastry and fine bakery products, confectionery including breath-refreshing and chewing gum, flavoured fermented milk products, edible cheese rinds, desserts, edible ices, several types of preserves of red fruits, seasonings, snacks, and alcoholic beverages [23,25].

2.2. Natural Blue Pigments

Naturally coloured foods in yellow, red, and green can be found on the market. Naturally blue foods are mainly blue mould cheeses namely the so-called 'blue-veined' cheeses, which include French Roquefort (sheep's milk cheese, mould produced by *Penicillium roqueforti*) [26], English Stilton, and Italian Gorgonzola (cow's milk cheese, *Penicillium glaucum*), boasting of a history of more than a thousand years [27]. In addition, naturally blue foods include blue corn (*Zea mays* L.) and purple sweet potato (*Ipomoea batatas* L.) [28] varieties such as Purple Majesty [29], Vitelotte [30], Ayamurasaki [31], and Congo [32]. However, in regard to the blue colourants, their use is limited, and natural sources have low stability [6]. At present, only anthocyanins (INS 163) and phycocyanins (INS 134-spirulina) have regulatory approval for their use as blue colourants [5].

Despite the wide range of natural pigments that are used in the food industry, anthocyanins (ANCs), carotenoids, phycobiliproteins, betalains, and chlorophylls remain the most frequently applied [33]. Edible natural pigments not only add colour but also carry the potential for health benefits as bioactive substances [34].

Naturally occurring blue pigments belong to anthocyanins and eight major structural classes: azulenes, quinones, tetrapyrrole, phenazine, indole and pyridine alkaloids, metalloproteins, and organometallics [35].

Natural blue pigments can be categorised according to their origin into those produced by representatives of all five kingdoms of organisms, i.e., animals, plants, prokaryotes [36], fungi, and protists [10,17,37–39] and pigments of mineral origin.

2.2.1. Animals

In animals, blue colours usually arise from the optical effects of blue light reflected by nanoscale structures rather than from the occurrence of true blue pigment molecules [10,17]. The most exemplary are the blue wings of the butterfly *Morpho* sp. [40] and the blue feathers of the bird *Sialia* sp. However, they live mainly in Central and South America. In our part of the globe, i.e., in Poland, it is sometimes possible to observe a butterfly whose wing colour is also based on the same phenomenon. It is a rare purple emperor butterfly (Figure 4b). Similarly, poisonous tree frogs have few natural enemies, and the colour is a deterrent (Figure 4a). The deterrent mechanism is also used by the male moor frog (*Rana arvalis*) during mating season [41].

Some animals, like crustaceans and arthropods, have blue blood due to the respiratory protein haemocyanin instead of the iron-based haemoglobin [42]. The haemocyanin chromophore contains a binuclear copper active site that reversibly binds oxygen molecules [10].

The α-crustacyanin is an example of a blue-coloured pigment found in the carapace of lobsters (*Nephrops*) Leach, 1814 [43], and β-crustacyanin (blue) is found in lobsters (*Homarus gammarus*) [44].

(**a**) (**b**)

Figure 4. Blue animals: (**a**) blue poison arrow frogs *Dendrobates tinctorius* '*azureus*' (Zamość Zoo, SE, Poland, photo: A. Szmagara); (**b**) in sunlight, many shades of blue and purple can be seen on the wings of the purple emperor butterfly (*Apatura iris*) when viewed from an angle (Lublin, SE Poland, photo: A. Szmagara).

From echinoderms, specifically from the vivid blue skin of calcified starfish called "blue star" (*Linckia laevigata* L.), a blue carotenoprotein called "linckiacyanin" (λ_{max} = 612 nm) can be isolated [45].

In ancient times, indigo dye was isolated from the hypobranchial gland of the sea snail *Hexaplex truncculus* (known as *Murex trunculus*, *Phyllonotus trunculus*) [46].

One instance of tetrapyrroles are biliverdins, some of the few blue pigments that occur in the animal kingdom and are responsible for the bluing of bruises [10].

Of these blue pigments of animal origin, a few azulene chromophore-based compounds have been identified in marine organisms like the gorgonians *Paramuricea chamaeleon* [47], *Euplexaura erecta* [48], and *Anthogorgia* sp. [49] and the marine sponge *Dysidea* sp. [10].

2.2.2. Plants

Blue in nature is seemingly popular, but not among flowers [50]. Indeed, flowers perceived by humans as being blue are infrequent (Figure 5), representing, according to various authors, about 7% [51] to <10% of the nearly 300,000 known flowering plant species [52]. Blue flowers are phylogenetically limited, only occurring in 372 out of 14,038 genera of angiosperms worldwide, and in 53 out of 406 families [53]. Moreover, blue is much more common among biotically pollinated flowers than among wind-pollinated flowers, possibly suggesting that investigating the rarity of blue flowers requires a deeper understanding of how animals perceive these colours [50].

The adaptive value of blue flowers should be enhanced by nutrient richness or other factors, abiotic and biotic, that can reduce additional costs of blue pigment synthesis [50]. They display key roles in plant propagation and defence mechanisms [54]. The subsequent production and localisation of anthocyanins in root, stem, and especially leaf tissues can allow the plant to develop resistance to environmental stresses like radiation, cold temperatures, and drought [55]. Such an example is research under which *Centaurea cyanus* cell cultures were evidently protected by anthocyanins from UVB-induced DNA damage [56].

The blue colour in plants is mainly related to anthocyanin content (Table 2). Customer demand for food products containing natural food ingredients and colours has prompted a global demand mainly for anthocyanins [57]. In general, health and nutritional supplements demand multipurpose properties, and anthocyanin is one of them. Anthocyanins are water-soluble pH-dependent plant pigments. Colour variation is affected by changing structural forms. When pH increases from acidic conditions, the flavylium cations (which normally look red, pH $\leq$ 3) become deprotonated, lose their colour (pH 3–6), and finally form quinonoidal bases (purple-blue; pH $\geq$ 6) [58]. Blue colour expression by anthocyanins may also result from co-pigmentation and/or the chelation of metal ions by the pigment, a mechanism widely observed in floral systems [58].

Figure 5. Examples of flowers perceived as blue: (**a**) *Pulmonaria officinalis*, (**b**) *Omphalodes verna*, (**c**) *Veronica chamaedrys*, (**d**) *Hyacinthus orientalis*, (**e**) *Myosotis sylvatica*, (**f**) *Geranium pratense*, (**g**) *Hydrangea macrophylla*, (**h**) *Scilla siberica*, (**i**) *Brunnera macrophylla*, (**j**) *Iris pallida*, (**k**) *Vinca minor*, (**l**) *Veronica persica*, (**m**) *Clematis alpina*, (**n**) *Viola tricolor*, (**o**) *Muscari armeniacum*, (**p**) *Cichorium intybus*, and (**q**) *Hepatica nobilis* (photo: A. Szmagara).

Among the anthocyanin pigments, the blue colour is characterised by delphinidin present in fruit: blackcurrants, blueberries, elderberries, and grapes [39,59], and typically these fruits are the most commonly used sources of anthocyanins in the food industry [60]. Anthocyanins are present also in other parts of plants, in flowers, leaves, and stems.

Anthocyanins extracted from butterfly pea (blue pea, *Clitoria ternatea* L.) flowers (Figure 6) are a prospective food colourant [61] and were investigated in rice and yoghurt drinks [62], in muffins [63], functional beverages [64], and powder drinks [65]. Clitoria flower extract at pH 5–8 and shikonin from gromwell roots (*Lithospermum erythrorhizon*) in alkaline solutions (pH 10–12) express blue hues [66]. The anthocyanins of red cabbage and purple sweet potato showed colours similar to indigo carmine (E132) at a pH of 8 [67].

Anthocyanin complexes with flavones and metal cations have been indicated as responsible for the blue colours of many floral systems [68]. In addition, certain nutrients, in particular aluminium Al^{3+} and Fe^{3+} cations, combined with a low soil pH $\geq$ 2.5 [69], may lead to a colour change from violet to blue in certain plants [50,55,58].

Figure 6. Infusion of dried butterfly pea flowers (*Clitoria ternatea* L.) (A. Szmagara).

Commelinin, from Asiatic dayflowers, is a blue pigment that is stable in concentrated solutions at pH $\geq$ 2.4; when diluted, the molecule readily dissociates and loses its blue colour [68]. Pires and colleagues employed pigment extracted from cornflower (*Centaurea cyanus* L.) flowers, which contain high amounts of anthocyanins (TAC = 26 μg/g) to improve yoghurt [70].

Trichotomine and its glycosides are bis(indiol) alkaloids isolated from Kusagi berries (*Clerodendron trichotomum* Thun.), a shrub native to Asia. In addition to high absorption at 660 nm (pH5) and similarity to brilliant blue (E133), they appear to be stable and safe [10,71]. For reasons linked to the difficulty of large-scale cultivation and the low amounts of pigment in the fruit, the berries have not been commercially exploited, and as a compound that does not have a long history of safe consumption, it requires a comprehensive safety assessment before approval and commercialisation [8].

Gardenia sp. and *Genipa americana* L. are sources of iridoids, pigments that occur both in free and glycosylated forms (genipin and geniposide). Genipin, after being exposed to oxygen, reacts with primary amino acids and protein hydrolysates to form water-soluble blue pigments [72].

Vaccinium bracteatum leaves are also rich in iridoids, and their aqueous extracts were used by natives of the south of the Yangtze River as the materials of 'Wu mi' to dye rice into a blue colour, which turned dark blue after cooking [73].

Another blue compound with an extended quinone structure, ventilein A (λ_{max} = 645 nm), was isolated as a minor constituent from *Ventilago calyculata* root bark [74] and from *Ventilago goughii* [10,75].

Azulenes belong to the class of plant-derived colourants, bicyclic azure-blue aromatic pigments, resulting from the fusion of a cyclopentadiene and a cycloheptatriene ring. They include, inter alia, chamazulene, a constituent of the volatile oil of some perennial herbs, like chamomile (*Matricaria chamomilla* L.) and yarrow (*Achillea millefolium* L.), which is a blue-coloured derivative resulting from the thermal decomposition of a colourless precursor during distillation. The use of azulenes as food colourants is constrained due to the slight water solubility and odour similar to naphthalene [6].

The blue colour can be related to blue copper proteins, which may be present, among others, where they usually have biosynthetic functions involving electron transfer [10,76]. Examples include stellacyanin [77] and plastocyanin [78], which are type I copper-binding proteins (cupredoxins) common in vascular plants. Other proteins of this type include cuscacyanin and phytocyaninin from cucumber [79] and umecyanin from horseradish root [80].

Table 2. Selected natural blue pigments produced by plants.

Compound	Plant	λ_{max}	ε	References
azulene	*Artemisia* sp. (oil)	576	362	[10]
diosindigo A	*Diospyros* sp. (tree; heartwood)	697	28,180	[10,81]
2,12′-bis(hamazulenyl)	*Ajania fruticulosa* (oil)	657	132	[10]
indigotin	*Indigofera tinctoria* (Indigo plant)	610	22,140	[10]
genipocyanin G_1	*Gardenia jasminoides, Genipa americana*	595	43,700	[10]
guaiazulene	*Matricaria chamomilla* (oil)	648	407	[10]
lactarazulene	*Artemisia* sp. (oil)	604	871	[10]
oenin	*Vitis vinifera* skin, aged wine	538	16,000	[10]
portisin A	*Vitis vinifera*; aged wine	587	82,900	[10]
shikonin	*Lithospermum erythrorhizon* (roots)	n/a	n/a	[66]
ternatin	butterfly pea (*Clitoria ternatea* L.)	548	n/a	[82]
trichotomine	*Clerodendron trichotomum* (fruit callus)	658	70,000	[10]
ventilein A	*Ventilago calyculata* (root bark) *Ventilago goughii*	645	n/a	[10]

where: λ_{max}, wavelength of maximum absorption, ε, molar extinction coefficient (or molar absorptivity) in M^{-1} cm^{-1}, n/a—data not available.

2.2.3. Protists

Blepharisma japonicum is one of the few protists that possesses a pigment. The pigments it produces, i.e., blepharins such as oxyblepharin A and analogues, are red, but their photoreaction products are blue (λ_{max} = 592) [10,83].

2.2.4. Fungi

Fungi and microorganisms produce a diverse range of blue compounds (Table 3), usually as a response to environmental stress or predators [10]. Moulds are a source of pigments that can be exploited by the food industry. This is consistent with the changing market preferences of consumers, who need a source to replace synthetic pigments [84]. Filamentous fungi are among the natural sources currently being investigated for pigment production. *Fusarium graminearum* produces, inter alia, a blue pigment (6–O–demethyl–5–deoxybostrycoidin anthrone) [85], and *Lactarius* sp. produces azulenes (blue) [84,85].

The usage of fungal pigments in food matrices also depends on their stability to pH fluctuations, heat, and UV light, which are attributes typically occurring in food processing [86].

Fungal species producing blue pigments are also found in extreme environments—a fungus of the genus *Periconia* isolated from a hypersaline environment (Puerto Rico) subjected to high solar radiation has been reported to produce a still unidentified and unusual pigment [87], and *Antarctomyces pellizariae*, a snow-dwelling ascomycete found on Robert Island, in the South Shetland Islands, Antarctica, produced a blue pigment [88].

Table 3. Natural blue pigments produced by fungi.

Compound	Organism	λ_{max}	ε	References
albatrellin	*Alabtrellus flettii* (Basidiomycete)	535	3162	[10]
candidine	*Candida lipolytica*	573	12,880	[10]
corticin A	*Corticium caeruleum*	565	6900	[10]
guaiazulene	*Lactarius* sp.	648	407	[10]
lactarazulene	*Lactarius* sp.	604	871	[10]
sanguinone A	*Mycena sanguinolenta*	578	437	[10]
scleroderris blue	*Gremmeniella abietina*	612	50,000	[10]
variegatic acid anion	Basidiomycete fungi	605	n/a	[10]
Blue pigments (unnamed)	some fungi such as *Penicillin* sp. and *Hypocrea* sp.	n/a	n/a	[10,89]

where: λ_{max}, wavelength of maximum absorption, ε, molar extinction coefficient (or molar absorptivity) in M^{-1} cm^{-1}, n/a—data not available.

Notwithstanding the listed benefits, there is a danger of mycotoxins associated with the use of fungal pigments in the food industry, as some fungi synthesise pigments together with mycotoxins. The presence of mycotoxins in pigments limits their use as additives [85,87]. For example, the EU and the US ban the consumption of *Monascus* pigments that are generated with the nephrotoxic and hepatotoxic citrinin mycotoxin, questioning their safe use [90], although *Monascus* red-coloured foods are consumed by over 1 billion Asians [37,87].

The development of fungal pigment production on a feasible scale and with industrial perspectives in mind is an approach worthy of consideration. Selecting efficient fungal strains with minimal/zero mycotoxin co-production and lower energy requirements is a crucial driver for production relevance [91]. Furthermore, major biological issues such as ensuring fungal strain stability, reducing mycotoxin co-production, and inducing higher pigment production titres can be addressed through the genetic engineering of fungal strains [92].

Anthocyanins, which are derived from red-pigmented fruit, are often used in the food industry as colouring agents, and among these, there are fungal infections with mycotoxin-producing microorganisms, including patulin [93].

2.2.5. Prokaryotes

The existence of pigments has been recorded throughout the microbial world, including bacteria, fungi, yeasts, algae, and protozoa [94]. These microorganisms can be isolated/cultivated from a variety of environmental sources, such as water, soil, plants, insects, and animals [94].

Pigmented species are numerous in the prokaryotic world (Table 4). The presence of blue pigments is echoed in the names of many genera and species of heterotrophic bacteria through the use of Greek, Latin, or neo-Latin terms, including *Vibrio azureus*, *Gemmobacter caeruleus*, *Rheinheimera coerulea*, *Actinoallomurus caesius*, *Saccharomonospora cyanea*, and *Ciceribacter lividus*. Phototrophic prokaryotes that use light absorbed by pigments can also exhibit a blue colour, as reflected in names such as Cyanothece [36]. Properties that include the colony colour and the presence of distinct pigments can be used for the taxonomic characterisation of prokaryotes [95], and the pigments may even be implicated as potential biosignatures of extraterrestrial life in astrobiology [96].

Carotenoids are rarely blue [36], like in the case of certain marine organisms. Examples include the caroteno-protein asteriarubin found in the starfish *Asterias rubens* (with astaxanthin derivatives) [97], crustacyanin known from *Homarus gammarus* (also with astaxanthin) [98], and marennine produced by the diatom *Haslea ostrearia.* Diatoms with blue tips, recorded as *H. ostrearia*, have been reported from almost all seas and oceans [99], in both the northern and southern hemispheres [100], for example, inhabiting oyster ponds on the Atlantic Coast (France) [101]. Moreover, other diatoms, like *H. provincialis* in the Mediterranean Sea [102] and *Haslea karadagensis* on the Crimean coast of the Black Sea (Ukraine) [100] produce blue pigments. A marennine-like blue pigment is also produced by the diatom *Haslea nusantara* found in the tropical region of the Southern Hemisphere in the Java Sea (Indonesia) [103], and cosmopolitan species of the blue diatom *Haslea silbo*, found on both sides of the Atlantic Ocean [104]. Some microalgae, which can grow in both saltwater or freshwater, and phytoplankton provide a rich source of blue phytobiliproteins [14,45]. Structurally, phycocyanins are bioactive peptides, classified based on their protein and pigment contents [105]. The best-known cyanobacterium is *Spirulina* spp., which has a high phycocyanin content of up to 20% dw.

Table 4. Natural blue pigments produced by prokaryotes.

Compound	Organism	λ_{max}	ε	References
actinorhodin	*Streptomyces coelicolor*	640	25,300	[10]
akashin A	*Streptomyces* sp. GW 48/1497 (marine)	619	16,232	[10]
ammosamide A	*Streptomyces* CNR-698 (marine)	584	5200	[10]
anthracyclinone-blue B	*Streptomyces galilaeus* mutant	608	28,890	[10,106]
bactobilin	*Clostridium tetanomorphum*	633	n/a	[10]
benthocyanin A	*Streptomyces prunicolor*	638	16,200	[10]
blue pigment (unnamed)	*Arthrobacter* sp., *Nocardia* sp.	648	17,380	[10]
daunorubicin	*Streptomyces peucetius*	530	6000	[10]
glaukothalin	*Rheinheimera* sp. HP1 (marine γ-Proteobacteria)	636	32,360	[10,107]
granaticin B	*Streptomyces violaceoruber*	630	8910	[10]
indigoidine	*Corynebacterium insidiosum*	602	23,400	[10,108]
indochrome A	*Arthrobacter polychromogenes*	570	38,100	[10]
kyanomycin	*Nonomuria* sp	600	11,480	[109]
lavanducyanin	*Streptomyces aeriouvifer*	705	1700	[10]
lemonnierin	*Pseudomonas lemonnieri*	625	56,230	[10]
marennine	*Haslea ostrearia* (marine diatom)	672	7200	[10,101]
N,N-dodecylindigoidine	*Shewanella violacea* DSS12 (marine)	636	n/a	[10]
phenazinomycin	*Streptomyces* sp. WK-2057 mycelia	745	6600	[10]
phycocyanobilin	*Spirulina* sp., common among cyanobacteria	604	17,100	[10]
prodeoxyviolacein	*Chromobacterium violaceum*	609	25,000	[10]
prodigiosin tetrapyrrole	*Serratia marcescens*, *Hahella* sp. (marine)	588	n/a	[10]
pyocyanin	*Pseudomonas aeruginosa*	745	5800	[10]
spirulina	*Spirulina platensis* (*Arthrospira platensis)*	604	17,100	[3]

where: λ_{max}, wavelength of maximum absorption, ε, molar extinction coefficient (or molar absorptivity) in M^{-1} cm^{-1}, n/a—data not available.

The main limitation of phycocyanin is its low thermal resistance, resulting in a fading colour [110]. Thermostable phycocyanin from the red microalga *Cyanidioschyzon merolae* is a new natural blue food colourant [111]. Cyanobacteria *Aphanizomenon* sp. produce a blue pigment called phycocyanin, which is used in the food and beverage industry [19,110].

The bacteria produce a whole palette of colour shades, among them blue pigments with market potential: *Corynebacterium insidiosum*—indigoidine, *Erwinia chrysanthemi*, and *Vogesella indigofera* [19,92,108,112].

Among actinomycetes, *Streptomyces coelicolor* is well known to produce the blue pigment actinorhodin [20,108], a pigment used in the food industry as an ice cream colourant. Other soil-born *Streptomyces* sp., i.e., *S. vietnamensis* [113], *S. shaanxiensis* [114], *S. caeruleatus* [115], and *Streptomyces* sp. A1013Y [116], are also responsible for producing blue pigments.

The first reported study concerning microbial indigo production was conducted in 1928, using *Pseudomonas* strains isolated from soil [117]. Since then, many microorganisms have been shown to be able to produce indigo [17], especially the genera *Pseudomonas*, like *P. fluorescens* [118] and *Acinetobacter* [119]. For example, the blue pigment pyocyanin, extracted from *Pseudomonas aeruginosa* [108,112], when assessed for its utilisation as a food colouring with agar, gave a pleasant colour at 25 mg mL^{-1} [120].

Another pigment is glaukothalin produced by *Rheinheimera* sp. isolated from the Wadden Sea (Germany) and Øresund (Denmark) [107].

Indigoidine is a pigment from the carotenoid group [121], which is synthesised by very few microorganisms [88], namely *Erwinia chrysanthemi* [122], *Phaeobacter* sp. [123], marine *Pseudomonas nigrifaciens* [124], *Rhodosporidium toruloides* [125], *Streptomyces chromofuscus* [126], and *Vogesella indigofera* [127].

Natural anthraquinoid compounds are rarely blue under acidic conditions, but there are a few exceptions, which include the microbial metabolites of anthracyclinone-blue B from the *Streptomyces galilaeus* mutant [106] and kyanomycin obtained from *Nonomuria* sp. [109].

Among alga-derived sources, *Porphyridium aerugineum* red microalga-derived blue colour (λ_{max} = 620 nm) has been used for acidic beverages. These pigments display a stable blue colour (not typical of blue colours from Cyanobacteria) at pH 4.0–5.0 for 1 month at room temperature or up to 40 min at 60 °C [33]. It can be successfully assayed in acidic, non-heat-treated carbonated beverages (Pepsi® Blue) or low-grade alcohol beverages (Bacardi Breezer®) [128].

2.2.6. Minerals

Minerals have long been used as pigments in food, cosmetics, and art. Currently, no blue minerals are used in the food industry. Only one mineral pigment with deep blue tones, ultramarine blue, is used in animal feed [58].

3. Health

The usage of natural pigments in place of synthetic ones is increasingly popular, as the former are widely regarded as safer, healthier, and more environmentally friendly [21,129]. Because of growing health awareness, replacing artificial colourants with natural alternatives is a prime challenge for the food industry [6].

3.1. Positive Health Benefits

Natural pigments not only offer colour but also provide prospective health benefits as important bioactive compounds [130].

The consumption of extracted pigments has been associated with human health promoting effects [45,131], but the bioaccessibility and bioavailability of pigments are determined by their chemical characteristics and the principal digestive processes.

An in vitro study with bacterial strains showed that after incubation with black rice anthocyanins, *Bifidobacteria* and *Lactobacillus* increased and pH values decreased [132]. Similarly, Sun et al. [133] found that after incubation of peonidine derivatives with various bacterial strains, pH values decreased and growth rates of *B. bifidum*, *B. adolescentis*, *B. infantis*, and *L. acidophilus* increased. They concluded that the metabolism of anthocyanins by microbiota bacteria results in a decrease in pH and provides a suitable medium for the proliferation of probiotic bacteria [134]. In order to enhance the effect of the anthocyanins and prevent their premature degradation, as well as modulate the gut microbiota, they can be supplied to the body after appropriate treatment, i.e., encapsulation with different materials [63,135].

Anthocyanins may not only enhance beneficial bacteria in gut microbiota but may also decrease several types of harmful bacteria. Flores et al. [136] found that *Clostridium histolyticum* was strongly reduced after colonic fermentation of some anthocyanins, i.e., cyanidin and delphinidin derivatives.

Factors affecting anthocyanin bioavailability include food processing (↑steam-blanching, ↑juice processing—milling, mashing, pressing, pasteurisation, ↓fermentation, ↓microwave cooking, ↓conservation, jam, squeeze), food matrix, hydrolysis by various enzymes in the small intestine and metabolism, and intestinal bacterial enzymatic activity in the gut microbiota [134].

Pigments can be used as antioxidants, anticancer agents, and antimicrobial agents [92]. Anthocyanins are known for their health-promoting properties, and these beneficial properties also include diabetes prevention [57]. The beneficial effects of an aqueous extract of *Clitoria ternatea* were studied in vivo in a mouse model of obesity and metabolic syndrome. The extract alleviated oxidative stress and inflammatory mediators. Moreover, the plasma leptin, free fatty acids, low-density lipoprotein cholesterol, and hepatic malondialdehyde levels were decreased. The extract significantly reduced total cholesterol and alleviated insulin resistance. The results showed that the aqueous extract of *C. ternatea* petals contains bioactive anthocyanins, which enforce significant hypolipidemic and anti-inflammatory effects by promoting reverse cholesterol transport in mice [137].

Iridoid genipin shows antimicrobial, anti-inflammatory, and anticancer properties, while geniposide (glycosylated form of genipin) has been described as a regulator of insulin and exerts protective effects in asthma [138].

The iridoid glucosides present in *Vaccinium bracteatum* Thunb. leaves [73] are responsible for the dark blue colour and most of the health-beneficial properties in the traditional food, 'Wu mi'. According to a millennia-old custom, VBT leaves are harvested in the spring around Tombsweeping Day to make the cereal food 'Wu mi'. The conventional process involves using the fresh leaves to homogenise and extract juice to soak rice, which is dyed dark blue after an soaking overnight. This process and product, 'Wu mi', was recorded in Shizhen Li's Compendium of Materia Medica as a functional food with qi-beneficial effects to improve eyesight, revitalise the body, maintain agerasia, and prolong life. Currently, there is a trend to use 'Wu mi' as a health food for diabetic patients because no drastic symptoms of glycaemic response were observed in diabetic patients after consuming 'Wu mi' compared to rice. Moreover, the antimicrobial activity of *Vaccinium bracteatum* Thunb. Leaves, traditionally used for food preservation in China, was verified [139]. The aqueous extracts can successfully inhibit the growth of *Escherichia coli*, *Staphylococcus aureus*, and *Bacillus subtilis*.

In addition to their colourant properties, bacterial and fungal pigments exhibit numerous biological activities such as antioxidant, antimicrobial, and anticancer effects [92]. Bioactive compounds of bacterial isolates such as pyocyanin (blue-green) serve as novel compounds with antioxidative, antimicrobial, antiviral, antitumor, antiprotozoa, antioxidant, anticancer, and immunomodulatory activities and also reduce allergy risks [108,130]. Pyocyanin has been used as a bio-control agent and possesses antibacterial and antifungal actions [92,140]. This dye can inhibit the development of *Escherichia coli* [140], *P. aeruginosa*, *Staphylococcus aureus*, *S. saprophyticus,* and *Enterococcus faecalis* [108] and has proven antimicrobial activity towards *Citrobacter* sp., which is common in urinary tract infections and wounds [19].

Algae or cyanobacteria are famous for their bioactive ingredients and dietary components [105]. Phycocyanin peptides show health-promoting properties, such as immunomodulatory [141], anti-inflammatory, anti-cancer [142,143], antidiabetic [144], neuroprotective [145], hepatoprotective [146], and antioxidant [147] effects [105].

Marennine pigments are natural blue pigments that exhibit different biological actions—e.g., antioxidant and free radical scavenging properties [101] and antimicrobial and antiproliferative properties—with great potential for food applications [99]. Marennine, the structure of which stays unsolved [148], displays an antiproliferative effect on the growth of lung malignant cells in cell models [149], and exhibits antiviral [150] and anticoagulant properties [151].

3.2. Negative Health Effects

All three synthetic blue pigments (E131, E132, and E133) are water-soluble and anionic, and belong to the group of non-azoic dyes [152]. E131 and E133 are triphenylmethane dyes while E132 is pyrrole-based.

Although these dyes are used in monitored doses evaluated to guarantee consumers' safety, their purity specifications allow concentrations of impurities such as aromatic non-sulphonated amines, with genotoxic and carcinogenic effects, and can be as high as 100 mg/kg of dye [5].

The synthetic dye brilliant blue (BB; E133) is a triphenylmethane dye, not an azo dye, but can induce reproductive and neurological disorders, and can also cause allergic reactions [153]. Allergic reactions were also reported after the use of the food dye patent blue (E131) [154].

Unfortunately, most artificially coloured foods, such as sweets, confectionery, ice cream, snacks, breakfast cereals, and cakes, are consumed daily by children [152]. Amounts in the range of 0.3–33 mg in sweets, 9.4–41.3 mg in breakfast cereals, 1.9–6 mg in ice cream, and 2.8–14.4 mg in snacks can be consumed daily by children [155]. It is even possible for a child to consume, from a variety of sources, cumulative amounts of colourings well above the recommended ADI levels, as each food may contain colourings at the maximum allowable concentration [5]. There are no reports of side effects in children caused by the aforementioned blue colourants. A large survey called the 'Southampton study' found behavioural disturbances, irritability, anxiety, and sleep disturbances after ingesting large amounts of artificial colourants and included six of the most common colourants, the so-called 'Southampton six', but none of the blue colours [156]. Allergic reactions may occur, including reactions caused by immune (immediate and late hypersensitivity) and non-immune (intolerance) mechanisms, which arise more rapidly in children. In addition, the long-term intake of these colourants can have prolonged consequences owing to the accumulation of these substances in the body [21,152]. The Acceptable Daily Intake (ADI) factors for individual synthetic dyes are (EU/US) [mg/kg bw] E131—(5/-); E132—(5/2.5); and E133—(6/12) [152].

Brilliant blue is reported to be marginally absorbable by the human gastrointestinal tract and is found unchanged in human faeces [57,157]. However, both brilliant blue and patent blue are absorbed via the oral mucosa, reaching the bloodstream. The studies by Lucova et al. [158] on the blue hues E131 (patent blue V) and E133 (brilliant blue) showed that both were able to pervade the bloodstream through the back of the tongue and, in slightly damaged skin, can infiltrate epithelial cells and reach the circulatory system without passing through the digestive system, making them more harmful as their opportunities for decomposition become minimal. Therefore, the use of these colourants in lollipops, chewing gum, sucking candies, and topical products should be strongly avoided [57].

There are reports of detrimental effects after chronic exposure to a high dose of brilliant blue by decreasing haemoglobin, haematocrit, and red blood cell count [9,157], as well as hepatocellular damage, kidney failure, and decreased sperm production as an effect of patent blue [158–161]. In vitro experiments on the effects of brilliant blue on serum and lymphocyte cell lines have shown that this dye has mutagenic and carcinogenic capacities [160] and causes retinal thinning [162].

Research has been reported on the issue of patent blue colourant binding to human serum albumin [157].

Brilliant blue represents the only approved food colouring that crosses the blood-brain barrier [29]. In an in vitro test, blue no. 1 (brilliant blue) inhibited neurite growth and worked in synergism with L-glutamic acid, which suggests the neurotoxicity potential. This is especially worrying for foetuses and children younger than 6 months of age in whom the blood-brain barrier is not fully developed [18]. blue no. 2 (indigo carmine) was found to be incapable of crossing the blood-brain barrier [18].

On the other hand, very few toxicological studies have been reported for natural food colourants, and only when they are adulterated by other synthetic food ingredients [57].

4. Quality Control—Food Safety Markers

The food industry uses blue dyes not only for consumption but also for food quality control, taking advantage of the pH-dependent colour change properties of the compound.

Freshness indicators are a type of smart packaging that offers non-invasive and non-destructive real-time monitoring of food quality and safety [163]. Based on research issued by FAO, approximately one-third of the total food produced for human consumption worldwide is wasted annually, costing an estimated USD 1 trillion. In industrialised countries (i.e., North America and European countries), food losses occur mainly at the distribution and consumption stages [164]. Freshness indicators have a promising role not only in protecting consumers from food poisoning but also in minimising food waste and increasing sustainability by offering more dynamic "use-by" dates [163,165].

As losses are particularly acute in the meat, fish, and poultry sectors—causing wastage of more than half of the total production—the need for the specific monitoring of these high-value products is highly desirable. The spoilage of these products is predominantly driven by microorganisms, which produce various metabolites (i.e., CO_2, H_2S, TVB-Ns) [166]. When these compounds begin to accumulate in the headspace of the package, a change in pH follows over time, which can be detected with a suitable pH-sensitive indicator. Spoilage metabolites react with the pH-sensitive dyes trapped in a matrix, resulting in a visible colour change readily differentiated by consumers [167]. The synthetic dyes phenol red (PR) and bromothymol blue (BTB) are used as real-time CO_2-sensitive freshness indicators in the three-layer system using cellulose-based binder, which was developed to determine the freshness/spoilage of chicken breasts [168], as well as the freshness of shrimp [169].

Of the approximately one-third of food produced worldwide that is lost or wasted, it is estimated that fruits and vegetables account for between 40% and 50% of the total [170]. Blue dyes, like methylene blue, are also used as nano-fibre smart indicators for the direct monitoring of fruit freshness [171].

To date, the development of freshness indicators based on synthetic or natural pH-sensitive dyes has been reported [172–174]. While natural dyes are non-toxic, stability issues hinder the application of natural dyes in smart labels for the food packaging industry, not to mention that natural dyes are often applied with natural matrices (e.g., starch, chitosan) that are not commercially used [175,176].

The recent literature describes commonly used natural dyes for more sustainable smart packaging [66,177–179]. An excellent example of such pigments are water-soluble anthocyanins that exhibit the ability to change colour with pH change and, in addition, have strong antimicrobial and antioxidant properties, making them a suitable agent for active packaging [180]. Colour changes are due to a modification of the chemical structure of the phenolic substances in anthocyanins as a result of pH changes [181] and thus can be effectively used in the development of pH-sensitive smart packaging to assess food freshness and quality [182,183].

The freshness of food depends not only on the storage time but also on the temperature. Fresh food spoils easily due to the increase in contaminants at a certain temperature. Extreme temperatures and their fluctuations have a major impact on the shelf life of refrigerated food products. Monitoring and controlling the storage temperature of food products, such as fish, for example, is crucial as temperature largely determines the rate of microbial activity. The result, i.e., the growth of harmful microorganisms, can be the same in both cases, i.e., too high a temperature or too long a storage time. Temperature fluctuations can be encountered at any point in the supply chain. Therefore, monitoring and recording the temperature history of these products from production to loading, unloading, temperature cycling in cold stores, storage exposures, and domestic transport to consumption is very important. Solutions capable of assessing the temperature history of foods are known as time-temperature indicators (TTIs), whose mechanism of action in most microbial TTIs is through irreversible colour change. The dye produced by *Pantoea agglomerans* may have a potentially interesting application as a food temperature indicator. The normally yellow cells of *P. agglomerans* secrete a water-soluble dark blue dye into the environment of the agar medium at temperatures above 10 °C. Furthermore, this dye turns pink under acidic conditions [184].

Determining the freshness of food also relies on O_2 and CO_2 measurements [185], as CO_2 inhibits the growth of bacteria and fungi, while it can also lower the pH in the food environment. The antimicrobial effect of CO_2 is due to its ability to create an anaerobic environment, which prevents enzymatic decarboxylation. The accumulation of CO_2 can also interfere with the membrane permeability of some microorganisms. Several microbial metabolites can affect the food pH, so controlling the amount of CO_2 and monitoring pH changes can be an effective method of identifying food spoilage and is crucial for extending the shelf life of food products. Modified atmosphere packaging (MAP) for non-reactive foods typically consists of a low O_2 concentration (0–2%) and a high CO_2 concentration (20–80%).

Furthermore, moisture content is an essential indicator to be observed when testing food quality, as increased moisture content provides a favourable growth environment for microorganisms and fungi, thus becoming a safety issue for product consumption. In addition to microbial growth and the associated changes in CO_2 content and pH level, moisture also results in a shorter shelf life due to the decomposition of the dry product, causing it to soften and become damp [185].

Natural colourants have been successfully used for the intelligent packaging of meat products [57] such as beef, pork, and poultry (red radish extract [186], purple sweet potatoes [182] and grape skin for chilled pork [187], blueberry [188] and red cabbage [189] for sausage [190], roselle (*Hibiscus sabdariffa*) for pork [183]), seafood and fish products such as shrimp and fish fillets (red cabbage for fish [191], red cabbage for prawns [192], butterfly pea flower (*Clitoria ternatea*) [193] and black rice bran for seafood [194]), and milk and dairy products (red cabbage for cheese [195], purple sweet potato for milk [13], grape for milk [196], red cabbage [197] and anthocyanins for milk [198]).

5. Ecological Aspects

The agri-food industry has become a world-leading sector, producing large quantities of highly coloured effluents [199].

Most of the colourants are water-soluble, making their isolation and treatment much more difficult and sometimes impossible by traditional coagulation, filtration, or adsorption methods, and they have been undegradable, persistent, and prevalent in the environment for many years [57]. Therefore, the treatment and reuse of industrial water is an important and urgent necessity. Drhimer and co-workers presented a method for removing brilliant blue by photocatalytic degradation with the presence of TiO_2 as a catalyst and its further recycling. The results showed 98% degradation of brilliant blue at the laboratory scale and 93.3% and 75% at the pilot-scale using recirculation reactors with flow rates of 800 and 200 $L \cdot h^{-1}$, respectively [199].

In view of the harmfulness of brilliant blue to natural habitats, methods are being developed to remove it from the environment. Yousefi et al. investigated the oxidative degradation of brilliant blue FCF in the presence of zero-valent iron as a catalyst, and the degradation took place over 30 min [153] When using green synthesised silver nanoparticles (AgNPs) as a nanocatalyst for BB reductive degradation, the reaction was twice as fast [200].

On the other hand, natural colourants are biodegradable and non-toxic [57]. Natural dyes are eco-friendly and do not release harmful by-products into the environment. Furthermore, natural pigments are a renewable resource, and, in addition, waste and by-products can also be used as a source. Sometimes, however, the production of colourants like anthocyanins takes place using a method for utilising fruit agro-waste after juice production [177], such as blackberry residues [54,201], blueberry pomace [188], or a mixture of their extracts [180], which are substantial sources of natural colourants due to their high anthocyanin content. This has understandable ecological implications. Also, processed garlic and its blue-green discolourations, which are derivatives of pyrrole compounds, may be the source of pigments [58,202]. The reasoning behind these pigments is strictly related to a decrease in the content of the compound thiosulfinate, which also results in a reduction in the aroma of allium. Eight compounds were also identified as blue or green and are usually tri- or tetrapyrroles [202]. Microbial pigments can also be produced quickly and easily in a culture medium, which can even be waste [130].

Using waste to produce pigments and thus contributing to a reduction in waste is very important. However, scientists are trying to go one step further and use natural blue dyes to directly reduce waste. The possibility of using the microalgae *Spirulina* sp., which produce a natural blue dye, to degrade plastics such as PET (polyethylene terephthalate) and PP (polypropylene) in freshwater environments is being explored [203].

From an ecological point of view, even for natural pigments, the method of extraction is also very important. The spontaneous release of marennin by microorganisms of microalgae makes this natural pigment of great interest for industrial applications, since usually long extraction procedures using environmentally harmful organic solvents and various separation techniques are required to isolate the pigments from plants or flowers and result in the generation of organic waste from unused plant parts [99].

Natural pigments are produced from microalgae grown in bodies of water, such as open ponds, raceways, and natural lakes, especially in tropical and subtropical regions, and unfortunately require vast areas of land for production. A favourable solution can be combination with biofuel production [204]. Of course, sustainable practises and conditions, such as locations outside priority areas for biodiversity and carbon storage (e.g., tropical rainforests) prevent deforestation and promote sustainable biofuel production practises [205]. These technological improvements include the development of biorefinery systems, in which high-value co-products such as pigments and proteins [206] are extracted along with biofuels [207,208], and the recycling of water and nutrients from cultivation (e.g., through anaerobic digestion) [209].

Particular attention should be paid to the fact that the overexploitation of algae from their natural sites can lead to their total exploitation, as well as to possible environmental degradation and ecological disasters, as sand from the seabed is maintained by the algae and, when they are not present, the sand is washed away.

In addition to colourants, microbial pigments are used as bioindicators, e.g., for the detection of heavy metals. For example, *Vogesella indigofera* produces a blue pigment (indigoidine) under normal environmental growth conditions; however, after exposure to heavy metals such as harmful hexavalent chromium, no pigment production is observed [92,210].

Pigments are used to produce solar cells sensitised with natural dye. Natural pigments, such as anthocyanins, also have found very interesting applications as natural dye-sensitised solar cells (NDSSCs) [211,212]. They are based on a thick nanoporous layer of a semiconductor, titanium dioxide (TiO_2), deposited by screen printing on a photoanode [213]. The TiO_2 layer provides a large surface area available for the adsorption of the dye, which must have properties such as the ability to adsorb onto the semiconductor surface and absorb photons. The sensitiser absorbs incident photons and is excited from the ground state to the excited state. Among the existing types of photosensitisers for this type of solar cell, organic dyes show an advantage due to low cost, easy manipulation, and environmentally friendly properties over ruthenium [214,215] and platinum complexes [216], which show high toxicity and are rare in nature, revealing difficult, expensive, and environmentally unfriendly production.

6. Economical Aspects

Due to their environmentally friendly nature and less cumbersome production techniques, naturally produced dyes have become an effective substitute for toxic synthetic dyes [57].

For both natural and synthetic dyes, the total cost must be considered, from the beginning of the production chain—acquisition or breeding, extraction, purification, transportation, and storage—to its use, the effects on the human body, and disposal/degradation in the environment. Also important are stability in light, acidic-alkaline conditions, and oxidative agents and colour intensity.

However, since the colour blue is rare in nature, only a few blue pigments are currently available. Currently, only phycocyanin, anthocyanin, metal chelates, and pigments derived from genipin are used industrially to produce blue hues [6]. For example, phycocyanin produced by the cyanobacterium *Arthrospira* (*Spirulina*) *platensis* reached a global market size of $348 million in 2018, and the market is estimated to reach $779 million by 2026 [129].

Natural dyes rarely match the intensity of artificial dyes. Most natural and synthetic colour additives have εmax values of 10^5 or 10^6 [217]. Colourants with lower εmax values must be used in higher concentrations to achieve the desired appearance, thus increasing costs and the risk of off-flavour [10]. The blue colourants with the highest ε values are blue no. 1 (brilliant blue) = 134,000, blue no. 2 (indigo carmine) = 7920, phycocyanin = 17,100, and trichotomine = 70,000 [10].

Colourants must also be stable enough to avoid significant degradation during the distribution and sales of both the ingredient and the food or beverage, which may include storage from days to years under refrigerated or ambient conditions. The most typical causes of instability include heat, light, oxygen, acid, and exposure to oxidants such as ascorbic acid or trace metals [10]. In the case of the natural colourant spirulina, the colour of the pigment is not affected by pH or light, but it is sensitive to heat [57]. This means that phycocyanin is not stable enough for most food and beverage applications [10]. But there are applications in which this natural dye with a bright blue colour is essential: fermented milk products, ice creams, soft drinks, milkshakes, desserts, and sweet cake decorations [57].

The extraction of natural dye from finished materials is time-consuming and labour-intensive. This can be demonstrated in detail by the example of spirulina extraction. The extraction process involves breaking down the cell wall, extracting the water-soluble protein-pigment complex, and then concentrating, and if necessary, purifying it [6]. Pigment losses of approximately 50% have been reported at elevated temperatures (>50 °C), regardless of the drying method (e.g., spray, oven, sun drying). Maceration at temperatures below 30 °C and air circulation through the suspension increase the extraction yield and prevent unpleasant odours [218]. Optimal pigment recovery has been achieved by repeated freeze-thaw cycles using fresh wet materials [219]. The residual cells are removed by filtration or centrifugation. Its use as a food colouring requires further concentration of the crude extract by vacuum distillation at moderate temperatures. Nevertheless, additional sterile filtration is recommended for food safety reasons. The addition of sugar improves the stability of the pigment during the heating process [218]. To increase the purity from ∼0.8 in the crude extract to more than 4, ammonium sulphate precipitation, ultrafiltration, charcoal adsorption with or without the addition of chitosan, and different chromatographic purification steps have been used [220]. However, these methods are time- and cost-intensive, as they involve a large number of processing steps. An option for purification on a larger scale can be aqueous two-phase extraction with the use of a polyethylene glycol/potassium phosphate mixture [221,222].

Spirulina is mainly produced by *Arthrospira platensis* (commonly named *Spirulina platensis*), the photoautotropic cyanobacteria cultured in open ponds and natural lakes, especially in tropical and subtropical regions. Despite the generally high phycocyanin content (60–70 mg/g), productivity is restricted because the biomass is strongly dependent on optimal light conditions [6,220]. In addition, there is a risk of foreign organism contamination, which presents problems in achieving the hygiene standards demanded for food applications.

Eriksen [220] recommended another organism, a unicellular rhodophyte, *Galdieria sulphuraria*, evaluated earlier as a potential human food source, as an appropriate alternative to spirulina production. Despite the pigment content being relatively low (10–25 mg/g), heterotrophic cultivation in the dark enables large-scale axenic production, resulting in a high biomass and thus a much higher phycocyanin yield. However, pigment extraction is hampered by the difficulty in breaking down cellulose-rich cell walls, with the consequence that *G. sulphuraria* has not yet been used for commercial spirulina production.

The economically favourable solution seems to be the production of spirulina as a high-value byproduct in the production of biofuel from microalgae [206–208]. Also beneficial is the recycling of water and nutrients from crops (e.g., through anaerobic digestion) [209], the development of more efficient harvesting techniques [223], and co-location with free sources of nutrients or CO_2 from industry [224].

In order to increase the yield and production of natural colourants, a suitable extraction procedure must be chosen. Different extraction techniques to extract natural pigments were described in detail in [54], and include traditional processes that are simple, economical, and straightforward to use, like Soxhlet extraction, maceration, and hydrodistillation. In addition, non-traditional extraction methods, often known as green extraction techniques, have recently emerged as a viable alternative to conventional extraction as they are less solvent- and time-consuming. Other new technologies, such as ultra-high pressure, vacuum cavitation, high-voltage electrical discharge, ohmic heating, pulsed electric fields, mechanical-chemical methods, and high-pressure homogenisation, have proven to be very effective methods for the extraction of plant pigments. The most common extraction methods for the recovery of anthocyanins from natural sources include solid-liquid extraction, supercritical fluid extraction, ultrasound-assisted extraction, and microwave-assisted extraction [57,225].

The criterion choice of suitable pigment extraction method is not only the yield and price but also the critical external factor affecting pigment stability and potential application [226]. Newer methods, such as ultrasound-assisted extraction, which uses cavitation effects and shear forces, significantly reduces extraction time but requires strict control to prevent the violation of anthocyanin structural integrity [227]. Microwave-assisted extraction, which is known for its efficiency, uses natural ionic conduction and dipole relaxation to accelerate solvent temperature, reduce viscosity, and facilitate anthocyanin diffusion also reduces extraction time. Strict control of parameters is necessary to prevent structural damage. Supercritical carbon dioxide extraction, which is a state-of-the-art technology with properties between gas and liquid, offers advantages such as high efficiency, environmentally friendly processing, safety, and minimal contamination. This method is particularly suited to heat-sensitive substances such as anthocyanins, but the cost of equipment and technological investment limit large-scale industrial applications [228].

The latest combined methods, such as ultrasound-assisted enzymatic extraction and ultrasound-assisted deep eutectic solvent extraction, seamlessly integrate enzymatic and deep eutectic solvent processes. Enzymatic methods using cellulase and pectinase increase anthocyanin yields, while ultrasonic processing further improves extraction efficiency [229].

Moreover, some pigment stabilisation methods are used. Increasing the stability of anthocyanins can be achieved either by modifying the structure of the molecule (intrinsic factors) through copigmentation, acylation, and biosynthesis or by controlling environmental factors (extrinsic factors) [230]. Encapsulation is an advanced technology that embeds bioactive substances in solid particles or liquid vesicles. In this way, it provides precise control over the release of these bioactive substances while providing benefits such as masking unwanted odours, improving stability, and maintaining bioactivity. Anthocyanins, which are light- and heat-sensitive, benefit greatly from encapsulation techniques to maintain their stability and extend their shelf life [231]. Various methods of encapsulation have been employed, including spray drying, freeze-drying, ionic gelation, liposome entrapment, nanoencapsulation, yeast encapsulation, phase separation, emulsification, complexation, molecular inclusion, and supercritical antisolvent precipitation [54].

Microcapsules, liposomes, and nanoparticles are commonly used for anthocyanin encapsulation [232]. Often composite materials, such as mixtures of carbohydrates with proteins and polysaccharides, are used to obtain the expected encapsulation properties. Typical materials for anthocyanins include carbohydrates, proteins, and water-soluble plant gums, as well as hydrocolloids, each of which offers unique advantages such as solubility and stability [135,233].

It also seems to be economically and commercially advantageous to produce pigments from microorganisms, e.g., carotenoids and *Monascus* pigments, because microbial growth conditions can be easily controlled [57]. Natural microbial pigments play a significant role as food colourings due to their low-cost production, easier extraction, high yield, and lack of raw material shortages and seasonal variations [92,234].

Marennine, produced by the diatom *Haslea ostrearia,* appears to be a good candidate for a new colourant for food and beverage products, especially with very good stability of the blue colour (λ_{max} = 620 nm) in acidic conditions (pH 1–6) [129] and at pH 8 (λ_{max} = 677 nm) [99], and with stability in the presence of common food antioxidants and preservatives such as ascorbic acid and sodium sulfite [99]. Indeed, most blue natural colourants lose their blue shades in an acidic medium: anthocyanins turn purple-pink at low pH, natural blue anthraquinone, except for anthracyclinone-blue B and kyanomycin, and quinoid dyes become red or orange, and phycocyanin from spirulina is unstable [10]. The shade of purified marennine blue is unaffected by low pH, and remains unaltered even after acidic hydrolysis in harsh conditions (100 °C, 16 h) [129].

Another natural pigment, jagua blue (from the fruit of *Genipa americana* L.) may be a potential new source of blue pigment. In the pH range of 3.6–5.0, the shade of jagua blue solutions was similar to that of blue no. 2 (indigo carmine) but jagua blue showed significantly higher stability during storage ($t_{1/2}$ = 86–105 days) than blue no. 2 ($t_{1/2} \leq 9$ days) and was less susceptible to acidic pH 3.6 ($t_{1/2}$ = 86 days) than spirulina ($t_{1/2}$ = 70 days) [235].

The cost of sourcing natural colours becomes the basis for adulteration—so-called economically motivated adulteration, fraud, or unfair competition [236]. Adulteration of food with illegal colours has been reported as a public safety concern [237], and there have been cases of the adulteration of many different types of food products in recent years [238]. Natural and artificial colouring agents can be visually identical, so any detection method would need to be able to provide information about the chemical composition of the colourants that are present. Hence, the need for food control to confirm the use of the correct/declared colours by analytical methods. Existing methods for the detection of artificial colourants include chemical determination by chromatographic methods such as HPLC [239], mass spectrometry [240], and capillary electrophoresis [241]. These methods typically require labour-intensive sample preparation techniques and specialised equipment and training. An alternative method is surface-enhanced Raman spectroscopy (SERS) [236].

The development of cost-effective and viable technologies for the preparation of natural food colourings and their use in food is currently a great challenge and a major need. Their incorporation into food products is very difficult because they are chemically unstable and show poor bioavailability. During food fortification, efficient technologies are needed to prevent the degradation of pigments and reserve their bioaccessibility in the human gastrointestinal system. There are good perspectives for the inclusion of plant pigments in the food industry. Encapsulation (micro- and nano-) is an excellent process to enhance its bioaccessibility, digestibility, and controlled and targeted release [45,54,57].

Stability can also be achieved by immobilising pigments in solids, such as zeolite matrices [45,242]. Stability studies of 'Maya Blue' (a mixture of indigo and palygorskite clay) have been conducted in the context of the development of hybrid pigments adsorbed in nanoporous solids such as mesoporous silica, zeolites, layered double hydroxides, and smectite, which allowed a degree of control over the photochemical and photophysical properties of the pigments, depending on the guest-host interaction, with the key parameters being the matching of pore size to the dimensions of the guest molecule [242,243]. This approach is not always ideal for food applications but is suitable for environmentally friendly applications.

One of the leading candidates for a replacement for brilliant blue is trichotomine (a natural colourant) from Kusagi berries from the Asian shrub *Clerodendron trichotomum* [10].

7. Socio-Cultural Aspects

7.1. Food Colour

Colour represents a crucial role in the acceptability of foods to enhance their actual appearance and quality [54]. The colour of food not only provides information about its edibility but also its palatability [1]. The evaluation of the hedonic reward from food is highly susceptible to suggestion [244].

The red colour of food is very common in nature and is typical of ripe fruits and fresh meat. In contrast, there are not many naturally occurring blue-coloured foods, and sometimes "blue" even means inedible (such as mould) (Figure 7) [244]. Therefore, it is not surprising that the colour red is considered appetising, while blue acts as an appetite suppressant [1,245,246]. In the past, the colour blue in food meant: watch out, don't touch, don't move, don't eat. The blue colour of food meant that the food was spoilt, harmful, and dangerous, and this was associated with the presence of mould. The repellent effect of the blue colour is still used today and has remained, for example, in the colouring of granulated molluscicide agents (i.e., metaldehyde, Snacol 5 GB, BROS) to make the colouring repellent to other animals.

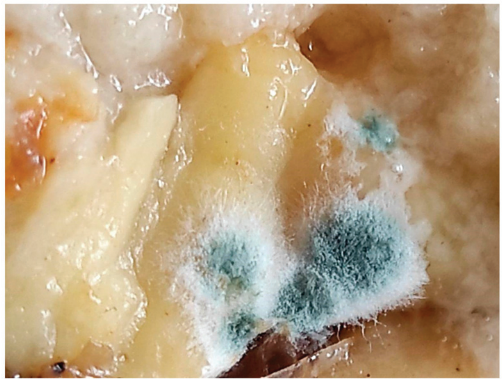

Figure 7. Blue mould on food (photo: A. Szmagara).

Food colour promotes psychological effects. The uncommon blue colour brings the sensation of artificial food and is not satiable. Studies by Suzuki et al. [247] proved this effect. The authors observed tasters' behaviour when eating identical soups with different colours: yellow, white, and blue. They aimed to verify whether the colour could affect the feeling of satiety. After ingestion, blue soups showed significantly lower satiety rates than white and yellow soups. The authors concluded that food colour might be associated with the expected flavour and produce different effects depending on their experiences. Since blue foods are rare, the visual signs of the blue colour may have caused cognitive unfamiliarity due to the difficulty of associating colours with some type of sensory experience [5].

Paakki and co-workers [32] investigated the consumer preference by comparing "traditional" yellow potatoes and blue potatoes to verify the feeling that blue food evokes. Only 28% of consumers selected blue potatoes due to their desire to try new and unusual things. Tasters who preferred blue potatoes tended to be more neophilic, responding positively to the consumption and application of atypical colours in food, variety, and trend-seeking, and younger than those choosing yellow potatoes [5,32].

Sometimes food products are given distinctive colours to help attract consumer attention [248]. This is likely to have been the case with the striking blue 'Bolt from the blue' drink introduced by Innocent Smoothies [29].

Moreover, the same colour of a drink can have a completely different meaning when shown in a plastic bathroom cup as opposed to a cocktail glass. In the former case, a blue-coloured drink can be interpreted as being associated with mouthwash and therefore associated with the taste of mint, whereas when the same colour is seen in a cocktail glass, it can be interpreted as signifying the orange flavour of blue curaçao [1].

Blue dyes are often added to candy, so the candy colour combinations most appealing to children were examined, as well as children and adolescents' acceptance of single candy colours and two-colour combinations [5,249], and in all combinations blue played an essential role in attracting them.

Galetović and co-workers [250] added phytobiliproteins from cyanobacteria to milk beverages, achieving satisfactory sensory acceptability, which increased after information that the blue-coloured dairy beverage had antioxidant properties. Natural blue-coloured products may attract consumers because of their unusual, differentiated colour, evoking a feeling of "novelty" and providing enticement to eat [251]. The association of "artificial" or "less filling" is also expected to be reduced for blue foods [6,32].

7.2. Background—Packing, Dishware, and Light

Cognitive thoughts about colours are stored in memory along with associated mental concepts or experiences, which may result from everyday knowledge of similar products and colours or learnt stereotypes and symbolic meanings of colours [252]. A cool colour, such as blue, evokes sedative emotions [253] and is the colour of peace and hope [254]. In contrast, blue should also not be forgotten in relation to defining sadness, loneliness, and depression.

Very interesting aspects concerning the impact of the colour blue are described, which do not relate to the food itself but to its surroundings. These concerned the colour of the packaging, the colour of the dishware, and also the lighting.

Few natural foods have blue colouring, but this shade is very commonly found on packaging [255]. Some research explores the relationship between packaging colour and product attributes [256]. For instance, warm-coloured packaging might be closely associated with the tastiness or sweetness of food, while cool colours might relate to the freshness or health attributes of the product [257]. Huang and Lu [252] researched consumer preferences and observed that products in blue packaging were associated with higher healthy perceptions and were more likely to be purchased than products in red packaging. Similarly, a study by Hallez and colleagues [258] examined how packaging design in warm or cool colours and the presence or absence of nutrition and environmental claims influenced consumer evaluations. They showed that green and blue packaging designs, representing cool colours, led to higher health and sustainability perceptions [258,259].

Pereira [260], when investigating the symbolic function of blue on food packaging, found that this colour is the second most recurrent. It is a typical colour for food products that incorporate the idea of diet in their design, reflecting a context in which the blue colour represents the concepts of health and beauty promoted by today's society as part of a wider process of promoting values and symbols. Its most common role was to indicate specific nutritional qualities associated with the concept of healthy eating, symbolising the ideas of moderation, restraint, and rationality. The blue colour's role was to indicate characteristics related to healthy eating, reduction in ingredients ("light", "zero", "decaffeinated" and "skimmed", but mainly associated with a reduced fat content), or even to highlight premium products from the others. The study shows that meaning-making is based on the relationship of opposition between the colour blue and the warm colours characteristic of the food world. Blue was also the second most dominant colour in dairy packaging since this colour conveys calmness, reliability, and hygiene [261], as well as freshness and coldness [262,263]. Therefore, the blue colour should be used when the intention is to convey the idea to the consumer that it is a high value-added product because of rigorous quality control correlated with a healthy-looking product, or because it is a food that stands out from others of the same class.

The impact of the background is also the impact of the dishware. Even the blue colour of the vessel can discourage consumption [7]. More precisely, according to Crumpacker [264], 'the term blue plate special became popular during the Great Depression because restaurant owners found that diners were satisfied with smaller portions of food if it was served on blue plates'.

Some studies have determined the effect of the colour of light (effect of light) on the desire to eat the products underneath. Cho and colleagues [265] reported that blue lighting significantly reduced food intake for breakfast in studied Swedish men but not in women when compared to yellow and white lighting. The overall intensity of the taste and the overall impression of the food did not differ significantly between the three lighting colours. This study provides empirical evidence that lighting colour can modulate meal size. In particular, blue lighting can reduce the amount of food consumed in men without reducing food acceptability [244,265]. Several other studies have also reported that blue lighting impairs people's perception (or the eye appeal) of various fruits and vegetables [266,267].

7.3. Thermal Perception and Feeling Thirsty

The colour of food is known to modulate not only consumers' motivation to eat but also to influence the thermal perception of food. Suzuki and co-workers [247], conducting a study on a female group, found that the blue colour of soup significantly decreased willingness to eat, ratings of palatability and comfort, but also the heat judgement of the meal, and significantly increased anxiety feelings compared to the white and yellow soups. This study provides new evidence that the colours of hot food can modulate postprandial satiety, thermal sensations, and peripheral temperature. Such an effect of colour may be useful for dietary strategies for people who need to control their appetite.

It is also known that the colour of the dish influences the perception of the temperature of the food being served [247]. With regard to foods consumed hot or warm, serving them in a blue dish will discourage eating, which can be used to control appetite. In the case of cold drinks, the blue colour of the dish further influences the consumer's feelings, intensifying the sensation of cold. A cold beverage item was evaluated as more "thirst-quenching" when served in a blue glass than in a green, yellow, or red glass" [268], and a hot beverage was perceived as the warmest when served in a red cup, followed by yellow, green, and blue cups [263]. Thus, the colour (warm or cold) of a beverage and its container has been shown to affect the perception of the temperature of the beverage [247].

In relation to taste, the colour blue is known to be associated with the perception of a salty taste. In general, sweet is widely linked with reddish/pink colours, sour with yellow/green, salty with white/blue, and bitter with black [1,269].

There is also an additional troublesome aspect related to the natural origin of dyes, specifically, the dye can have an unpleasant taste or odour that will be an obstacle to its use in food. Such a situation is reported in the case of spirulina, which is obtained from algae. That said, blue spirulina (going under the brand name Blue Majik), one of the blue dyes that is currently the most popular, can taint the food to which it is added with an unpleasant fishy taste [270]. Attempts have even been made to adapt production methods to remove the unpleasant fishy smell/taste through the use of basil leaf extract [271].

8. Politics and Governance—Regulations

Before the 19th century, food was mostly prepared at home. Only occasionally and by wealthy people were dyes extracted from animals, vegetables, or minerals used as food decoration [272,273]. After the Industrial Revolution, food was increasingly processed at a large scale, and new technologies, including preservation, altered the natural appearance of foods [3]. Therefore, inexpensive and stable synthetic and mineral dyes with high colouring power and light shades were excessively used for a wide range of food products. Some of these dyes, such as indigo, had toxic properties. To restrain their overuse in the United States (US), a list of approved food colourants was published in 1906 (US Food and Drug Act) [272]. Among the blue dyes on this list was indigotine. In 1929, a further blue dye, brilliant blue, was added to the list.

In 1960, the Colour Additives Amendment included the Delaney clause banning additives that cause cancer in humans or animals [274]. In the UK, several colours were forbidden in 1923, and a legally binding list of permitted colours was established in 1957 [272]. The Joint Expert Committee on Food Additives (JECFA), co-managed by the FAO and WHO, was established as early as 1956 and has since comprehensively reviewed 1500 substances, including food colourants, setting standards for safety assessment worldwide. The WHO's International Programme on Chemical Safety (IPCS) also assesses the health effects of chemicals in food.

Currently, colourings are probably the most strictly regulated food additives worldwide [273]. In most countries, the use of food additives is regulated by strict rules. However, despite global cooperation and harmonisation efforts, regulations vary from country to country. Legislation determines which substances can be used, their source, purity, in which foods, and the concentrations that can be added. However, legislation is based on the traditional local use of the additive. Worldwide, the two main authorities regulating food additives are the European Food Safety Authority (EFSA) in the European Union (EU) and the US Food and Drug Administration (FDA) in the United States [275]. Since 1956, the Joint Expert Committee on Food Additives (JECFA), which acts as an international scientific committee of experts responsible for assessing the risks associated with the consumption of additives, has made recommendations to the Food and Agriculture

Organisation (FAO), the World Health Organisation (WHO), and 51 member countries of both organisations [276]. The food category system comprises 16 main categories, for a total of 266 categories, including subcategories [277]. The JECFA assigns all additives an acceptable value in the relevant category.

The introduction of new natural colours is often significant for local people in their place of origin. For example, the list of colours awaiting adoption at stage 5/8 currently includes the natural blue dye of plant origin, jagua (genipin-glycine) blue (INS 183) [278], and the record is annotated with the comment that Colombia has expressed their appreciation for the conclusions regarding the use of jagua (genipin-glycine) blue (INS 183), highlighting the significant benefits of its inclusion in the GSFA for indigenous communities in their country and the Latin American region, while recognising jagua (genipin-glycine) blue (INS 183) as a valuable resource and stressing that its inclusion in the GSFA will open up new commercial opportunities and drive biodiversity conservation and the adoption of sustainable agricultural practises.

As trade becomes increasingly global, sourcing from different continents, regional and national regulations can become trade barriers that increase transaction costs, or more specifically compliance costs, leading to negative economic impacts. In addition to the economic aspects, technical barriers can impede the global use of all available food through free trade to reduce hunger and poverty [279].

In both the EU and the US, only approved dyes can be used in food. However, the regulations for food dyes in the EU and the US are different and embedded in two very different legal frameworks. As a result, the definition of food colourant, approval requirements, approved colourants and their specifications, restrictions on their use, and responsibilities for rulemaking and compliance monitoring are different. The main regulations governing the use of colours in food in the EU and the US are listed in Table 5.

Table 5. Adequate Daily Intake (ADI) values of synthetic dyes.

Colourant	ADI (mg/kg)		
	EU [a]	**US** [b]	**JECFA** [c]
Patent Blue V	5	banned	No ADI allocated
Indigotine/FD&C Blue no. 2	5	2.5	0–5
Brilliant blue FCF/FD&C Blue no. 1	6	12	0–6

where: [a] Food additive re-evaluations [159,280,281]. [b] [USFDA] US Food and Drug Administration (2011) [273]. [c] Evaluations of the Joint FAO/WHO Expert Committee on Food Additives [282].

Food exporters and importers are perplexed since the same food colour may be allowed in one country but banned in another [283]. Patent blue V in the USA, Australia, and New Zealand is banned, but in the EU it is used as E131 in food. Indigo carmine is used in the EU (E132) and US (FD&C No. 2) but is already banned in Japan, Australia, and Norway. Brilliant blue is currently still permitted in the EU (E133) and US (FD&C No. 1) with different ADI values (Table 5). However, at the national level, some European countries (Austria, Belgium, France, Norway, Sweden, Switzerland, and Germany) have already banned its use [284,285]. For ease of identification, each pigment is given a colour index name (C.I.) and a colour index number (C.I. No.) (Table 6). The colour index number conveys some information about the chemical composition of the pigment, as some pigment classes have specific number ranges [286]. In 1989, the CCFA created the International Numbering System (INS) to provide an international numeric system for identifying additives in the list of food ingredients. It is also an alternative to using a specific name, often long and complicated [9,275].

Table 6. Artificial and natural dyes authorised in various countries (modified, according to [9,217]).

Colourant	INS	E	Colour Index	Colour Index Number	CAS	Number in Japan	US	EU	Australia/New Zealand	Japan	Brazil	China	India
Indanthrone blue	130	E130	Vat Blue 4	69,800	81-77-6	n/a	×	×	×	×	×	×	×
Patent blue V	131	E131	Acid Blue 3 Food Blue 5	42,051	3536-49-0	n/a	×	√	×	×	√	×	×
Indigo carmine	132	E132	Food Blue 1 Acid Blue 74	73,015	860-22-0	221	√	√	√	√	√	√	√
Brilliant blue	133	E133	Food Blue 2 Acid Blue 9	42,090	3844-45-9	220	√	√	√	√	√	√	√

Notes: INS—International Number System, E—encoding used in the EU, √—dye allowed, ×—prohibited food dye, n/a –data not available.

Phycocyanin, a pigment found in spirulina species discussed earlier in this review, is the most stable natural dye for the blue shade. However, it is not permitted as a raw material for dye production in the US and EU. *Spirulina* sp. is classified by the FDA as a cyanobacterium and is considered a food rather than a source of dye; therefore, it does not comply with the regulations of 21CFR 73.260 [3]. Due to conflictual restrictions imposed on some natural dyes in different countries, the approval and commercialisation of safe and new dyes is usually delayed. Therefore, the joint regulatory authority can issue international standard codes for natural colourants to ensure consumer safety and health.

The principal markets of food-grade biocolourants are in the US, EU, Japan, and the emerging markets are in China, India, and South Korea. Developing countries such as India and China can play an important role in supplying natural colours either in processed forms or as raw materials to the EU markets due to their favourable climatic and production conditions coupled with the growth in their middle-income families. More research supporting the safety of food products could influence regulation in the US, Asia, and the EU [57].

9. Perspectives

The search for sustainable and harmless colourings for food and beverages continues. Currently, one of the biggest challenges in the colourant industry is obtaining natural blue colourants. Because, in line with consumers' preferences, interest in blue food products is not waning, food and beverage manufacturers continue to look for natural blue colour as an alternative to synthetic dyes. Both for food intended for direct consumption and for monitoring the freshness of products. Some blue dyes have been discovered whose structure has not yet been determined [10] and properties are not known in detail, so their use in food is not yet possible.

Unfortunately, the use of NPs is limited by their intrinsic molecular instability, as well as their higher cost compared to synthetic pigments and the need for higher concentrations to achieve equivalent colour intensity [45,287]. However, as mentioned earlier, they are associated with serious stability and pH limitation issues. For example, acidic foods that use temperatures above 60 °C during processing cannot use anthocyanins as a blue pigment [5]. The stability of the natural pigments determines the use, even for different products in a related food group, as in a study of the fortification of yoghurt and fermented milk with the natural blue pigments, during which better results were obtained in the case of yoghurt for butterfly pea extract, while in the case of fermented milk for spirulina [288].

A prospect may be the production of blue pigments using genetic modification. For example, genetically modified blue silkworms capable of producing high levels of natural blue pigment (indigoidin) in the posterior silk gland have been successfully obtained [289], as have blue flowers obtained through genetic modification rather than artificial dyeing. Many ornamental plants grown for high-volume cut flowers, such as rose and chrysanthemum, lily, carnation, and gerbera, lack key genes for the production of the blue pigment delphinidin or do not have an intracellular environment suitable for blue colour [290]. Blue flowers, such as rose and chrysanthemum, were developed using genetic engineering at the end of the 20th century [11,291]. After studying the flavonoid profiles of hundreds of rose cultivars, suitable hosts were selected for high delphinidin accumulation to produce a blue flower colour. Overexpression of the viola F3′5′H gene resulted in the accumulation of delphinidin to 95% of all anthocyanidins and resulted in a new blue colour [11,292]. Also, dahlia, phalaenopsis, lily, and chrysanthemum are examples of these genetically modified blue flowers [290].

Consumer awareness of the multifaceted benefits of food colourants will encourage the commercialisation of safe and novel food colourants. Many consumers are unaware that in 2008, Nestle replaced the blue colour in candy with a colour derived from spirulina [57,293].

The socio-cultural aspects presented are of great importance in working towards an increasingly healthy society (obesity-related metabolic diseases), dwindling food resources, and therefore the need to eat smaller portions of food. It is worth building on previous findings about the effect of blue surroundings and dishes on reducing appetite.

Similarly, the blue colour of the vessels influencing the satisfaction of the sensation of thirst can have both positive and negative implications when we seemingly feel less thirsty, but in fact the correct level of hydration is not provided to the organism.

The health-promoting properties of plants such as *Clitoria* have great potential, and interest in colour can be used to encourage regular consumption of infusions with health-promoting properties.

Furthermore, in addition to looking for new sources, better methods of obtaining natural dyes from already known sources still need to be developed. For example, spray-drying, freeze-drying, encapsulation, and coatings improve the colour of anthocyanins [57].

There is undoubtedly an advantage of natural dyes over synthetic ones, but among the natural ones, those of microbial origin seem to be the most economically viable [94]. For several reasons, successively: dyes of animal origin—the necessity of breeding, the difficulty of extraction, of plant origin—cultivation dependent on year-round availability, external factors, weather, climate of plant growth, i.e., temperature and humidity, natural disasters and human factors related to plant harvesting, protection against pathogens and pests, multi-stage extraction, stability, and water-solubility of the pigment [130]. The exploitation of plants on a large scale may lead to the loss of valuable species. Microorganisms such as fungi, bacteria, algae, and actinomycetes are a reliable and readily available alternative source of natural pigments [287]. Microorganisms are advantageous over plants for biopigment production in terms of availability, labour and cost efficiency (easy and rapid multiplication in a low-cost medium), yield, stability, easy downstream processing, and weather- and season-independent growth [92,294]. Microbial culture can be achieved by solid and submerged fermentation on natural raw materials or industrial organic wastes. Microbial pigments not only act as colouring agents in various food and cosmetic industries but also have anticancer, antioxidant, anti-inflammatory, and antimicrobial properties [112]. The main disadvantage of dyes of fungal origin is the possibility of contamination with mycotoxins. Moreover, bacteria have numerous advantages over fungi for pigment production, including a shorter life cycle and relatively easy genetic modification [19,92,295]. However, research on bacterial blue pigments is limited, probably because few bacteria are capable of producing blue pigment [295].

The authorised artificial colours, indigo carmine (E132) and brilliant blue (E133), are used in so many groups of food, in foodstuffs for everyday use, even where one would not expect them to be at all, and even in foods considered to be popular such as pickled cucumbers (together with natural colours such as chlorophyll copper complex, annatto extract, turmeric, beta-carotene, oleoresin of paprika, and other authorised artificial colours such as fast green FCF, tartrazine, sunset yellow FCF) at 300 mg/kg singly or in combination [278]. In addition, synthetic blue dyes, E132 and E133, are still permitted in various food groups: dairy and dairy-based desserts, bakery products of various types, and vegetable purées. Although a natural substitute, the algae-derived colour E134, is already permitted in these same groups, at specific maximum concentration levels (GMP—Good Manufacture Practise).

Of the natural colours, the following are permitted as food colourants: anthocyanins (INS 163) [296]—Table 7, with the last of which, 163 (xi)—butterfly pea flower extract, which was introduced in 2021 [297] and, from 2023, spirulina extract (INS 134), which can be used in the indicated food category under the conditions of good manufacturing practise (GMP).

Table 7. Permitted colourants of the anthocyanin group [296].

Colourant INS No.	Description/Plant Source
163 (ii)	Grape skin extract
163 (iii)	Blackcurrant extract
163 (iv)	Purple corn colour
163 (v)	Red cabbage colour
163 (vi)	Black carrot extract
163 (vii)	Purple sweet potato colour
163 (viii)	Red radish colour
163 (ix)	Elderberry colour
163 (x)	Hibiscus colour
163 (xi)	Butterfly pea flower extract

Moreover, the plant-derived colour INS 183—jagua (genipin-glycine) blue is on the legislative path [278] at step 5 of 8. The legislative pathway for the approval of new blue colours, i.e., gardenia blue (INS 165) is currently underway ([278] in: Appendix XI, Part A: List of substances used as food additives proposed for evaluation by JECFA). Proposed by Japan, the gardenia blue dye is intended to add or restore colour to food. It thus imparts colour to food, thereby improving the organoleptic properties of that food, which would otherwise not be coloured or whose colour has been affected by processing and needs to be restored. The proposed maximum use levels are based on the amount of colour required technologically to achieve the desired effect in different foods. The use of blue gardenia pigments in foods is still not legal in the United States or European Union but is in Japan, China, and Korea [10,58,298].

It is sometimes found that natural colourings (INS 163) are used or proposed in much higher quantities than synthetic ones in the same food group (Table 8).

Table 8. Maximum food colourant (allowed and under legislation process) levels in different food groups, according to the JECFA [277,278].

Food Category		Food Additive/INS				
		Indigotine (Indigo Carmine)	Brilliant Blue FCF	Spirulina [a]	Anthocyanins	Jagua (Genipin -Glycine) Blue [b]
No.	Name	132	133	134	163	183
		Maximum Level [mg/kg]				
01.1.4	Flavoured fluid milk drinks	300	150	GMP	100	160
01.3	Condensed milk and analogues (plain)			GMP		
01.4.3	Clotted cream (plain)			GMP		
01.4.4	Cream analogues			GMP	150	
01.5	Milk powder and cream powder and powder analogues (plain)			GMP		
01.5.2	Milk and cream powder analogues				150	
01.6.1	Unripened cheese	200		GMP		
01.6.2	Ripened cheese			GMP		
01.6.2.2	Rind of ripened cheese	100	100		1000	
01.6.4	Unripened cheese			GMP		

Table 8. *Cont.*

No.	Name	Indigotine (Indigo Carmine)	Brilliant Blue FCF	Spirulina [a]	Anthocyanins	Jagua (Genipin -Glycine) Blue [b]
		132	133	134	163	183
		Maximum Level [mg/kg]				
01.6.4.2	Flavoured processed cheese, including containing fruit, vegetables, meat, etc.	100			1000	44
01.6.5	Cheese analogues	200	100	GMP	1000	
01.7	Dairy-based desserts (e.g., pudding, fruit or flavoured yoghurt)	150	150	GMP	200	120
01.8.1	Liquid whey and whey products, excluding whey cheeses			GMP		
02.2.2	Fat spreads, dairy fat spreads, and blended spreads			GMP		
02.3	Fat emulsions mainly of type oil-in-water, including mixed and/or flavoured products based on fat emulsions	100	100	GMP		160
02.4	Fat-based desserts, excluding dairy-based dessert products of food category	150	150	GMP	200	200
03.0	Edible ices, including sherbet and sorbet	150	150	GMP	100	120
04.1.2	Processed fruit			GMP		
04.1.2.3	Fruit in vinegar, oil, or brine				1500	
04.1.2.4	Canned or bottled (pasteurised) fruit		200		1500	
04.1.2.5	Jams, jellies, marmalades	300	100		500	120
04.1.2.6	Fruit-based spreads (e.g., chutney) excluding products of food category 04.1.2.5		100		500	
04.1.2.7	Candied fruit	200	100		1000	
04.1.2.8	Fruit preparations, including pulp, purees, fruit toppings and coconut milk	150	100		500	120
04.1.2.8	Regional standard for: Date Paste	150	100			
04.1.2.9	Fruit-based desserts, including fruit-flavoured water -based desserts	150	150		500	120
04.1.2.10	Fermented fruit products				500	
04.1.2.11	Fruit fillings for pastries	150	250		500	120
04.2.2.2.	Dried vegetables (including mushrooms and fungi, roots and tubers, pulses and legumes, and aloe vera), seaweeds, and nuts and seeds			GMP		
04.2.2.3	Vegetables (including mushrooms and fungi, roots and tubers, pulses and legumes, and aloe vera), and seaweeds in vinegar, oil, brine, or soybean sauce	150	500	GMP	100	
04.2.2.4	Canned or bottled (pasteurized) or retort pouch vegetables (including mushrooms and fungi, roots and tubers, pulses and legumes, and aloe vera), and seaweeds		200	GMP		
04.2.2.4	Processed Tomato Concentrates	200	100			
04.2.2.5	Vegetable (including mushrooms and fungi, roots and tubers, pulses and legumes, and aloe vera), seaweed, and nut and seed purees and spreads (e.g., peanut butter)			GMP	100	

Table 8. *Cont.*

Food Category		Food Additive/INS				
		Indigotine (Indigo Carmine)	Brilliant Blue FCF	Spirulina [a]	Anthocyanins	Jagua (Genipin -Glycine) Blue [b]
No.	Name	132	133	134	163	183
		Maximum Level [mg/kg]				
04.2.2.6	Vegetable (including mushrooms and fungi, roots and tubers, pulses and legumes, and aloe vera), seaweed, and nut and seed pulps and preparations (e.g., vegetable desserts and sauces, candied vegetables)	200	100	GMP	100	
04.2.2.6	Regional standard for: Harissa (Red Hot Pepper Paste)	200	100			
04.2.2.7	Fermented vegetable (including mushrooms and fungi, roots and tubers, pulses and legumes, and aloe vera) and seaweed products, excluding fermented soybean products of food categories 06.8.6, 06.8.7, 12.9.1, 12.9.2.1 and 12.9.2.3	300	100		100	
04.2.2.8	Cooked or fried vegetables (including mushrooms and fungi, roots and tubers, pulses and legumes, and aloe vera), and seaweeds			GMP		
05.0	Confectionery			GMP		
05.1.3	Cocoa-based spreads, including fillings		100		200	
05.1.4	Cocoa and chocolate products	450	100		200	800
05.1.5	Imitation chocolate, chocolate substitute products	300	100		200	
05.2	Confectionery including hard and soft candy, nougats, etc.	300	300			800
05.2.2	Soft candy				1700	
05.3	Chewing gum	300	300		500	800
05.4	Decorations (e.g., for fine bakery wares), toppings (non-fruit) and sweet sauces	300	500		500	120
06.3	Breakfast cereals, including rolled oats		200	GMP	200	2000
06.4.3	Pre-cooked pastas and noodles and like products			GMP		
06.5	Cereal and starch based desserts (e.g., rice pudding, tapioca pudding)	150	150	GMP	200	84
06.6	Batters (e.g., for breading or batters for fish or poultry)			GMP		
06.7	Pre-cooked or processed rice products, including rice cakes (Oriental type only)			GMP		
06.8	Soybean products (excluding soybean-based seasonings and condiments of food category 12.9)			GMP		
07.0	Bakery wares			GMP		
07.1	Bread and ordinary bakery wares		100			
07.1.1.1	Yeast-leavened breads and specialty breads		100			
07.1.1.2	Soda breads		100			
07.1.2	Crackers, excluding sweet crackers		100		200	
07.1.3	Other ordinary bakery products (e.g., bagels, pita, English muffins)		100			
07.1.4	Bread-type products, including bread stuffing and bread crumbs		100		200	

Table 8. *Cont.*

Food Category		Food Additive/INS				
		Indigotine (Indigo Carmine)	Brilliant Blue FCF	Spirulina [a]	Anthocyanins	Jagua (Genipin -Glycine) Blue [b]
No.	Name	132	133	134	163	183
		Maximum Level [mg/kg]				
07.1.5	Steamed breads and buns		100			
07.1.6	Mixes for bread and ordinary bakery wares		100			
07.2	Fine bakery wares (sweet, salty, savoury) and mixes	200	200			
08.0	Meat and meat products, including poultry and game		100			
08.1.2	Fresh meat, poultry, and game, comminuted				1000	
08.2	Processed meat, poultry, and game products in whole pieces or cuts			GMP	5000	
08.3	Processed comminuted meat, poultry, and game products			GMP	5000	
08.4	Edible casings (e.g., sausage casings)			GMP	5000	
09.1.1	Fresh fish	300	300			
09.1.2	Fresh mollusks, crustaceans, and echinoderms		500			
09.2.1	Frozen fish, fish fillets, and fish products, including mollusks, crustaceans, and echinoderms	300	500			
09.2.2	Frozen battered fish, fish fillets, and fish products, including mollusks, crustaceans, and echinoderms		500		500	
09.2.3	Frozen minced and creamed fish products, including mollusks, crustaceans, and echinoderms		500		GMP	
09.2.4.1	Cooked fish and fish products	300	100		500	
09.2.4.2	Cooked mollusks, crustaceans, and echinoderms	250	100		1000	
09.2.4.3	Fried fish and fish products, including mollusks, crustaceans, and echinoderms		500		1000	
09.2.5	Smoked, dried, fermented, and/or salted fish and fish products, including mollusks, crustaceans, and echinoderms				1000	
09.3	Semi-preserved fish and fish products, including mollusks, crustaceans, and echinoderms			GMP		
09.3.1	Fish and fish products, including mollusks, crustaceans, and echinoderms, marinated and/or in jelly		500		500	
09.3.2	Fish and fish products, including mollusks, crustaceans, and echinoderms, pickled and/or in brine		500		1500	
09.3.3	Salmon substitutes, caviar, and other fish roe products	300	500		1500	
09.3.4	Semi-preserved fish and fish products, including mollusks, crustaceans, and echinoderms (e.g., fish paste), excluding products of food categories 09.3.1–09.3.3	300			1500	

Table 8. *Cont.*

Food Category		Food Additive/INS				
		Indigotine (Indigo Carmine)	**Brilliant Blue FCF**	**Spirulina [a]**	**Anthocyanins**	**Jagua (Genipin -Glycine) Blue [b]**
No.	**Name**	**132**	**133**	**134**	**163**	**183**
		Maximum Level [mg/kg]				
09.4	Fully preserved, including canned or fermented fish and fish products, including mollusks, crustaceans, and echinoderms	300	500	GMP	1500	
10.1	Fresh eggs	300	GMP		1500	
10.2.3	Dried and/or heat coagulated egg products			GMP		
10.3	Preserved eggs, including alkaline, salted, and canned eggs			GMP		
10.4	Egg-based desserts (e.g., custard)	300	150	GMP	200	
11.4	Other sugars and syrups (e.g., xylose, maple syrup, sugar toppings)	300				120
11.6	Table-top sweeteners, including those containing high-intensity sweeteners			GMP		
12.2 12.2.2	Seasonings and condiments	300	100	GMP		600
12.3	Vinegars			GMP		
12.4	Mustards	300	100	GMP	200	
12.5	Soups and broths	50	50	GMP	500	
12.6	Sauces and like products	300	100	GMP		
12.6.1	Emulsified sauces and dips (e.g., mayonnaise, salad dressing, onion dip)				300	
12.6.2	Non-emulsified sauces (e.g., ketchup, cheese sauce, cream sauce, brown gravy)				300	
12.6.3	Mixes for sauces and gravies				300	
12.7	Salads (e.g., macaroni salad, potato salad) and sandwich spreads excluding cocoa- and nut-based spreads of food categories 04.2.2.5 and 05.1.3			GMP	1500	
12.8	Yeast and like products			GMP		
12.9	Soybean-based seasonings and condiments			GMP		
12.10	Protein products other than from soybeans			GMP		
13.3	Dietetic foods intended for special medical purposes (excluding products of food category 13.1)	50	50	GMP	250	
13.4	Dietetic formulae for slimming purposes and weight reduction	50	50	GMP	250	65
13.5	Dietetic foods (e.g., supplementary foods for dietary use) excluding products of food categories 13.1–13.4 and 13.6	300	300	GMP	250	65
13.6	Food supplements	300	300	GMP	500	
14.1.4	Water-based flavoured drinks, including "sport", "energy", or "electrolyte" drinks and particulated drinks	100	100	GMP	300	80
14.2.1	Beer and malt beverages			GMP		
14.2.2	Cider and perry	200	200	GMP	300	
14.2.4	Wines (other than grape)	200	200		300	
14.2.5	Mead			GMP		

Table 8. *Cont.*

Food Category		Food Additive/INS				
		Indigotine (Indigo Carmine)	Brilliant Blue FCF	Spirulina [a]	Anthocyanins	Jagua (Genipin -Glycine) Blue [b]
No.	Name	132	133	134	163	183
		Maximum Level [mg/kg]				
14.2.6	Distilled spirituous beverages containing more than 15% alcohol	300	200	GMp	300	
14.2.7	Aromatized alcoholic beverages (e.g., beer, wine and spirituous cooler-type beverages, low alcoholic refreshers)	200	200	GMP	300	
15.0	Ready-to-eat savouries			GMP		
15.1	Snacks—potato, cereal, flour or starch based (from roots and tubers, pulses and legumes)	200	200		500	600 (in blue/purple tortilla chips 1200
15.2	Processed nuts, including coated nuts and nut mixtures (with, e.g., dried fruit)	100	100		300	800
15.3	Snacks—fish based				400	
16.0	Prepared foods			GMP		

Notes: GMP—dye may be used in this food category under the conditions of Good Manufacturing Practise, [a]—from 2023, [b]—in 2024 on 5th from 8 steps in the JECFA legislation procedure.

10. Conclusions

Colour is an important part of consumers' perception of food and an important factor in determining its taste. Therefore, the food industry uses natural or synthetic dyes to make processed foods more appealing to consumers. Colourant is added to compensate for colour loss due to processing or storage, or to compensate for differences in natural colour. Dye is also added to products without natural colour, such as confectionery and sugar-based soft drinks, to make them attractive to consumers and to match their expectations. However, consumer preference for naturally derived colours—which are closely linked to the image of healthy, safe, and good-quality products—has risen sharply as a large number of synthetic colours have recognised side effects on human health.

The subject of blue food colourants fits into the three traditional pillars of sustainability: environmental, social, and economic, and is expanded by another: the human aspect, culture, and safety.

Currently, it is necessary to link this theme in particular with the health-related aspects of sustainability. It seems most necessary to introduce changing consumption and production patterns. Blue pigments have not only colourful properties but need to be chosen for their rich health-promoting, antioxidant, anticancer, and antidiabetic properties, which are now important for a large group of people, and which are not described in detail in this review.

From an economic point of view, the calculus may not be obvious at first sight since synthetic dyes are apparently cheap, but considering the overall balance, the choice is clear. There are several blue natural dyes that could become good substitutes for synthetic dyes (spirulina, marennine, trichotomine, genipin, and clitoria), those in the approval process, and many that are still waiting to be tested for use in the food industry. It is necessary to select specific pigments in order to obtain at the same time specific health benefits tailored to individual needs, also using modern techniques of non-destructive extraction of the most valuable components and improving the stability and bioavailability of the pigment.

Aspects related to the sustainability of natural pigments and stability in the presence of agents that could potentially cause decomposition also include attempts to advance technological solutions (encapsulation) for their use by increasing bioavailability. More research is required to assess the chemical composition of food colourants derived from natural sources. Furthermore, the stability of the food colourants has to be considered when they are used in food products with varied pH and temperature ranges.

At the same time, lower-cost production solutions are being sought, such as production from waste or the production of pigment as a valuable by-product.

Sociological and cultural aspects related to the possibility of reducing consumption, not only through the disincentive blue colour of the food itself but also the blue surroundings of the food, are also irrelevant and undeniably important, especially for diabetics and those promoting a healthy lifestyle.

The aspect of quality control of food using blue dyes is also very important, as is the environmental aspect of using one group of blue dyes (anthocyanins) to build solar cells.

It should also be remembered that blue is one of the primary colours and is sometimes used, including in the food industry, to create derived colours, especially green (in combination with yellow dyes, natural or synthetic, sometimes also harmful).

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: We gratefully acknowledge the professional and useful comments of the editor and the reviewers.

Conflicts of Interest: The author declares no conflicts of interest.

References

1. Spence, C. On the Psychological Impact of Food Colour. *Flavour* **2015**, *4*, 21. [CrossRef]
2. FDA. *21 CFR Part 70-Color Additives*; Food Drug Administration: Jersey City, NJ, USA, 2023.
3. Downham, A.; Collins, P. Colouring Our Foods in the Last and next Millennium. *Int. J. Food Sci. Technol.* **2000**, *35*, 5–22. [CrossRef]
4. Meggos, H. Food Colors-An International Perspective. *Manuf. Confect.* **1995**, *75*, 59.
5. Neves, M.I.L.; Silva, E.K.; Meireles, M.A.A. Natural Blue Food Colorants: Consumer Acceptance, Current Alternatives, Trends, Challenges, and Future Strategies. *Trends Food Sci. Technol.* **2021**, *112*, 163–173. [CrossRef]
6. Buchweitz, M. 17—Natural Solutions for Blue Colors in Food. In *Handbook on Natural Pigments in Food and Beverages*; Carle, R., Schweiggert, R.M., Eds.; Woodhead Publishing: Sawston, UK, 2016; pp. 355–384. ISBN 978-0-08-100371-8.
7. Spence, C. What Is so Unappealing about Blue Food and Drink? *Int. J. Gastron. Food Sci.* **2018**, *14*, 1–8. [CrossRef]
8. Lee, S.-M.; Lee, K.-T.; Lee, S.-H.; Song, J.-K. Origin of Human Colour Preference for Food. *J. Food Eng.* **2013**, *119*, 508–515. [CrossRef]
9. Mota, I.G.C.; Neves, R.A.M.D.; Nascimento, S.S.D.C.; Maciel, B.L.L.; Morais, A.H.D.A.; Passos, T.S. Artificial Dyes: Health Risks and the Need for Revision of International Regulations. *Food Rev. Int.* **2023**, *39*, 1578–1593. [CrossRef]
10. Newsome, A.G.; Culver, C.A.; van Breemen, R.B. Nature's Palette: The Search for Natural Blue Colorants. *J. Agric. Food Chem.* **2014**, *62*, 6498–6511. [CrossRef]
11. Pina, F.; Basílio, N.; Parola, A.J.; Melo, M.J.; Oliveira, J.; de Freitas, V. The Triumph of the Blue in Nature and in Anthropocene. *Dye. Pigment.* **2023**, *210*, 110925. [CrossRef]
12. Newsome, A.G.; Murphy, B.T.; van Breemen, R.B. Isolation and Characterization of Natural Blue Pigments from Underexplored Sources. In *Physical Methods in Food Analysis*; ACS Symposium Series; American Chemical Society: Washington, DC, USA, 2013; Volume 1138, pp. 105–125. ISBN 978-0-8412-2884-9.
13. Liu, B.; Xu, H.; Zhao, H.; Liu, W.; Zhao, L.; Li, Y. Preparation and Characterization of Intelligent Starch/PVA Films for Simultaneous Colorimetric Indication and Antimicrobial Activity for Food Packaging Applications. *Carbohydr. Polym.* **2017**, *157*, 842–849. [CrossRef]
14. Manzoor, M.; Singh, J.; Gani, A.; Noor, N. Valorization of Natural Colors as Health-Promoting Bioactive Compounds: Phytochemical Profile, Extraction Techniques, and Pharmacological Perspectives. *Food Chem.* **2021**, *362*, 130141. [CrossRef] [PubMed]
15. Paik, Y.-S.; Lee, C.-M.; Cho, M.-H.; Hahn, T.-R. Physical Stability of the Blue Pigments Formed from Geniposide of Gardenia Fruits: Effects of PH, Temperature, and Light. *J. Agric. Food Chem.* **2001**, *49*, 430–432. [CrossRef] [PubMed]
16. Neri-Numa, I.A.; Angolini, C.F.F.; Bicas, J.L.; Ruiz, A.L.T.G.; Pastore, G.M. Iridoid Blue-Based Pigments of *Genipa americana* L.(Rubiaceae) Extract: Influence of PH and Temperature on Color Stability and Antioxidant Capacity during In Vitro Simulated Digestion. *Food Chem.* **2018**, *263*, 300–306. [CrossRef] [PubMed]

17. Santos, M.C.d.; Bicas, J.L. Natural Blue Pigments and Bikaverin. *Microbiol. Res.* **2021**, *244*, 126653. [CrossRef] [PubMed]
18. Kobylewski, S.; Jacobson, M.F. Toxicology of Food Dyes. *Int. J. Occup. Environ. Health* **2012**, *18*, 220–246. [CrossRef]
19. Devi, M.; Ramakrishnan, E.; Deka, S.; Parasar, D.P. Bacteria as a Source of Biopigments and Their Potential Applications. *J. Microbiol. Methods* **2024**, *219*, 106907. [CrossRef]
20. Manikprabhu, D.; Lingappa, K. γ Actinorhodin a Natural and Attorney Source for Synthetic Dye to Detect Acid Production of Fungi. *Saudi J. Biol. Sci.* **2013**, *20*, 163–168. [CrossRef]
21. Martins, N.; Barros, L.; Ferreira, I.C.F.R. In Vivo Antioxidant Activity of Phenolic Compounds: Facts and Gaps. *Trends Food Sci. Technol.* **2016**, *48*, 1–12. [CrossRef]
22. König, J. 2—Food Colour Additives of Synthetic Origin. In *Colour Additives for Foods and Beverages*; Scotter, M.J., Ed.; Woodhead Publishing: Oxford, UK, 2015; pp. 35–60. ISBN 978-1-78242-011-8.
23. Silva, M.M.; Reboredo, F.H.; Lidon, F.C. Food Colour Additives: A Synoptical Overview on Their Chemical Properties, Applications in Food Products, and Health Side Effects. *Foods* **2022**, *11*, 379. [CrossRef]
24. Bevziuk, K.; Chebotarev, A.; Fizer, M.; Klochkova, A.; Pliuta, K.; Snigur, D. Protonation of Patented Blue V in Aqueous Solutions: Theoretical and Experimental Studies. *J. Chem. Sci.* **2018**, *130*, 12. [CrossRef]
25. EU. Commission Regulation (EU) No 1129/2011 of 11 November 2011 Amending Annex II to Regulation (EC) No 1333/2008 of the European Parliament and of the Council by Establishing a Union List of Food Additives. *Off. J. Eur. Union L* **2011**, *L295*, 1–177.
26. Cleere, M.M.; Novodvorska, M.; Geib, E.; Whittaker, J.; Dalton, H.; Salih, N.; Hewitt, S.; Kokolski, M.; Brock, M.; Dyer, P.S. New Colours for Old in the Blue-Cheese Fungus *Penicillium roqueforti*. *NPJ Sci. Food* **2024**, *8*, 3. [CrossRef] [PubMed]
27. López-Díaz, T.M.; Alegría, Á.; Rodríguez-Calleja, J.M.; Combarros-Fuertes, P.; Fresno, J.M.; Santos, J.A.; Flórez, A.B.; Mayo, B. Blue Cheeses: Microbiology and Its Role in the Sensory Characteristics. *Dairy* **2023**, *4*, 410–422. [CrossRef]
28. Hernández-Santos, B.; Lerdo-Reyes, A.A.; Téllez-Morales, J.A.; Rodríguez-Miranda, J. Chemical Composition, Techno-Functional Properties, and Bioactive Components of Blends of Blue Corn/Purple Sweet Potato for Its Possible Application in the Food Industry. *J. Food Meas. Charact.* **2023**, *17*, 1909–1920. [CrossRef]
29. Spence, C. What's the Story with Blue Steak? On the Unexpected Popularity of Blue Foods. *Front. Psychol.* **2021**, *12*, 638703. [CrossRef] [PubMed]
30. Pereira, R.N.; Rodrigues, R.M.; Genisheva, Z.; Oliveira, H.; de Freitas, V.; Teixeira, J.A.; Vicente, A.A. Effects of Ohmic Heating on Extraction of Food-Grade Phytochemicals from Colored Potato. *LWT* **2016**, *74*, 493–503. [CrossRef]
31. Tensiska, T.; Marta, H.; Cahyana, Y.; Amirah, N.S. Application of Encapsulated Anthocyanin Pigments from Purple Sweet Potato (*Ipomoea Batatas* L.) in Jelly Drink. *KnE Life Sci.* **2017**, *2*, 482–493. [CrossRef]
32. Paakki, M.; Sandell, M.; Hopia, A. Consumer's Reactions to Natural, Atypically Colored Foods: An Investigation Using Blue Potatoes. *J. Sens. Stud.* **2016**, *31*, 78–89. [CrossRef]
33. Luzardo-Ocampo, I.; Ramírez-Jiménez, A.K.; Yañez, J.; Mojica, L.; Luna-Vital, D.A. Technological Applications of Natural Colorants in Food Systems: A Review. *Foods* **2021**, *10*, 634. [CrossRef]
34. Paillié-Jiménez, M.E.; Stincone, P.; Brandelli, A. Natural Pigments of Microbial Origin. *Front. Sustain. Food Syst.* **2020**, *4*, 590439. [CrossRef]
35. Xu, F.; Gage, D.; Zhan, J. Efficient Production of Indigoidine in *Escherichia Coli*. *J. Ind. Microbiol. Biotechnol.* **2015**, *42*, 1149–1155. [CrossRef] [PubMed]
36. Jehlička, J.; Edwards, H.G.M.; Oren, A. Analysis of Brown, Violet and Blue Pigments of Microorganisms by Raman Spectroscopy. *TrAC Trends Anal. Chem.* **2022**, *146*, 116501. [CrossRef]
37. Dufossé, L. Chapter 19—Current and Potential Natural Pigments from Microorganisms (Bacteria, Yeasts, Fungi, and Microalgae). In *Handbook on Natural Pigments in Food and Beverages*, 2nd ed.; Schweiggert, R., Ed.; Woodhead Publishing: Sawston, UK, 2024; pp. 419–436. ISBN 978-0-323-99608-2.
38. Gürses, A.; Açıkyıldız, M.; Güneş, K.; Şahin, E. Chapter 4—Natural Dyes and Pigments in Food and Beverages. In *Renewable Dyes and Pigments*; Ul Islam, S., Ed.; Elsevier: Amsterdam, The Netherlands, 2024; pp. 49–76. ISBN 978-0-443-15213-9.
39. Singh, T.; Pandey, V.K.; Dash, K.K.; Zanwar, S.; Singh, R. Natural Bio-Colorant and Pigments: Sources and Applications in Food Processing. *J. Agric. Food Res.* **2023**, *12*, 100628. [CrossRef]
40. de Campos Vidal, B. Butterfly Scale Form Birefringence Related to Photonics. *Micron* **2011**, *42*, 801–807. [CrossRef]
41. Sztatecsny, M.; Preininger, D.; Freudmann, A.; Loretto, M.-C.; Maier, F.; Hödl, W. Don't Get the Blues: Conspicuous Nuptial Colouration of Male Moor Frogs (*Rana arvalis*) Supports Visual Mate Recognition during Scramble Competition in Large Breeding Aggregations. *Behav. Ecol. Sociobiol.* **2012**, *66*, 1587–1593. [CrossRef]
42. Magnus, K.A.; Ton-That, H.; Carpenter, J.E. Recent Structural Work on the Oxygen Transport Protein Hemocyanin. *Chem. Rev.* **1994**, *94*, 727–735. [CrossRef]
43. Quarmby, R.; Nordens, D.A.; Zagalsky, P.F.; Ceccaldi, H.J.; Daumas, R. Studies on the Quaternary Structure of the Lobster Exoskeleton Carotenoprotein, Crustacyanin. *Comp. Biochem. Physiol. Part B Comp. Biochem.* **1977**, *56*, 55–61. [CrossRef]
44. Nishida, Y.; Berg, P.C.; Shakersain, B.; Hecht, K.; Takikawa, A.; Tao, R.; Kakuta, Y.; Uragami, C.; Hashimoto, H.; Misawa, N. Astaxanthin: Past, Present, and Future. *Mar. Drugs* **2023**, *21*, 514. [CrossRef]
45. Jurić, S.; Jurić, M.; Król-Kilińska, Ż.; Vlahoviček-Kahlina, K.; Vinceković, M.; Dragović-Uzelac, V.; Donsì, F. Sources, Stability, Encapsulation and Application of Natural Pigments in Foods. *Food Rev. Int.* **2022**, *38*, 1735–1790. [CrossRef]

46. Karapanagiotis, I.; De Villemereuil, V.; Magiatis, P.; Polychronopoulos, P.; Vougogiannopoulou, K.; Skaltsounis, A. Identification of the Coloring Constituents of Four Natural Indigoid Dyes. *J. Liq. Chromatogr. Relat. Technol.* **2006**, *29*, 1491–1502. [CrossRef]
47. Imre, S.; Thomson, R.; Yalhi, B. Linderazulene, a New Naturally Occurring Pigment from the Gorgonian *Paramuricea Chamaeleon*. *Experientia* **1981**, *37*, 442–443. [CrossRef]
48. Bandaranayake, W.M. The Nature and Role of Pigments of Marine Invertebrates. *Nat. Prod. Rep.* **2006**, *23*, 223–255. [CrossRef] [PubMed]
49. Chen, D.; Yu, S.; van Ofwegen, L.; Proksch, P.; Lin, W. Anthogorgienes A–O, New Guaiazulene-Derived Terpenoids from a Chinese Gorgonian *Anthogorgia* Species, and Their Antifouling and Antibiotic Activities. *J. Agric. Food Chem.* **2012**, *60*, 112–123. [CrossRef]
50. Dyer, A.G.; Jentsch, A.; Burd, M.; Garcia, J.E.; Giejsztowt, J.; Camargo, M.G.G.; Tjørve, E.; Tjørve, K.M.C.; White, P.; Shrestha, M. Fragmentary Blue: Resolving the Rarity Paradox in Flower Colors. *Front. Plant Sci.* **2021**, *11*, 618203. [CrossRef] [PubMed]
51. Kattge, J.; Bönisch, G.; Díaz, S.; Lavorel, S.; Prentice, I.C.; Leadley, P. TRY Plant Trait Database—Enhanced Coverage and Open Acces. *Glob. Change Biol.* **2020**, *26*, 119–188. [CrossRef] [PubMed]
52. Lee, D. *Nature's Palette: The Science of Plant Color*; University of Chicago Press: Chicago, IL, USA, 2010; ISBN 978-0-226-47105-1.
53. Gottsberger, G.; Gottlieb, O.R. Blue Flower Pigmentation and Evolutionary Advancement. *Biochem. Syst. Ecol.* **1981**, *9*, 13–18. [CrossRef]
54. Ghosh, S.; Sarkar, T.; Das, A.; Chakraborty, R. Natural Colorants from Plant Pigments and Their Encapsulation: An Emerging Window for the Food Industry. *LWT* **2022**, *153*, 112527. [CrossRef]
55. Chalker-Scott, L. Environmental Significance of Anthocyanins in Plant Stress Responses. *Photochem. Photobiol.* **1999**, *70*, 1–9. [CrossRef]
56. Takahashi, A.; Takeda, K.; Ohnishi, T. Light-Induced Anthocyanin Reduces the Extent of Damage to DNA in UV-Irradiated *Centaurea cyanus* Cells in Culture. *Plant Cell Physiol.* **1991**, *32*, 541–547. [CrossRef]
57. Renita, A.A.; Gajaria, T.K.; Sathish, S.; Kumar, J.A.; Lakshmi, D.S.; Kujawa, J.; Kujawski, W. Progress and Prospective of the Industrial Development and Applications of Eco-Friendly Colorants: An Insight into Environmental Impact and Sustainability Issues. *Foods* **2023**, *12*, 1521. [CrossRef]
58. Sigurdson, G.T.; Tang, P.; Giusti, M.M. Natural Colorants: Food Colorants from Natural Sources. *Annu. Rev. Food Sci. Technol.* **2017**, *8*, 261–280. [CrossRef] [PubMed]
59. Oancea, A.-M.; Onofrei, C.; Turturică, M.; Bahrim, G.; Râpeanu, G.; Stănciuc, N. The Kinetics of Thermal Degradation of Polyphenolic Compounds from Elderberry (*Sambucus nigra* L.) Extract. *Food Sci. Technol. Int.* **2018**, *24*, 361–369. [CrossRef] [PubMed]
60. Sezgin, A.; Ayyıldız, S. Food Additives: Colorants. In *Science within Food: Up-to-Date Advances on Research and Educational Ideas*; Food Science Series N°1; Formatex Research Center: Badajoz, Spain, 2017; pp. 87–94. ISBN 978-84-947512-1-9.
61. Netravati Gomez, S.; Pathrose, B.; Mini, R.N.; Meagle, J.P.; Kuruvila, B. Comparative Evaluation of Anthocyanin Pigment Yield and Its Attributes from Butterfly Pea (*Clitorea ternatea* L.) Flowers as Prospective Food Colorant Using Different Extraction Methods. *Future Foods* **2022**, *6*, 100199. [CrossRef]
62. Nikijuluw, C.; Andarwulan, N. Color Characteristic of Butterfly Pea (*Clitoria ternatea* L.) Anthocyanin Extracts and Brilliant Blue. *Sci. Repos.* **2013**.
63. Ab Rashid, S.; Tong, W.Y.; Leong, C.R.; Abdul Ghazali, N.M.; Taher, M.A.; Ahmad, N.; Tan, W.-N.; Teo, S.H. Anthocyanin Microcapsule from *Clitoria ternatea*: Potential Bio-Preservative and Blue Colorant for Baked Food Products. *Arab. J. Sci. Eng.* **2021**, *46*, 65–72. [CrossRef]
64. Lakshan, S.A.T.; Jayanath, N.Y.; Abeysekera, W.P.K.M.; Abeysekera, W.K.S.M. A Commercial Potential Blue Pea (*Clitoria ternatea* L.) Flower Extract Incorporated Beverage Having Functional Properties. *Evid.-Based Complement. Altern. Med.* **2019**, *2019*, e2916914. [CrossRef]
65. Marpaung, A.M.; Lee, M.; Kartawiria, I.S. The Development of Butterfly Pea (*Clitoria ternatea*) Flower Powder Drink by Co-Crystallization. *Indones. Food Sci. Technol. J.* **2020**, *3*, 34–37. [CrossRef]
66. Roy, S.; Kim, H.-J.; Rhim, J.-W. Effect of Blended Colorants of Anthocyanin and Shikonin on Carboxymethyl Cellulose/Agar-Based Smart Packaging Film. *Int. J. Biol. Macromol.* **2021**, *183*, 305–315. [CrossRef]
67. Ahmadiani, N. Anthocyanin Based Blue Colorants. Master's Thesis, The Ohio State University, Columbus, OH, USA, 2012.
68. Yoshida, K.; Mori, M.; Kondo, T. Blue Flower Color Development by Anthocyanins: From Chemical Structure to Cell Physiology. *Nat. Prod. Rep.* **2009**, *26*, 884–915. [CrossRef]
69. Sigurdson, G.T.; Giusti, M.M. Bathochromic and Hyperchromic Effects of Aluminum Salt Complexation by Anthocyanins from Edible Sources for Blue Color Development. *J. Agric. Food Chem.* **2014**, *62*, 6955–6965. [CrossRef]
70. Pires, T.C.; Dias, M.I.; Barros, L.; Barreira, J.C.; Santos-Buelga, C.; Ferreira, I.C. Incorporation of Natural Colorants Obtained from Edible Flowers in Yogurts. *LWT* **2018**, *97*, 668–675. [CrossRef]
71. Koda, T.; Ichi, T.; Odake, K.; Furuta, H.; Sekiya, J. Blue Pigment Formation by *Clerodendron trichotomum* Callus. *Biosci. Biotechnol. Biochem.* **1992**, *56*, 2020–2022. [CrossRef]
72. Náthia-Neves, G.; Vardanega, R.; Meireles, M.A.A. Extraction of Natural Blue Colorant from *Genipa americana* L. Using Green Technologies: Techno-Economic Evaluation. *Food Bioprod. Process.* **2019**, *114*, 132–143. [CrossRef]

73. Fan, M.; Li, T.; Li, Y.; Qian, H.; Zhang, H.; Rao, Z.; Wang, L. *Vaccinium bracteatum* Thunb. as a Promising Resource of Bioactive Compounds with Health Benefits: An Updated Review. *Food Chem.* **2021**, *356*, 129738. [CrossRef] [PubMed]
74. Hanumaiah, T.; Marshall, D.S.; Rao, B.; Rao, J.; Rao, K.; Thomson, R.H. Naphthoquinone-Lactones and Extended Quinones from Ventilago Calyculata. *Phytochemistry* **1985**, *24*, 2669–2672. [CrossRef]
75. Jammula, S.; Pepalla, S.; Rao, K.; Rao, P. Chemical Components from *Ventilago goughii*, Gamble. *Acta Cienc. Indica Chem.* **1993**, *19*, 36.
76. Nersissian, A.; Immoos, C.; Hill, M.; Hart, P.; Williams, G.; Herrmann, R.; Valentine, J. Uclacyanins, Stellacyanins, and Plantacyanins Are Distinct Subfamilies of Phytocyanins: Plant-Specific Mononuclear Blue Copper Proteins. *Protein Sci. A Publ. Protein Soc.* **1998**, *7*, 1915–1929. [CrossRef]
77. Hart, P.J.; Eisenberg, D.; Nersissian, A.M.; Valentine, J.S.; Herrmann, R.G.; Nalbandyan, R.M. A Missing Link in Cupredoxins: Crystal Structure of Cucumber Stellacyanin at 1.6 Å Resolution. *Protein Sci.* **1996**, *5*, 2175–2183. [CrossRef]
78. Guss, J.M.; Freeman, H.C. Structure of Oxidized Poplar Plastocyanin at 1·6 Å Resolution. *J. Mol. Biol.* **1983**, *169*, 521–563. [CrossRef]
79. Guss, J.M.; Merritt, E.; Phizackerley, R.P.; Freeman, H. The Structure of a Phytocyanin, the Basic Blue Protein from Cucumber, Refined at 1.8 Å Resolution. *J. Mol. Biol.* **1996**, *262*, 686–705. [CrossRef]
80. Paul, K.; Stigbrand, T. Umecyanin, a Novel Intensely Blue Copper Protein from Horseradish Root. *Biochim. Biophys. Acta* **1970**, *221*, 255–263. [CrossRef] [PubMed]
81. Sankaram, A.V.; Reddy, V.V.N.; Sidhu, G.S. A Pentacyclic Quinone Diosindigo B from the Heartwood of Diospyros Melanoxylon. *Phytochemistry* **1981**, *20*, 1093–1096. [CrossRef]
82. Fu, L.; Xu, B.-T.; Xu, X.-R.; Gan, R.-Y.; Zhang, Y.; Xia, E.-Q.; Li, H.-B. Antioxidant Capacities and Total Phenolic Contents of 62 Fruits. *Food Chem.* **2011**, *129*, 345–350. [CrossRef] [PubMed]
83. Spitzner, D.; Höfle, G.; Klein, I.; Pohlan, S.; Ammermann, D.; Jaenicke, L. On the Structure of Oxyblepharismin and Its Formation from Blepharismin. *Tetrahedron Lett.* **1998**, *39*, 4003–4006. [CrossRef]
84. Caro, Y.; Venkatachalam, M.; Lebeau, J.; Fouillaud, M.; Dufossé, L. Pigments and Colorants from Filamentous Fungi. In *Fungal Metabolites*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 499–568. [CrossRef]
85. Lagashetti, A.C.; Dufossé, L.; Singh, S.K.; Singh, P.N. Fungal Pigments and Their Prospects in Different Industries. *Microorganisms* **2019**, *7*, 604. [CrossRef]
86. Molelekoa, T.B.J.; da Silva, L.S.; Regnier, T.; Augustyn, W. Application and Stability of Fungal Pigments Using Jelly Sweets as a Food Model System. *Int. J. Food Sci. Technol.* **2023**, *58*, 6761–6774. [CrossRef]
87. Dufossé, L.; Fouillaud, M.; Caro, Y.; Mapari, S.A.; Sutthiwong, N. Filamentous Fungi Are Large-Scale Producers of Pigments and Colorants for the Food Industry. *Curr. Opin. Biotechnol.* **2014**, *26*, 56–61. [CrossRef]
88. Sajjad, W.; Din, G.; Rafiq, M.; Iqbal, A.; Khan, S.; Zada, S.; Ali, B.; Kang, S. Pigment Production by Cold-Adapted Bacteria and Fungi: Colorful Tale of Cryosphere with Wide Range Applications. *Extremophiles* **2020**, *24*, 447–473. [CrossRef]
89. Jaklitsch, W.M.; Stadler, M.; Voglmayr, H. Blue Pigment in *Hypocrea caerulescens* Sp. Nov. and Two Additional New Species in Sect. *Trichoderma*. *Mycologia* **2012**, *104*, 925–941. [CrossRef]
90. Carvalho, J.C.d.; Oishi, B.O.; Pandey, A.; Soccol, C.R. Biopigments from Monascus: Strains Selection, Citrinin Production and Color Stability. *Braz. Arch. Biol. Technol.* **2005**, *48*, 885–894. [CrossRef]
91. Meruvu, H.; Dos Santos, J.C. Colors of Life: A Review on Fungal Pigments. *Crit. Rev. Biotechnol.* **2021**, *41*, 1153–1177. [CrossRef] [PubMed]
92. Narsing Rao, M.P.; Xiao, M.; Li, W.-J. Fungal and Bacterial Pigments: Secondary Metabolites with Wide Applications. *Front. Microbiol.* **2017**, *8*, 1113. [CrossRef] [PubMed]
93. Sadok, I.; Szmagara, A.; Krzyszczak, A. Validated QuEChERS-Based UHPLC-ESI-MS/MS Method for the Postharvest Control of Patulin (Mycotoxin) Contamination in Red-Pigmented Fruits. *Food Chem.* **2023**, *400*, 134066. [CrossRef]
94. Tuli, H.S.; Chaudhary, P.; Beniwal, V.; Sharma, A.K. Microbial Pigments as Natural Color Sources: Current Trends and Future Perspectives. *J. Food Sci. Technol.* **2015**, *52*, 4669–4678. [CrossRef]
95. Oren, A. Characterization of Pigments of Prokaryotes and Their Use in Taxonomy and Classification. In *Methods in Microbiology*; Elsevier: Amsterdam, The Netherlands, 2011; Volume 38, pp. 261–282. ISBN 0580-9517.
96. Schwieterman, E.W.; Cockell, C.S.; Meadows, V.S. Nonphotosynthetic Pigments as Potential Biosignatures. *Astrobiology* **2015**, *15*, 341–361. [CrossRef]
97. Bernhard, K.; Englert, G.; Meister, W.; Vecchi, M.; Renstrøm, B.; Liaaen-Jensen, S. Carotenoids of the Carotenoprotein Asteriarubin. Optical Purity of Asterinic Acid. *Helv. Chim. Acta* **1982**, *65*, 2224–2229. [CrossRef]
98. Britton, G.; Weesie, R.J.; Askin, D.; Warburton, J.D.; Gallardo-Guerrero, L.; Jansen, F.J.; de Groot, H.J.M.; Lugtenburg, J.; Cornard, J.-P.; Merlin, J.-C. Carotenoid Blues: Structural Studies on Carotenoproteins. *Pure Appl. Chem.* **1997**, *69*, 2075–2084. [CrossRef]
99. Gabed, N.; Verret, F.; Peticca, A.; Kryvoruchko, I.; Gastineau, R.; Bosson, O.; Séveno, J.; Davidovich, O.; Davidovich, N.; Witkowski, A.; et al. What Was Old Is New Again: The Pennate Diatom *Haslea ostrearia* (Gaillon) Simonsen in the Multi-Omic Age. *Mar. Drugs* **2022**, *20*, 234. [CrossRef]
100. Gastineau, R.; Davidovich, N.A.; Bardeau, J.-F.; Caruso, A.; Leignel, V.; Hardivillier, Y.; Jacquette, B.; Davidovich, O.I.; Rincé, Y.; Gaudin, P.; et al. *Haslea Karadagensis* (Bacillariophyta): A Second Blue Diatom, Recorded from the Black Sea and Producing a Novel Blue Pigment. *Eur. J. Phycol.* **2012**, *47*, 469–479. [CrossRef]

101. Pouvreau, J.-B.; Morancais, M.; Taran, F.; Rosa, P.; Dufossé, L.; Guérard, F.; Pin, S.; Fleurence, J.; Pondaven, P. Antioxidant and Free Radical Scavenging Properties of Marennine, a Blue-Green Polyphenolic Pigment from the Diatom *Haslea Ostrearia* (Gaillon/Bory) Simonsen Responsible for the Natural Greening of Cultured Oysters. *J. Agric. Food Chem.* **2008**, *56*, 6278–6286. [CrossRef] [PubMed]
102. Gastineau, R.; Hansen, G.; Davidovich, N.A.; Davidovich, O.; Bardeau, J.-F.; Kaczmarska, I.; Ehrman, J.M.; Leignel, V.; Hardivillier, Y.; Jacquette, B. A New Blue-Pigmented Hasleoid Diatom, *Haslea provincialis*, from the Mediterranean Sea. *Eur. J. Phycol.* **2016**, *51*, 156–170. [CrossRef]
103. Prasetiya, F.S.; Sunarto, S.; Bachtiar, E.; Agung, M.U.K.; Nathanael, B.; Pambudi, A.C.; Lestari, A.D.; Astuty, S.; Mouget, J.-L. Effect of the Blue Pigment Produced by the Tropical Diatom *Haslea nusantara* on Marine Organisms from Different Trophic Levels and Its Bioactivity. *Aquac. Rep.* **2020**, *17*, 100389. [CrossRef]
104. Gastineau, R.; Hansen, G.; Poulin, M.; Lemieux, C.; Turmel, M.; Bardeau, J.-F.; Leignel, V.; Hardivillier, Y.; Morançais, M.; Fleurence, J.; et al. *Haslea silbo*, A Novel Cosmopolitan Species of Blue Diatoms. *Biology* **2021**, *10*, 328. [CrossRef]
105. Ashaolu, T.J.; Samborska, K.; Lee, C.C.; Tomas, M.; Capanoglu, E.; Tarhan, Ö.; Taze, B.; Jafari, S.M. Phycocyanin, a Super Functional Ingredient from Algae; Properties, Purification Characterization, and Applications. *Int. J. Biol. Macromol.* **2021**, *193 Pt B*, 2320–2331. [CrossRef]
106. Eckardt, K.; Tresselt, D.; Ihn, W.; Schumann, G.; Eritt, I.; Sedmera, P.; Novak, J. Anthracyclinone-blue A and B, New Natural Anthracyclinones Containing Nitrogen in the Molecules: Isolation, Chemical Structures and Biosynthesis. *J. Basic Microbiol.* **1991**, *31*, 371–376. [CrossRef]
107. Grossart, H.-P.; Thorwest, M.; Plitzko, I.; Brinkhoff, T.; Simon, M.; Zeeck, A. Production of a Blue Pigment (Glaukothalin) by Marine *Rheinheimera* spp. *Int. J. Microbiol.* **2009**, *2009*, 701735. [CrossRef]
108. Venil, C.K.; Dufossé, L.; Renuka Devi, P. Bacterial Pigments: Sustainable Compounds With Market Potential for Pharma and Food Industry. *Front. Sustain. Food Syst.* **2020**, *4*, 100. [CrossRef]
109. Pfefferle, C.-M.; Breinholt, J.; Olsen, C.E.; Kroppenstedt, R.M.; Wellington, E.M.; Gürtler, H.; Fiedler, H.-P. Kyanomycin, a Complex of Unusual Anthracycline-Phospholipid Hybrids from *Nonomuria* Species. *J. Nat. Prod.* **2000**, *63*, 295–298. [CrossRef]
110. Orlandi, V.T.; Martegani, E.; Giaroni, C.; Baj, A.; Bolognese, F. Bacterial Pigments: A Colorful Palette Reservoir for Biotechnological Applications. *Biotechnol. Appl. Biochem.* **2022**, *69*, 981–1001. [CrossRef]
111. Rahman, D.Y.; Sarian, F.D.; van Wijk, A.; Martinez-Garcia, M.; van der Maarel, M.J.E.C. Thermostable Phycocyanin from the Red Microalga *Cyanidioschyzon merolae*, a New Natural Blue Food Colorant. *J. Appl. Phycol.* **2017**, *29*, 1233–1239. [CrossRef] [PubMed]
112. Venil, C.K.; Lakshmanaperumalsamy, P. An Insightful Overview on Microbial Pigment, Prodigiosin. *Electron. J. Biol.* **2009**, *5*, 49–61.
113. Zhu, H.; Guo, J.; Yao, Q.; Yang, S.; Deng, M.; Phuong, L.T.B.; Hanh, V.T.; Ryan, M.J. *Streptomyces vietnamensis* Sp. Nov., a Streptomycete with Violet-Blue Diffusible Pigment Isolated from Soil in Vietnam. *Int. J. Syst. Evol. Microbiol.* **2007**, *57*, 1770–1774. [CrossRef] [PubMed]
114. Lin, Y.B.; Wang, X.Y.; Fang, H.; Ma, Y.N.; Tang, J.; Tang, M.; Wei, G.H. *Streptomyces shaanxiensis* Sp. Nov., a Blue Pigment-Producing Streptomycete from Sewage Irrigation Soil. *Int. J. Syst. Evol. Microbiol.* **2012**, *62*, 1725–1730. [CrossRef]
115. Zhu, H.; Guo, J.; Yao, Q.; Yang, S.; Deng, M.; Li, T. *Streptomyces caeruleatus* Sp. Nov., with Dark Blue Diffusible Pigment. *Int. J. Syst. Evol.* **2011**, *61*, 507–511. [CrossRef]
116. Zhu, Y.; Shang, X.; Yang, L.; Zheng, S.; Liu, K.; Li, X. Purification, Identification and Properties of a New Blue Pigment Produced from *Streptomyces* Sp. A1013Y. *Food Chem.* **2020**, *308*, 125600. [CrossRef]
117. Gray, P. The Formation of Indigotin from Indol by Soil Bacteria. In Proceedings of the Royal Society of London, Series B, Containing Papers of a Biological Character; Royal Society: London, UK, 1928; Volume 102, pp. 263–280. [CrossRef]
118. Andreani, N.A.; Carraro, L.; Martino, M.E.; Fondi, M.; Fasolato, L.; Miotto, G.; Magro, M.; Vianello, F.; Cardazzo, B. A Genomic and Transcriptomic Approach to Investigate the Blue Pigment Phenotype in Pseudomonas Fluorescens. *Int. J. Food Microbiol.* **2015**, *213*, 88–98. [CrossRef]
119. Wang, J.; Zhang, X.; Fan, J.; Zhang, Z.; Ma, Q.; Peng, X. Indigoids Biosynthesis from Indole by Two Phenol-Degrading Strains, *Pseudomonas* Sp. PI1 and *Acinetobacter* Sp. PI2. *Appl. Biochem. Biotechnol.* **2015**, *176*, 1263–1276. [CrossRef]
120. Nawaz, A.; Chaudhary, R.; Shah, Z.; Dufossé, L.; Fouillaud, M.; Mukhtar, H.; ul Haq, I. An Overview on Industrial and Medical Applications of Bio-Pigments Synthesized by Marine Bacteria. *Microorganisms* **2020**, *9*, 11. [CrossRef]
121. Abel, G.; Amobonye, A.; Bhagwat, P.; Pillai, S. Diversity, Stability and Applications of Mycopigments. *Process Biochem.* **2023**, *133*, 270–284. [CrossRef]
122. Reverchon, S.; Rouanet, C.; Expert, D.; Nasser, W. Characterization of Indigoidine Biosynthetic Genes in *Erwinia chrysanthemi* and Role of This Blue Pigment in Pathogenicity. *J. Bacteriol.* **2002**, *184*, 654–665. [CrossRef] [PubMed]
123. Cude, W.N.; Mooney, J.; Tavanaei, A.A.; Hadden, M.K.; Frank, A.M.; Gulvik, C.A.; May, A.L.; Buchan, A. Production of the Antimicrobial Secondary Metabolite Indigoidine Contributes to Competitive Surface Colonization by the Marine Roseobacter *Phaeobacter* Sp. Strain Y4I. *Appl. Environ. Microbiol.* **2012**, *78*, 4771–4780. [CrossRef] [PubMed]
124. Soliev, A.B.; Hosokawa, K.; Enomoto, K. Bioactive Pigments from Marine Bacteria: Applications and Physiological Roles. *Evid.-Based Complement. Altern. Med.* **2011**, *2011*, 670349. [CrossRef] [PubMed]

125. Wehrs, M.; Gladden, J.M.; Liu, Y.; Platz, L.; Prahl, J.-P.; Moon, J.; Papa, G.; Sundstrom, E.; Geiselman, G.M.; Tanjore, D.; et al. Sustainable Bioproduction of the Blue Pigment Indigoidine: Expanding the Range of Heterologous Products in *R. toruloides* to Include Non-Ribosomal Peptides. *Green Chem.* **2019**, *21*, 3394–3406. [CrossRef]
126. Yu, D.; Xu, F.; Valiente, J.; Wang, S.; Zhan, J. An Indigoidine Biosynthetic Gene Cluster from *Streptomyces Chromofuscus* ATCC 49982 Contains an Unusual IndB Homologue. *J. Ind. Microbiol. Biotechnol.* **2013**, *40*, 159–168. [CrossRef]
127. Day, P.A.; Villalba, M.S.; Herrero, O.M.; Arancibia, L.A.; Alvarez, H.M. Formation of Indigoidine Derived-Pigments Contributes to the Adaptation of *Vogesella* Sp. Strain EB to Cold Aquatic Iron-Oxidizing Environments. *Antonie Leeuwenhoek* **2017**, *110*, 415–428. [CrossRef]
128. Dufossé, L.; Galaup, P.; Yaron, A.; Arad, S.M.; Blanc, P.; Chidambara Murthy, K.N.; Ravishankar, G.A. Microorganisms and Microalgae as Sources of Pigments for Food Use: A Scientific Oddity or an Industrial Reality? *Trends Food Sci. Technol.* **2005**, *16*, 389–406. [CrossRef]
129. Francezon, N.; Herbaut, M.; Bardeau, J.-F.; Cougnon, C.; Bélanger, W.; Tremblay, R.; Jacquette, B.; Dittmer, J.; Pouvreau, J.-B.; Mouget, J.-L.; et al. Electrochromic Properties and Electrochemical Behavior of Marennine, a Bioactive Blue-Green Pigment Produced by the Marine Diatom Haslea Ostrearia. *Mar. Drugs* **2021**, *19*, 231. [CrossRef]
130. Di Salvo, E.; Lo Vecchio, G.; De Pasquale, R.; De Maria, L.; Tardugno, R.; Vadalà, R.; Cicero, N. Natural Pigments Production and Their Application in Food, Health and Other Industries. *Nutrients* **2023**, *15*, 1923. [CrossRef]
131. Ngamwonglumlert, L.; Devahastin, S.; Chiewchan, N. Natural Colorants: Pigment Stability and Extraction Yield Enhancement via Utilization of Appropriate Pretreatment and Extraction Methods. *Crit. Rev. Food Sci. Nutr.* **2017**, *57*, 3243–3259. [CrossRef]
132. Zhu, Y.; Sun, H.; He, S.; Lou, Q.; Yu, M.; Tang, M.; Tu, L. Metabolism and Prebiotics Activity of Anthocyanins from Black Rice (*Oryza sativa* L.) In Vitro. *PLoS ONE* **2018**, *13*, e0195754. [CrossRef] [PubMed]
133. Sun, H.; Zhang, P.; Zhu, Y.; Lou, Q.; He, S. Antioxidant and Prebiotic Activity of Five Peonidin-Based Anthocyanins Extracted from Purple Sweet Potato (*Ipomoea batatas* (L.) Lam.). *Sci. Rep.* **2018**, *8*, 5018. [CrossRef] [PubMed]
134. Eker, M.E.; Aaby, K.; Budic-Leto, I.; Rimac Brnčić, S.; El, S.N.; Karakaya, S.; Simsek, S.; Manach, C.; Wiczkowski, W.; de Pascual-Teresa, S. A Review of Factors Affecting Anthocyanin Bioavailability: Possible Implications for the Inter-Individual Variability. *Foods* **2020**, *9*, 2. [CrossRef] [PubMed]
135. Wu, Y.; Han, Y.; Tao, Y.; Li, D.; Xie, G.; Show, P.L.; Lee, S.Y. In Vitro Gastrointestinal Digestion and Fecal Fermentation Reveal the Effect of Different Encapsulation Materials on the Release, Degradation and Modulation of Gut Microbiota of Blueberry Anthocyanin Extract. *Food Res. Int.* **2020**, *132*, 109098. [CrossRef]
136. Flores, G.; Ruiz del Castillo, M.L.; Costabile, A.; Klee, A.; Bigetti Guergoletto, K.; Gibson, G.R. In Vitro Fermentation of Anthocyanins Encapsulated with Cyclodextrins: Release, Metabolism and Influence on Gut Microbiota Growth. *J. Funct. Foods* **2015**, *16*, 50–57. [CrossRef]
137. Wang, Y.; Liu, T.; Xie, Y.; Li, N.; Liu, Y.; Wen, J.; Zhang, M.; Feng, W.; Huang, J.; Guo, Y.; et al. Clitoria Ternatea Blue Petal Extract Protects against Obesity, Oxidative Stress, and Inflammation Induced by a High-Fat, High-Fructose Diet in C57BL/6 Mice. *Food Res. Int.* **2022**, *162*, 112008. [CrossRef]
138. Náthia-Neves, G.; Tarone, A.G.; Tosi, M.M.; Maróstica Júnior, M.R.; Meireles, M.A.A. Extraction of Bioactive Compounds from Genipap (*Genipa americana* L.) by Pressurized Ethanol: Iridoids, Phenolic Content and Antioxidant Activity. *Food Res. Int.* **2017**, *102*, 595–604. [CrossRef]
139. Zheng, Y.; Chen, L.; Liu, Y.; Shi, L.; Wan, S.; Wang, L. Evaluation of Antimicrobial Activity of Water-Soluble Flavonoids Extract from *Vaccinium bracteatum* Thunb. Leaves. *Food Sci. Biotechnol.* **2019**, *28*, 1853–1859. [CrossRef]
140. Jayaseelan, S.; Ramaswamy, D.; Dharmaraj, S. Pyocyanin: Production, Applications, Challenges and New Insights. *World J. Microbiol. Biotechnol.* **2014**, *30*, 1159–1168. [CrossRef]
141. Chen, H.-W.; Yang, T.-S.; Chen, M.-J.; Chang, Y.-C.; Wang, E.I.-C.; Ho, C.-L.; Lai, Y.-J.; Yu, C.-C.; Chou, J.-C.; Chao, L.K.-P.; et al. Purification and Immunomodulating Activity of C-Phycocyanin from *Spirulina platensis* Cultured Using Power Plant Flue Gas. *Process Biochem.* **2014**, *49*, 1337–1344. [CrossRef]
142. Hamdan, N.T.; Jwad, B.A.A.A.A.; Jasim, S.A. Synergistic Anticancer Effects of Phycocyanin and Citrullus Colocynthis Extract against WiDr, HCT-15 and HCT-116 Colon Cancer Cell Lines. *Gene Rep.* **2021**, *22*, 100972. [CrossRef]
143. Wen, Y.; Wen, P.; Hu, T.-G.; Linhardt, R.J.; Zong, M.-H.; Wu, H.; Chen, Z.-Y. Encapsulation of Phycocyanin by Prebiotics and Polysaccharides-Based Electrospun Fibers and Improved Colon Cancer Prevention Effects. *Int. J. Biol. Macromol.* **2020**, *149*, 672–681. [CrossRef] [PubMed]
144. Prabakaran, G.; Sampathkumar, P.; Kavisri, M.; Moovendhan, M. Extraction and Characterization of Phycocyanin from *Spirulina platensis* and Evaluation of Its Anticancer, Antidiabetic and Antiinflammatory Effect. *Int. J. Biol. Macromol.* **2020**, *153*, 256–263. [CrossRef] [PubMed]
145. Min, S.K.; Park, J.S.; Luo, L.; Kwon, Y.S.; Lee, H.C.; Jung Shim, H.; Kim, I.-D.; Lee, J.-K.; Shin, H.S. Assessment of C-Phycocyanin Effect on Astrocytes-Mediated Neuroprotection against Oxidative Brain Injury Using 2D and 3D Astrocyte Tissue Model. *Sci. Rep.* **2015**, *5*, 14418. [CrossRef]
146. Gammoudi, S.; Athmouni, K.; Nasri, A.; Diwani, N.; Grati, I.; Belhaj, D.; Bouaziz-Ketata, H.; Fki, L.; El Feki, A.; Ayadi, H. Optimization, Isolation, Characterization and Hepatoprotective Effect of a Novel Pigment-Protein Complex (Phycocyanin) Producing Microalga: Phormidium VersicolorNCC-466 Using Response Surface Methodology. *Int. J. Biol. Macromol.* **2019**, *137*, 647–656. [CrossRef]

147. Fratelli, C.; Burck, M.; Amarante, M.C.A.; Braga, A.R.C. Antioxidant Potential of Nature's "Something Blue": Something New in the Marriage of Biological Activity and Extraction Methods Applied to C-Phycocyanin. *Trends Food Sci. Technol.* **2021**, *107*, 309–323. [CrossRef]
148. Singh, J.; Meehnian, H.; Gupta, P.; Verma, M. Food Colours: The Potential Sources of Food Adulterants and Their Food Safety Concerns. In *Biotechnological Approaches in Food Adulterants*; CRC Press/Taylor & Francis Group: Boca Raton, FL, USA, 2020; pp. 79–101. ISBN 978-0-367-36986-6.
149. Carbonnelle, D.; Pondaven, P.; Morançais, M.; Massé, G.; Bosch, S.; Jacquot, C.; Briand, G.; Robert, J.; Roussakis, C. Antitumor and Antiproliferative Effects of an Aqueous Extract from the Marine Diatom *Haslea ostrearia* (Simonsen) against Solid Tumors: Lung Carcinoma (NSCLC-N6), Kidney Carcinoma (E39) and Melanoma (M96) Cell Lines. *Anticancer Res.* **1999**, *19*, 621–624.
150. Gastineau, R.; Pouvreau, J.-B.; Hellio, C.; Morançais, M.; Fleurence, J.; Gaudin, P.; Bourgougnon, N.; Mouget, J.-L. Biological Activities of Purified Marennine, the Blue Pigment Responsible for the Greening of Oysters. *J. Agric. Food Chem.* **2012**, *60*, 3599–3605. [CrossRef]
151. Bergé, J.-P.; Bourgougnon, N.; Alban, S.; Pojer, F.; Billaudel, S.; Chermann, J.-C.; Robert, J.; Franz, G. Antiviral and Anticoagulant Activities of a Water-Soluble Fraction of the Marine Diatom *Haslea Ostrearia*. *Planta Medica* **1999**, *65*, 604–609. [CrossRef]
152. Feketea, G.; Tsabouri, S. Common Food Colorants and Allergic Reactions in Children: Myth or Reality? *Food Chem.* **2017**, *230*, 578–588. [CrossRef]
153. Yousefi, M.; Ghanbari, F.; Zazouli, M.; Madihi Bidgoli, S. Brilliant Blue FCF Degradation by Persulfate/Zero Valent Iron: The Effects of Influencing Parameters and Anions. *Desalination Water Treat.* **2017**, *70*, 364–371. [CrossRef]
154. Chadwick, B.L.; Hunter, M.L.; Evans, M.T.; Hunter, B. Allergic Reaction to the Food Dye Patent Blue. *Br. Dent. J.* **1990**, *168*, 386–387. [CrossRef] [PubMed]
155. Stevens, L.J.; Burgess, J.R.; Stochelski, M.A.; Kuczek, T. Amounts of Artificial Food Dyes and Added Sugars in Foods and Sweets Commonly Consumed by Children. *Clin. Pediatr.* **2015**, *54*, 309–321. [CrossRef] [PubMed]
156. McCann, D.; Barrett, A.; Cooper, A.; Crumpler, D.; Dalen, L.; Grimshaw, K.; Kitchin, E.; Lok, K.; Porteous, L.; Prince, E.; et al. Food Additives and Hyperactive Behaviour in 3-Year-Old and 8/9-Year-Old Children in the Community: A Randomised, Double-Blinded, Placebo-Controlled Trial. *Lancet* **2007**, *370*, 1560–1567. [CrossRef]
157. Amchova, P.; Kotolova, H.; Ruda-Kucerova, J. Health Safety Issues of Synthetic Food Colorants. *Regul. Toxicol. Pharmacol.* **2015**, *73*, 914–922. [CrossRef]
158. Lucová, M.; Hojerová, J.; Pažoureková, S.; Klimová, Z. Absorption of Triphenylmethane Dyes Brilliant Blue and Patent Blue through Intact Skin, Shaven Skin and Lingual Mucosa from Daily Life Products. *Food Chem. Toxicol.* **2013**, *52*, 19–27. [CrossRef]
159. EFSA. Panel on Food Additives and Nutrient Sources added to Food (ANS). Scientific Opinion on the Re-evaluation of Brilliant Blue FCF (E 133) as a Food Additive. *EFSA J.* **2010**, *8*, 1853. [CrossRef]
160. Kus, E.; Eroğlu, H. Genotoxic and Cytotoxic Effects of Sunset Yellow and Brilliant Blue, Colorant Food Additives, on Human Blood Lymphocytes. *Pak. J. Pharm. Sci.* **2015**, *28*, 227–230.
161. Mahmoud, N. Toxic Effects of the Synthetic Food Dye Brilliant Blue on Liver, Kidney and Testes Functions in Rats. *J. Egypt. Soc. Toxicol.* **2006**, *34*, 77–84.
162. Jindal, A.; Pathengay, A.; Mithal, K.; Chhablani, J.; Pappuru, R.K.; Flynn, H. Macular Toxicity Following Brilliant Blue G-Assisted Macular Hole Surgery-a Report of Three Cases. *Nepal. J. Ophthalmol. A Biannu. Peer-Rev. Acad. J. Nepal Ophthalmic Soc. Nepjoph* **2014**, *6*, 98–101. [CrossRef]
163. Kuswandi, B.; Wicaksono, Y.; Jayus; Abdullah, A.; Heng, L.Y.; Ahmad, M. Smart Packaging: Sensors for Monitoring of Food Quality and Safety. *Sens. Instrum. Food Qual. Saf.* **2011**, *5*, 137–146. [CrossRef]
164. Blakeney, M. *Food Loss and Food Waste: Causes and Solutions*; Edward Elgar Publishing: Cheltenham, UK, 2019; ISBN 978-1-78897-539-1.
165. Müller, P.; Schmid, M. Intelligent Packaging in the Food Sector: A Brief Overview. *Foods* **2019**, *8*, 16. [CrossRef] [PubMed]
166. Rukchon, C.; Nopwinyuwong, A.; Trevanich, S.; Jinkarn, T.; Suppakul, P. Development of a Food Spoilage Indicator for Monitoring Freshness of Skinless Chicken Breast. *Talanta* **2014**, *130*, 547–554. [CrossRef] [PubMed]
167. Kim, D.; Lee, S.; Lee, K.; Baek, S.; Seo, J. Development of a PH Indicator Composed of High Moisture-Absorbing Materials for Real-Time Monitoring of Chicken Breast Freshness. *Food Sci. Biotechnol.* **2017**, *26*, 37–42. [CrossRef] [PubMed]
168. Karaca, I.M.; Haskaraca, G.; Ayhan, Z.; Gültekin, E. Development of Real Time-PH Sensitive Intelligent Indicators for Monitoring Chicken Breast Freshness/Spoilage Using Real Packaging Practices. *Food Res. Int.* **2023**, *173*, 113261. [CrossRef] [PubMed]
169. Yang, D.; Liu, Q.; Zeng, X.; Chen, X.; Li, M.; Wu, X.; Liu, Y.; Zheng, Y.; Xiang, J.; Wang, C.; et al. Novel PH-Responsive Indicator Films Based on Bromothymol Blue-Anchored Chitin for Shrimp Freshness Monitoring. *Int. J. Biol. Macromol.* **2023**, *253*, 127052. [CrossRef]
170. Parsafar, B.; Ahmadi, M.; Jahed Khaniki, G.R.; Shariatifar, N.; Rahimi Foroushani, A. The Impact of Fruit and Vegetable Waste on Economic Loss Estimation. *Glob. J. Environ. Sci. Manag.* **2023**, *9*, 871–884. [CrossRef]
171. Zhang, W.; An, H.; Sun, X.; Du, H.; Li, Y.; Yang, M.; Zhu, Z.; Wen, Y. Dual-Functional Smart Indicator for Direct Monitoring Fruit Freshness. *Food Packag. Shelf Life* **2023**, *40*, 101192. [CrossRef]
172. Luo, X.; Zaitoon, A.; Lim, L.-T. A Review on Colorimetric Indicators for Monitoring Product Freshness in Intelligent Food Packaging: Indicator Dyes, Preparation Methods, and Applications. *Compr. Rev. Food Sci. Food Saf.* **2022**, *21*, 2489–2519. [CrossRef]
173. Obaidi, A.A.; Karaca, I.M.; Ayhan, Z.; Haskaraca, G.; Gultekin, E. Fabrication and Validation of CO2-Sensitive Indicator to Monitor the Freshness of Poultry Meat. *Food Packag. Shelf Life* **2022**, *34*, 100930. [CrossRef]

174. Shaik, M.I.; Azhari, M.F.; Sarbon, N.M. Gelatin-Based Film as a Color Indicator in Food-Spoilage Observation: A Review. *Foods* **2022**, *11*, 3797. [CrossRef] [PubMed]
175. Ezati, P.; Tajik, H.; Moradi, M. Fabrication and Characterization of Alizarin Colorimetric Indicator Based on Cellulose-Chitosan to Monitor the Freshness of Minced Beef. *Sens. Actuators B Chem.* **2019**, *285*, 519–528. [CrossRef]
176. Smolander, M.; Hurme, E.; Latva-Kala, K.; Luoma, T.; Alakomi, H.-L.; Ahvenainen, R. Myoglobin-Based Indicators for the Evaluation of Freshness of Unmarinated Broiler Cuts. *Innov. Food Sci. Emerg. Technol.* **2002**, *3*, 279–288. [CrossRef]
177. Bhargava, N.; Sharanagat, V.S.; Mor, R.S.; Kumar, K. Active and Intelligent Biodegradable Packaging Films Using Food and Food Waste-Derived Bioactive Compounds: A Review. *Trends Food Sci. Technol.* **2020**, *105*, 385–401. [CrossRef]
178. Chi, W.; Cao, L.; Sun, G.; Meng, F.; Zhang, C.; Li, J.; Wang, L. Developing a Highly PH-Sensitive κ-Carrageenan-Based Intelligent Film Incorporating Grape Skin Powder via a Cleaner Process. *J. Clean. Prod.* **2020**, *244*, 118862. [CrossRef]
179. Talukder, S.; Mendiratta, S.K.; Kumar, R.R.; Agrawal, R.K.; Soni, A.; Luke, A.; Chand, S. Jamun Fruit (*Syzgium cumini*) Skin Extract Based Indicator for Monitoring Chicken Patties Quality during Storage. *J. Food Sci. Technol.* **2020**, *57*, 537–548. [CrossRef]
180. Kurek, M.; Garofulić, I.E.; Bakić, M.T.; Ščetar, M.; Uzelac, V.D.; Galić, K. Development and Evaluation of a Novel Antioxidant and PH Indicator Film Based on Chitosan and Food Waste Sources of Antioxidants. *Food Hydrocoll.* **2018**, *84*, 238–246. [CrossRef]
181. Shahid, M.; Shahid-ul-Islam; Mohammad, F. Recent Advancements in Natural Dye Applications: A Review. *J. Clean. Prod.* **2013**, *53*, 310–331. [CrossRef]
182. Choi, I.; Lee, J.Y.; Lacroix, M.; Han, J. Intelligent PH Indicator Film Composed of Agar/Potato Starch and Anthocyanin Extracts from Purple Sweet Potato. *Food Chem.* **2017**, *218*, 122–128. [CrossRef]
183. Zhang, J.; Zou, X.; Zhai, X.; Huang, X.; Jiang, C.; Holmes, M. Preparation of an Intelligent PH Film Based on Biodegradable Polymers and Roselle Anthocyanins for Monitoring Pork Freshness. *Food Chem.* **2019**, *272*, 306–312. [CrossRef]
184. Fujikawa, H.; Akimoto, R. New Blue Pigment Produced by *Pantoea agglomerans* and Its Production Characteristics at Various Temperatures. *Appl. Environ. Microbiol.* **2011**, *77*, 172–178. [CrossRef] [PubMed]
185. Yousefi, H.; Su, H.-M.; Imani, S.M.; Alkhaldi, K.M.; Filipe, C.D.; Didar, T.F. Intelligent Food Packaging: A Review of Smart Sensing Technologies for Monitoring Food Quality. *ACS Sens.* **2019**, *4*, 808–821. [CrossRef] [PubMed]
186. Chayavanich, K.; Thiraphibundet, P.; Imyim, A. Biocompatible Film Sensors Containing Red Radish Extract for Meat Spoilage Observation. *Spectrochim. Acta Part A Mol. Biomol. Spectrosc.* **2020**, *226*, 117601. [CrossRef] [PubMed]
187. Golasz, L.B.; Silva, J.d.; Silva, S.B.d. Film with Anthocyanins as an Indicator of Chilled Pork Deterioration. *Food Sci. Technol.* **2013**, *33*, 155–162. [CrossRef]
188. Luchese, C.L.; Abdalla, V.F.; Spada, J.C.; Tessaro, I.C. Evaluation of Blueberry Residue Incorporated Cassava Starch Film as PH Indicator in Different Simulants and Foodstuffs. *Food Hydrocoll.* **2018**, *82*, 209–218. [CrossRef]
189. Vo, T.-V.; Dang, T.-H.; Chen, B.-H. Synthesis of Intelligent PH Indicative Films from Chitosan/Poly(Vinyl Alcohol)/Anthocyanin Extracted from Red Cabbage. *Polymers* **2019**, *11*, 1088. [CrossRef]
190. Wardana, A.A.; Widyaningsih, T.D. *Development of Edible Films from Tapioca Starch and Agar, Enriched with Red Cabbage (*Brassica oleracea*) as a Sausage Deterioration Bio-Indicator*; IOP Publishing: Bristol, UK, 2017; Volume 109, p. 012031.
191. Silva-Pereira, M.C.; Teixeira, J.A.; Pereira-Júnior, V.A.; Stefani, R. Chitosan/Corn Starch Blend Films with Extract from *Brassica oleraceae* (Red Cabbage) as a Visual Indicator of Fish Deterioration. *LWT-Food Sci. Technol.* **2015**, *61*, 258–262. [CrossRef]
192. Anugrah, D.S.B.; Darmalim, L.V.; Sinanu, J.D.; Pramitasari, R.; Subali, D.; Prasetyanto, E.A.; Cao, X.T. Development of Alginate-Based Film Incorporated with Anthocyanins of Red Cabbage and Zinc Oxide Nanoparticles as Freshness Indicator for Prawns. *Int. J. Biol. Macromol.* **2023**, *251*, 126203. [CrossRef]
193. Narayanan, G.P.; Radhakrishnan, P.; Baiju, P. Fabrication Of Butterfly Pea Flower Anthocyanin-Incorporated Colorimetric Indicator Film Based On Gelatin/Pectin For Monitoring Fish Freshness. *Food Hydrocoll. Health* **2023**, *4*, 100159. [CrossRef]
194. Wu, C.; Sun, J.; Zheng, P.; Kang, X.; Chen, M.; Li, Y.; Ge, Y.; Hu, Y.; Pang, J. Preparation of an Intelligent Film Based on Chitosan/Oxidized Chitin Nanocrystals Incorporating Black Rice Bran Anthocyanins for Seafood Spoilage Monitoring. *Carbohydr. Polym.* **2019**, *222*, 115006. [CrossRef]
195. Bandyopadhyay, S.; Saha, N.; Zandraa, O.; Pummerová, M.; Sáha, P. Essential Oil Based PVP-CMC-BC-GG Functional Hydrogel Sachet for 'Cheese': Its Shelf Life Confirmed with Anthocyanin (Isolated from Red Cabbage) Bio Stickers. *Foods* **2020**, *9*, 307. [CrossRef] [PubMed]
196. Ma, Q.; Wang, L. Preparation of a Visual PH-Sensing Film Based on Tara Gum Incorporating Cellulose and Extracts from Grape Skins. *Sens. Actuators B Chem.* **2016**, *235*, 401–407. [CrossRef]
197. Pereira, V.A.; de Arruda, I.N.Q.; Stefani, R. Active Chitosan/PVA Films with Anthocyanins from Brassica Oleraceae (Red Cabbage) as Time-Temperature Indicators for Application in Intelligent Food Packaging. *Food Hydrocoll.* **2015**, *43*, 180–188. [CrossRef]
198. Wang, S.; Li, R.; Han, M.; Zhuang, D.; Zhu, J. Intelligent Active Films of Sodium Alginate and Konjac Glucomannan Mixed by Lycium Ruthenicum Anthocyanins and Tea Polyphenols for Milk Preservation and Freshness Monitoring. *Int. J. Biol. Macromol.* **2023**, *253*, 126674. [CrossRef]
199. Drhimer, F.; Rahmani, M.; Regraguy, B.; El Hajjaji, S.; Mabrouki, J.; Amrane, A.; Fourcade, F.; Assadi, A.A. Treatment of a Food Industry Dye, Brilliant Blue, at Low Concentration Using a New Photocatalytic Configuration. *Sustainability* **2023**, *15*, 5788. [CrossRef]
200. David, L.; Moldovan, B. Green Synthesis of Biogenic Silver Nanoparticles for Efficient Catalytic Removal of Harmful Organic Dyes. *Nanomaterials* **2020**, *10*, 202. [CrossRef]

201. da Fonseca Machado, A.P.; Rezende, C.A.; Rodrigues, R.A.; Barbero, G.F.; e Rosa, P.d.T.V.; Martínez, J. Encapsulation of Anthocyanin-Rich Extract from Blackberry Residues by Spray-Drying, Freeze-Drying and Supercritical Antisolvent. *Powder Technol.* **2018**, *340*, 553–562. [CrossRef]
202. Block, E. *Garlic and Other Alliums: The Lore and the Science*; RSC Publishing: Cambridge, UK, 2010; ISBN 978-0-85404-190-9.
203. Khoironi, A.; Anggoro, S.; Sudarno, S. Evaluation of the Interaction among Microalgae *Spirulina* Sp, Plastics Polyethylene Terephthalate and Polypropylene in Freshwater Environment. *J. Ecol. Eng.* **2019**, *20*, 161–173. [CrossRef]
204. Correa, D.F.; Beyer, H.L.; Possingham, H.P.; García-Ulloa, J.; Ghazoul, J.; Schenk, P.M. Freeing Land from Biofuel Production through Microalgal Cultivation in the Neotropical Region. *Environ. Res. Lett.* **2020**, *15*, 094094. [CrossRef]
205. De Man, R.; German, L. Certifying the Sustainability of Biofuels: Promise and Reality. *Energy Policy* **2017**, *109*, 871–883. [CrossRef]
206. Mathimani, T.; Pugazhendhi, A. Utilization of Algae for Biofuel, Bio-Products and Bio-Remediation. *Biocatal. Agric. Biotechnol.* **2019**, *17*, 326–330. [CrossRef]
207. Chia, S.R.; Chew, K.W.; Show, P.L.; Yap, Y.J.; Ong, H.C.; Ling, T.C.; Chang, J. Analysis of Economic and Environmental Aspects of Microalgae Biorefinery for Biofuels Production: A Review. *Biotechnol. J.* **2018**, *13*, 1700618. [CrossRef] [PubMed]
208. Moreno-Garcia, L.; Adjallé, K.; Barnabé, S.; Raghavan, G. Microalgae Biomass Production for a Biorefinery System: Recent Advances and the Way towards Sustainability. *Renew. Sustain. Energy Rev.* **2017**, *76*, 493–506. [CrossRef]
209. González-González, L.M.; Correa, D.F.; Ryan, S.; Jensen, P.D.; Pratt, S.; Schenk, P.M. Integrated Biodiesel and Biogas Production from Microalgae: Towards a Sustainable Closed Loop through Nutrient Recycling. *Renew. Sustain. Energy Rev.* **2018**, *82*, 1137–1148. [CrossRef]
210. Gu, J.-D.; Cheung, K. Phenotypic Expression of *Vogesella indigofera* upon Exposure to Hexavalent Chromium, $Cr6^+$. *World J. Microbiol. Biotechnol.* **2001**, *17*, 475–480. [CrossRef]
211. Calogero, G.; Bartolotta, A.; Di Marco, G.; Di Carlo, A.; Bonaccorso, F. Vegetable-Based Dye-Sensitized Solar Cells. *Chem. Soc. Rev.* **2015**, *44*, 3244–3294. [CrossRef]
212. Lucioli, S.; Di Bari, C.; Forni, C.; Di Carlo, A.; Barrajón-Catalán, E.; Micol, V.; Nota, P.; Teoli, F.; Matteocci, F.; Frattarelli, A.; et al. Anthocyanic Pigments from Elicited in Vitro Grown Shoot Cultures of *Vaccinium corymbosum* L., Cv. Brigitta Blue, as Photosensitizer in Natural Dye-Sensitized Solar Cells (NDSSC). *J. Photochem. Photobiol. B Biol.* **2018**, *188*, 69–76. [CrossRef]
213. Grätzel, M. Dye-Sensitized Solar Cells. *J. Photochem. Photobiol. C Photochem. Rev.* **2003**, *4*, 145–153. [CrossRef]
214. Amiri, O.; Salavati-Niasari, M.; Mir, N.; Beshkar, F.; Saadat, M.; Ansari, F. Plasmonic Enhancement of Dye-Sensitized Solar Cells by Using Au-Decorated Ag Dendrites as a Morphology-Engineered. *Renew. Energy* **2018**, *125*, 590–598. [CrossRef]
215. Amiri, O.; Salavati-Niasari, M.; Farangi, M.; Mazaheri, M.; Bagheri, S. Stable Plasmonic-Improved Dye Sensitized Solar Cells by Silver Nanoparticles Between Titanium Dioxide Layers. *Electrochim. Acta* **2015**, *152*, 101–107. [CrossRef]
216. Wu, W.; Xu, X.; Yang, H.; Hua, J.; Zhang, X.; Zhang, L.; Long, Y.; Tian, H. D–π–M–π–A Structured Platinum Acetylide Sensitizer for Dye-Sensitized Solar Cells. *J. Mater. Chem.* **2011**, *21*, 10666–10671. [CrossRef]
217. Sharma, V.; McKone, H.T.; Markow, P.G. A Global Perspective on the History, Use, and Identification of Synthetic Food Dyes. *J. Chem. Educ.* **2011**, *88*, 24–28. [CrossRef]
218. Christiansen, C.; Heyde, A.; Schiffelbein, O. Protein-Rich Spirulina Extracts. PCT Patent 2012104091, 9 August 2012.
219. Sarada, R.; Pillai, M.G.; Ravishankar, G.A. Phycocyanin from *Spirulina* Sp: Influence of Processing of Biomass on Phycocyanin Yield, Analysis of Efficacy of Extraction Methods and Stability Studies on Phycocyanin. *Process Biochem.* **1999**, *34*, 795–801. [CrossRef]
220. Eriksen, N.T. Production of Phycocyanin—A Pigment with Applications in Biology, Biotechnology, Foods and Medicine. *Appl. Microbiol. Biotechnol.* **2008**, *80*, 1–14. [CrossRef] [PubMed]
221. Patil, G.; Chethana, S.; Madhusudhan, M.C.; Raghavarao, K.S.M.S. Fractionation and Purification of the Phycobiliproteins from *Spirulina Platensis*. *Bioresour. Technol.* **2008**, *99*, 7393–7396. [CrossRef] [PubMed]
222. Rito-Palomares, M.; Nuñez, L.; Amador, D. Practical Application of Aqueous Two-Phase Systems for the Development of a Prototype Process for c-Phycocyanin Recovery from *Spirulina maxima*. *J. Chem. Technol. Biotechnol.* **2001**, *76*, 1273–1280. [CrossRef]
223. Singh, G.; Patidar, S. Microalgae Harvesting Techniques: A Review. *J. Environ. Manag.* **2018**, *217*, 499–508. [CrossRef]
224. Judd, S.J.; Al Momani, F.; Znad, H.; Al Ketife, A. The Cost Benefit of Algal Technology for Combined CO_2 Mitigation and Nutrient Abatement. *Renew. Sustain. Energy Rev.* **2017**, *71*, 379–387. [CrossRef]
225. Zielinski, A.A.F.; del Pilar Sanchez-Camargo, A.; Benvenutti, L.; Ferro, D.M.; Dias, J.L.; Ferreira, S.R.S. High-Pressure Fluid Technologies: Recent Approaches to the Production of Natural Pigments for Food and Pharmaceutical Applications. *Trends Food Sci. Technol.* **2021**, *118*, 850–869. [CrossRef]
226. Wijesekara, T.; Xu, B. A Critical Review on the Stability of Natural Food Pigments and Stabilization Techniques. *Food Res. Int.* **2024**, *179*, 114011. [CrossRef]
227. Azman, E.M.; Charalampopoulos, D.; Chatzifragkou, A. Acetic Acid Buffer as Extraction Medium for Free and Bound Phenolics from Dried Blackcurrant (*Ribes nigrum* L.) Skins. *J. Food Sci.* **2020**, *85*, 3745–3755. [CrossRef] [PubMed]
228. Tan, J.; Han, Y.; Han, B.; Qi, X.; Cai, X.; Ge, S.; Xue, H. Extraction and Purification of Anthocyanins: A Review. *J. Agric. Food Res.* **2022**, *8*, 100306. [CrossRef]
229. Zhang, L.; Fan, G.; Khan, M.A.; Yan, Z.; Beta, T. Ultrasonic-Assisted Enzymatic Extraction and Identification of Anthocyanin Components from Mulberry Wine Residues. *Food Chem.* **2020**, *323*, 126714. [CrossRef] [PubMed]

230. Cai, D.; Li, X.; Chen, J.; Jiang, X.; Ma, X.; Sun, J.; Tian, L.; Vidyarthi, S.K.; Xu, J.; Pan, Z. A Comprehensive Review on Innovative and Advanced Stabilization Approaches of Anthocyanin by Modifying Structure and Controlling Environmental Factors. *Food Chem.* **2022**, *366*, 130611. [CrossRef]
231. Pieczykolan, E.; Kurek, M.A. Use of Guar Gum, Gum Arabic, Pectin, Beta-Glucan and Inulin for Microencapsulation of Anthocyanins from Chokeberry. *Int. J. Biol. Macromol.* **2019**, *129*, 665–671. [CrossRef]
232. Ji, Y. Synthesis of Porous Starch Microgels for the Encapsulation, Delivery and Stabilization of Anthocyanins. *J. Food Eng.* **2021**, *302*, 110552. [CrossRef]
233. Weiss, V.; Okun, Z.; Shpigelman, A. Utilization of Hydrocolloids for the Stabilization of Pigments from Natural Sources. *Curr. Opin. Colloid Interface Sci.* **2023**, *68*, 101756. [CrossRef]
234. Malik, K.; Tokas, J.; Goyal, S. Microbial Pigments: A Review. *Int. J. Microb. Res. Technol.* **2012**, *1*, 361–365.
235. Brauch, J.; Zapata, S.; Buchweitz, M.; Aschoff, J.; Carle, R. Jagua Blue Derived from *Genipa Americana* L. Fruit: A Natural Alternative to Commonly Used Blue Food Colorants? *Food Res. Int.* **2016**, *89*, 391–398. [CrossRef]
236. Gukowsky, J.C.; Xie, T.; Gao, S.; Qu, Y.; He, L. Rapid Identification of Artificial and Natural Food Colorants with Surface Enhanced Raman Spectroscopy. *Food Control* **2018**, *92*, 267–275. [CrossRef]
237. Johnson, R. *Food Fraud and Economically Motivated Adulteration of Food and Food Ingredients*; Library of Congress: Washington, DC, USA, 2014.
238. Tarantelli, T.; Sheridan, R. *Toxic Industrial Colorants Found in Imported Foods*; State Department of Agriculture & Markets Food Laboratory: New York, NY, USA, 2011.
239. Yoshioka, N.; Ichihashi, K. Determination of 40 Synthetic Food Colors in Drinks and Candies by High-Performance Liquid Chromatography Using a Short Column with Photodiode Array Detection. *Talanta* **2008**, *74*, 1408–1413. [CrossRef] [PubMed]
240. Chen, S.; Li, S.; Fang, K.; Wang, Y.; Yang, Y.; Han, C.; Shen, Y. Rapid Determination of 93 Banned Industrial Dyes in Beverage, Fish, Cookie Using Solid-Supported Liquid-Liquid Extraction and Ultrahigh-Performance Liquid Chromatography Quadrupole Orbitrap High-Resolution Mass Spectrometry. *Food Chem.* **2022**, *388*, 132976. [CrossRef] [PubMed]
241. Schuster, R.; Gratzfeld-Hüsgen, A. Analysis of Synthetic Dyes in Food Samples by Capillary Zone Electrophoresis. In *Hewlett R Packard Application Note*; HP Company: Palo Alto, CA, USA, 1995.
242. Teepakakorn, A.P.; Bureekaew, S.; Ogawa, M. Adsorption-Induced Dye Stability of Cationic Dyes on Clay Nanosheets. *Langmuir* **2018**, *34*, 14069–14075. [CrossRef] [PubMed]
243. Dejoie, C.; Martinetto, P.; Dooryhee, E.; Van Elslande, E.; Blanc, S.; Bordat, P.; Brown, R.; Porcher, F.; Anne, M. Association of Indigo with Zeolites for Improved Color Stabilization. *Appl. Spectrosc.* **2010**, *64*, 1131–1138. [CrossRef]
244. Schlintl, C.; Schienle, A. Effects of Coloring Food Images on the Propensity to Eat: A Placebo Approach with Color Suggestions. *Front. Psychol.* **2020**, *11*, 589826. [CrossRef]
245. Spence, C.; Levitan, C.A.; Shankar, M.U.; Zampini, M. Does Food Color Influence Taste and Flavor Perception in Humans? *Chemosens. Percept.* **2010**, *3*, 68–84. [CrossRef]
246. Wadhera, D.; Capaldi-Phillips, E.D. A Review of Visual Cues Associated with Food on Food Acceptance and Consumption. *Eat. Behav.* **2014**, *15*, 132–143. [CrossRef]
247. Suzuki, M.; Kimura, R.; Kido, Y.; Inoue, T.; Moritani, T.; Nagai, N. Color of Hot Soup Modulates Postprandial Satiety, Thermal Sensation, and Body Temperature in Young Women. *Appetite* **2017**, *114*, 209–216. [CrossRef]
248. Garber, L.L.J.; Hyatt, E.M.; Starr, R.G., Jr. Placing Food Color Experimentation into a Valid Consumer Context. *J. Food Prod. Mark.* **2001**, *7*, 3–24. [CrossRef]
249. Moskowitz, H. Children and "Tween" Acceptance of Single Candy Colors and Two-Color Combinations. *J. Sens. Stud.* **2002**, *17*, 115–120. [CrossRef]
250. Galetović, A.; Seura, F.; Gallardo, V.; Graves, R.; Cortés, J.; Valdivia, C.; Núñez, J.; Tapia, C.; Neira, I.; Sanzana, S.; et al. Use of Phycobiliproteins from Atacama Cyanobacteria as Food Colorants in a Dairy Beverage Prototype. *Foods* **2020**, *9*, 244. [CrossRef] [PubMed]
251. Granato, D.; Barba, F.J.; Bursać Kovačević, D.; Lorenzo, J.M.; Cruz, A.G.; Putnik, P. Functional Foods: Product Development, Technological Trends, Efficacy Testing, and Safety. *Annu. Rev. Food Sci. Technol.* **2020**, *11*, 93–118. [CrossRef] [PubMed]
252. Huang, L.; Lu, J. Eat with Your Eyes: Package Color Influences the Perceptions of Food Taste and Healthiness Moderated by External Eating. *Mark. Manag.* **2015**, *25*, 71–87.
253. Su, J.; Wang, S. Influence of Food Packaging Color and Foods Type on Consumer Purchase Intention: The Mediating Role of Perceived Fluency. *Front. Nutr.* **2024**, *10*, 1344237. [CrossRef]
254. Kaya, N.; Epps, H.H. Relationship between Color and Emotion: A Study of College Students. *Coll. Stud. J.* **2004**, *38*, 396–406.
255. Muniz, V.; Ribeiro, I.; Beckmam, K.; Godoy, R. The Impact of Color on Food Choice. *Braz. J. Food Technol.* **2023**, *26*, e2022088. [CrossRef]
256. Theben, A.; Gerards, M.; Folkvord, F. The Effect of Packaging Color and Health Claims on Product Attitude and Buying Intention. *Int. J. Environ. Res. Public Health* **2020**, *17*, 1991. [CrossRef]
257. Baptista, I.Y.F. The Flavor of the Color and the Texture of the Shape: Effects of Visual Aspects on Expectation and Perception of Chocolates. Ph.D. Thesis, Universidade Estadual de Campinas, Campinas, Brazil, 2022.
258. Hallez, L.; Vansteenbeeck, H.; Boen, F.; Smits, T. Persuasive Packaging? The Impact of Packaging Color and Claims on Young Consumers' Perceptions of Product Healthiness, Sustainability and Tastiness. *Appetite* **2023**, *182*, 106433. [CrossRef]

259. Steiner, K.; Florack, A. The Influence of Packaging Color on Consumer Perceptions of Healthfulness: A Systematic Review and Theoretical Framework. *Foods* **2023**, *12*, 3911. [CrossRef]
260. Pereira, C.P.d.A. A Cor Do Infinito e a Beleza Inatingível: Sobre a Função Simbólica Do Azul Em Embalagens de Alimento. *Blucher Des. Proc.* **2014**, *1*, 58–66. [CrossRef]
261. Guilhon, D.; Castro, E.; Silva, V. *Perfil Cromático de Embalagens de Produtos Lácteos–Um Estudo Preliminar*; Sociedade Brasileira de Design da Informação: Curitiba, Brazil, 2021; pp. 131–148.
262. Berthold, A.; Guion, S.; Siegrist, M. The Influence of Material and Color of Food Packaging on Consumers' Perception and Consumption Willingness. *Food Humanit.* **2024**, *2*, 100265. [CrossRef]
263. Guéguen, N.; Jacob, C. Coffee Cup Color and Evaluation of a Beverage's "Warmth Quality". *Color Res. Appl.* **2014**, *39*, 79–81. [CrossRef]
264. Crumpacker, B. *The Sex Life of Food: When Body and Soul Meet to Eat*; Thomas Dunne Books: New York, NY, USA, 2006; ISBN 0-312-34207-1.
265. Cho, S.; Han, A.; Taylor, M.H.; Huck, A.C.; Mishler, A.M.; Mattal, K.L.; Barker, C.A.; Seo, H.-S. Blue Lighting Decreases the Amount of Food Consumed in Men, but Not in Women. *Appetite* **2015**, *85*, 111–117. [CrossRef] [PubMed]
266. Suk, H.-J.; Park, G.L.; Kim, Y. Bon Appétit! An Investigation about the Best and Worst Color Combinations of Lighting and Food. *J. Lit. Art. Stud.* **2012**, *2*, 559–566.
267. Yang, F.; Cho, S.; Seo, H.-S. Effects of Light Color on Consumers' Acceptability and Willingness to Eat Apples and Bell Peppers. *J. Sens. Stud.* **2016**, *31*, 3–11. [CrossRef]
268. Guéguen, N. The Effect of Glass Colour on the Evaluation of a Beverage's Thirst-Quenching Quality. *Curr. Psychol. Lett. Behav. Brain Cogn.* **2003**, *11*, 1–6. [CrossRef]
269. Motoki, K.; Spence, C.; Velasco, C. When Visual Cues Influence Taste/Flavour Perception: A Systematic Review. *Food Qual. Prefer.* **2023**, *111*, 104996. [CrossRef]
270. Spence, C. On the Manipulation, and Meaning(s), of Color in Food: A Historical Perspective. *J. Food Sci.* **2023**, *88*, A5–A20. [CrossRef]
271. Agustini, T.; Amalia, U.; Dewi, E.; Kurniasih, R. Application of Basil Leaf Extracts to Decrease *Spirulina Platensis* off-Odour in Increasing Food Consumption. *Int. Food Res. J.* **2019**, *26*, 1789–1794.
272. Burrows, A. Palette of Our Palates: A Brief History of Food Coloring and Its Regulation. *Compr. Rev. Food Sci. Food Saf.* **2009**, *8*, 394–408. [CrossRef]
273. Lehto, S.; Buchweitz, M.; Klimm, A.; Straßburger, R.; Bechtold, C.; Ulberth, F. Comparison of Food Colour Regulations in the EU and the US: A Review of Current Provisions. *Food Addit. Contam. Part A* **2017**, *34*, 335–355. [CrossRef] [PubMed]
274. Sanchez, M.C. *Food Law and Regulation for Non-Lawyers: A US Perspectives*, Food Science Text Series; 1st ed.; Springer: Cham, Switzerland, 2015; ISBN 978-3-319-12472-8.
275. Carocho, M.; Barreiro, M.F.; Morales, P.; Ferreira, I.C.F.R. Adding Molecules to Food, Pros and Cons: A Review on Synthetic and Natural Food Additives. *Compr. Rev. Food Sci. Food Saf.* **2014**, *13*, 377–399. [CrossRef] [PubMed]
276. World Health Organization. Joint FAO/WHO Expert Committee on Food Additives. In *Evaluation of Certain Food Additives: Eighty-Second Report of the Joint FAO/WHO Expert Committee on Food Additives*, 82nd ed.; World Health Organization: Geneva, Switzerland, 2016; ISBN 978-92-4-121000-3.
277. *CXS 192-1995*; Codex Alimentarius International Food Standards, General Standard for Food Additives. Food and Agriculture Organization-World Health Organization: Geneva, Switzerland, 2023; pp. 1–535.
278. JECFA. Codex Alimentarius Commisssion, JOINT FAO/WHO Food Standards Programme Codex Alimentarius Commission. In Proceedings of the Report of the Fifty Fourth Session of the Codex Committee on Food Additives, Chengdu, China, 22–26 April 2024; pp. 1–196.
279. Magnuson, B.; Munro, I.; Abbot, P.; Baldwin, N.; López-Garcia, R.; Ly, K.; McGirr, L.; Roberts, A.; Socolovsky, S. Review of the Regulation and Safety Assessment of Food Substances in Various Countries and Jurisdictions. *Food Addit. Contam. Part A Chem. Anal. Control Expo. Risk Assess.* **2013**, *30*, 1147–1220. [CrossRef] [PubMed]
280. EFSA. Panel on Food Additives and Nutrient Sources added to Food (ANS) Scientific Opinion on the Re-evaluation of Indigo Carmine (E 132) as a Food Additive. *EFSA J.* **2014**, *12*, 3768. [CrossRef]
281. EFSA. Panel on Food Additives and Nutrient Sources added to Food (ANS) Scientific Opinion on the Re-evaluation of Patent Blue V (E 131) as a Food Additive. *EFSA J.* **2013**, *11*, 2818.
282. Food and Agriculture Organization. Compendium of Food Additive Specifications. In *Joint FAO/WHO Expert Committee on Food Additives (JECFA)*; Food and Agriculture Organization: Rome, Italy, 2016.
283. Oplatowska-Stachowiak, M.; Elliott, C.T. Food Colors: Existing and Emerging Food Safety Concerns. *Crit. Rev. Food Sci. Nutr.* **2015**, *57*, 524–548. [CrossRef]
284. Okafor, S.N.; Obonga, W.; Ezeokonkwo, M.A.; Nurudeen, J.; Orovwigho, U.; Ahiabuike, J. Assessment of the Health Implications of Synthetic and Natural Food Colourants—A Critical Review. *Pharm. Biosci. J.* **2016**, *4*, 01–11. [CrossRef]
285. Pereira, H.; Deuchande, T.; Fundo, J.F.; Leal, T.; Pintado, M.E.; Amaro, A.L. Painting the Picture of Food Colouring Agents: Near-Ubiquitous Molecules of Everyday Life—A Review. *Trends Food Sci. Technol.* **2024**, *143*, 104249. [CrossRef]
286. Lomax, S.Q.; Learner, T. A Review of the Classes, Structures, and Methods of Analysis of Synthetic Organic Pigments. *J. Am. Inst. Conserv.* **2006**, *45*, 107–125. [CrossRef]

287. Rodriguez-Amaya, D. Natural Food Pigments and Colorants. *Curr. Opin. Food Sci.* **2016**, *7*, 20–26. [CrossRef]
288. Gamage, G.C.V.; Goh, J.K.; Choo, W.S. Application of Anthocyanins from Blue Pea Flower in Yoghurt and Fermented Milk: An Alternate Natural Blue Colour to Spirulina. *Int. J. Gastron. Food Sci.* **2024**, *37*, 100957. [CrossRef]
289. Jia, L.; Lu, W.; Hu, D.; Feng, M.; Wang, A.; Wang, R.; Sun, H.; Wang, P.; Xia, Q.; Ma, S. Genetically Engineered Blue Silkworm Capable of Synthesizing Natural Blue Pigment. *Int. J. Biol. Macromol.* **2023**, *235*, 123863. [CrossRef] [PubMed]
290. Noda, N. Recent Advances in the Research and Development of Blue Flowers. *Breed. Sci.* **2018**, *68*, 79–87. [CrossRef] [PubMed]
291. Azadi, P.; Bagheri, H.; Nalousi, A.M.; Nazari, F.; Chandler, S.F. Current Status and Biotechnological Advances in Genetic Engineering of Ornamental Plants. *Biotechnol. Adv.* **2016**, *34*, 1073–1090. [CrossRef]
292. Katsumoto, Y.; Fukuchi-Mizutani, M.; Fukui, Y.; Brugliera, F.; Holton, T.; Karan, M.; Nakamura, N.; Yonekura-Sakakibara, K.; Togami, J.; Pigeaire, A.; et al. Engineering of the Rose Flavonoid Biosynthetic Pathway Successfully Generated Blue-Hued Flowers Accumulating Delphinidin. *Plant Cell Physiol.* **2007**, *48*, 1589–1600. [CrossRef]
293. Scotter, M. Emerging and Persistent Issues with Artificial Food Colours: Natural Colour Additives as Alternatives to Synthetic Colours in Food and Drink. *Qual. Assur. Saf. Crops Foods* **2011**, *3*, 28–39. [CrossRef]
294. Joshi, V.K.; Attri, D.; Bala, A.; Bhushan, S. Microbial Pigments. *Indian J. Biotechnol.* **2003**, *2*, 362–369.
295. Venil, C.K.; Zakaria, Z.A.; Ahmad, W.A. Bacterial Pigments and Their Applications. *Process Biochem.* **2013**, *48*, 1065–1079. [CrossRef]
296. *CXG 36-1989*; Codex Alimentarius-Class Names and the International Numbering System for Food Additives. Food and Agriculture Organization-World Health Organization: Geneva, Switzerland, 2023.
297. Department of Health and Human Services Food and Drug Administration. *Listing of Color Additives Exempt From Certification: Butterfly Pea Flower Extract-Federal Register*; Food and Drug Administration: Silver Spring, MD, USA, 2021; Volume 86 FR 49230, pp. 49230–49234.
298. Jespersen, L.; Strømdahl, L.D.; Olsen, K.; Skibsted, L.H. Heat and Light Stability of Three Natural Blue Colorants for Use in Confectionery and Beverages. *Eur. Food Res. Technol.* **2005**, *220*, 261–266. [CrossRef]

sustainability

MDPI

Article

Valuing in the Agrifood System: The Case of Fresh Grain Legumes in Denmark

Ane Kirstine Aare *, Stine Rosenlund Hansen, Niels Heine Kristensen and Henrik Hauggaard-Nielsen

Department of People and Technology, Roskilde University, 4000 Roskilde, Denmark
* Correspondence: akaare@ruc.dk; Tel.: +45-46743620

Abstract: Transitioning towards more sustainable food products, such as plant proteins, requires a change in practice by several actors in the agrifood system. Change of this kind involves everyday choices about what food to produce, sell, prepare, and eat. Inspired by science and technology studies (STS) thinking, we investigate how such choices are influenced by socio-material practices of valuing. We use the case of fresh grain legumes for human consumption to explore how valuing is simultaneously affected by and shapes the agrifood system. Through interviews with 24 actors in the Danish agrifood system, we identify valuing parameters ranging from taste, nitrogen fixation, durability, and nutrition to price. The study reveals differences regarding *what* and *how* actors value depending on the actors' position in the agrifood system and how the fresh grain legumes travel from field to plate. Where values conflict, we observe how some valuing practices have the power to exclude others and thereby prevent specific enactments of the fresh grain legumes. We argue that looking for valuing practices can help us understand how agrifood systems come into being, and that valuing *differently* can represent active involvement, both academically and practically, in encouraging change in the agrifood system. By using STS-thinking, the study brings novel insights about barriers towards more plant-based diets and contributes to the diversification of theoretical perspectives on sustainable transitions.

Keywords: valuing; sustainable transition; agrifood system; fresh grain legumes; STS

Citation: Aare, A.K.; Hansen, S.R.; Kristensen, N.H.; Hauggaard-Nielsen, H. Valuing in the Agrifood System: The Case of Fresh Grain Legumes in Denmark. *Sustainability* **2023**, *15*, 2946. https://doi.org/10.3390/su15042946

Academic Editors: Hamid El Bilali, Tarek Ben Hassen and Carola Strassner

Received: 21 December 2022
Revised: 31 January 2023
Accepted: 31 January 2023
Published: 6 February 2023

1. Introduction

Considerable attention is directed towards the adverse effects of our current agrifood systems and the urgent need for a transition towards more sustainable ways of producing, distributing, processing, and eating food. Increasing the production and consumption of plant protein is one way to counteract some of the environmental and climatic consequences associated with food production [1,2]. Substituting meat with plant protein can reduce greenhouse gas emissions from animal production, including the negative effects of soy production and imports [3] and inefficient land use for fodder production compared with production for direct human consumption [4]. Furthermore, leguminous symbiotic atmospheric nitrogen (N) fixation abilities allow for reduced fertiliser input compared with other major crops, while the diversification of the cropping system with the introduction of grain legumes (GL) can reduce infestation rates as well as pest and disease pressure [5,6]. Furthermore, it is acknowledged that increasing GLS in diets will improve human health [7] and the number of varieties of eatable GLs might offer important sources of taste and textures for kitchens in their experimentation for future sustainable cooking [8,9]. Hence, there is growing national and international political awareness and support for the production and consumption of GLs [10,11].

GLs can be harvested dry for long-term storage or harvested at their green stage and sold as a seasonal fresh product, often in their pods or as storable frozen products. In comparison with dry GLs, fresh grain legumes (FGL) allow for earlier harvest and thereby early establishment of cover crops, with the ensuing benefits for soil health, nutrient cycling, etc. [12–14]. Despite their manifold potential, the production of GLs in Europe is low due to a focus on cereal production after the Second World War [15]. In Denmark, the strategy of animal and dairy production for export has similarly resulted in specialised land use dedicated for cereal-fodder production combined with the import of soy as a protein source [16,17]. New national dietary advice that highlights the need for increased plant protein as part of a sustainable diet [18] suggests new opportunities for increased production and consumption of FGLs in Denmark. However, such changes involve shifts across the entire agrifood system.

The agrifood system is organised in a complex and interconnected web of people, places, materiality, technology, knowledge, and power [19]. The system is held together through interwoven activities such as producing, distributing, and cooking, and leads to diverse societal outcomes, such as foods, jobs, environmental impacts, etc. At the same time, the agrifood system is determined by the bio-geophysical and human environments in which it is situated [20,21]. Ericksen (2008) argues that agrifood systems are "heterogeneous over space and time and replete with non-linear feedbacks". Applying the systems approach, thus, helps us in "understanding the critical factors that lead to particular outcomes or the interactions that govern a specific behavior of interest" [20]. Hence, paying attention to this complexity is vital in understanding transition processes towards more sustainable agrifood systems [22–24]. However, a considerable amount of research is directed at understanding the challenges faced and suggesting innovations within specific parts of the agrifood system [25,26]. In this study, we attempt to include several perspectives and experiences of different actors in the FGL system to shed light on how they are interconnected and how they all play a role in the transition towards the greater production and consumption of more sustainable crops.

Several theoretical approaches have been applied to explore the transition of agrifood systems in all their complexity. Since the late 1990s, different kinds of systems theories (e.g., socio-technical systems theory and science and technology studies (STS)) have, despite different ontologies, been concerned with the diversity of the actors involved in the agrifood system [27]. The socio-technical systems perspective examines historical and systemic changes associated with the introduction of new innovations as a combination of technological readiness, available infrastructure, regulations, and cultural and social norms [28,29]. Including the word *socio* in the theoretical concept indicates acknowledgement of the social aspect of transitioning. However, "discussions of sociotechnical transitions and their governance routinely obscure the central role that practitioners themselves play in generating, sustaining and overthrowing every-day practices." [30]. Instead of seeking to identify immanent dynamics in agrifood systems, for example, STS theories operate with relational ontologies where realities are enacted through constant negotiation and entanglements of human and non-humans in everyday life [31]. The STS perspective, thus, offers the study of such entanglements through socio-material practices of everyday life, and we apply this approach in order to understand the development of agrifood systems and their potential for change.

In order to acknowledge agrifood systems as interconnected and affected by day-to-day practices, we explore how FGLs are brought into being through the practices of enacting values in an object [32,33]. *Valuing* becomes relevant because "the performance of valuations are . . . not only ubiquitous; their outcomes participate in the ordering of society" [33]. Thus, we argue that valuing reveals how actors relate and engage with objects [32,34] and that this engagement (or lack thereof) is a part of making decisions about continuing or implementing new (sustainable) practices.

Studying the practice of valuing includes perceiving *value* in more than just monetary terms; it is also related to convenience, interest, preferences, emotions, etc. [33]. Inspired by relational ontology, we recognise that objects (e.g., foods) do not have an immanent value independent of the networks and relations of which they are part (see e.g., [34–36]). Instead "objects come into being—and disappear—with the practices in which they are manipulated. And since the object of manipulation tends to differ from one practice to another, reality multiplies" [37]. An important aspect in this regard is that values are not only enacted through social processes, but through concrete matter, and, thus, socio-material practices as well [38]. Thereby, the shapes, weights, textures, sizes, etc., of objects, as well as their containment of other objects, such as nutrients or water, are part of practices and of how objects are valued. The objects with which we engage and that are brought into being through the interaction are, thus, also a result of its materiality.

The idea that objects are *brought into being* and how this results in multiple realities also suggests that objects and realities can differ when engaging in new relations, and, therefore, hold potential for change (what Mol refers to as ontological politics [39,40]). As a consequence, values attached to a specific object may "be conflicting or not, overlapping or not, combine with each other, contradict each other" [33]. The acknowledgement that multiple versions of an object exist at the same time substantiates the argument for considering all these versions (e.g., experienced by different actors) when trying to understand the potential for increased production and consumption of FGLs.

The ontological perspective levels out different kinds of knowledge and ways of knowing. If valuing takes place in concrete relations and practices, the actors become the experts, valuing according to their specific knowledge, position, perception, and aims [32]. Instead of looking for the *right* valuing, we attempt to understand actors' ways of rationalising, prioritising, and making decisions in the everyday performance of agrifood systems. Different practices of valuing reveal what is valued by some actors but not by others. This might indicate unspoken practices of (de)valuing or windows of opportunity for valuing differently.

That valuing is relational does not mean it is random. The practice affects, as well as is affected by, the dominance of specific realities over others that each bring different versions of objects and their valuation into being [39]. Thus, there are mechanisms of power at stake when different versions of objects are unable to co-exist easily.

In this study, we seek to understand how, in practice, the valuing within the Danish agrifood system affects whether, why, and how FGLs are grown, sold, and cooked, as well as some of the dilemmas and complexities in valuing processes when different ways of valuing contradict or do not point in the same direction. This offers an idea of the potential future role of FGLs in future agrifood systems.

2. Materials and Methods

The study was based on semi-structured interviews with 24 actors across the Danish agrifood system who are engaged with FGLs, e.g., through knowing, producing, processing, trading, or cooking. We identified the actors through a purposive snowball sampling [41] to find relevant participants and understand how actors engaged with FGLs are related (see Figure 1). The snowball sampling method was chosen for two reasons. Firstly, as the population is perceived as hard-to-reach, the number of actors engaged specifically in producing, distribution and cooking FGLs in Denmark is limited and innovative actors trying to engage with FGLs might not officially call attention to their experimentation and ambitions [42]. Secondly, as the study seeks to understand the agrifood system in which FGLs are placed, the aim of the sampling was not only to identify actors but also the relations between them [41]. The sampling was carried out until sufficient actors were identified. In this study, this was considered the case when the sampling included several representatives engaged in both producing, distributing, and cooking FGLs combined with the point where many actors referred to already identified interviewees. Some of the actors interviewed had experience of FGL while others did not. Thus, the study also explored the actors' valuing of a crop with which they do not yet have a relationship or have only a limited relationship. We argue that the inclusion of such (pre)valuing practices are crucial in order to understand how transitioning entails the establishment of new practices and relations.

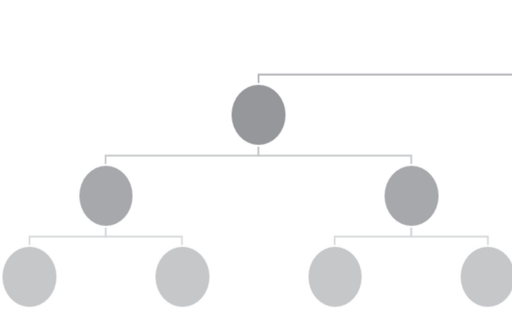

Figure 1. The snowball sampling strategy. From the initial interview (dark grey) new actors are identified (lighter grey). This sample continues until sufficient actors are identified.

We started the sampling with a central large-scale processor of frozen FGLs in Denmark to get in contact with large-scale growers of FGLs. As a second starting point, we added a small-scale grower of fresh Borlotti beans identified through a promotional event for growers of GLs in order to avoid being locked into specific networks of actors operating solely in large-scale production and distribution through the sampling method. This strategy allowed us to establish contact with a diverse network of actors, but also revealed that, despite their differences, large-scale production and alternative food networks were not two strictly separate networks since some growers sell through both mainstream distribution channels (retail and wholesale) and through direct sales (restaurants and private costumers), for example. However, when engaging with the STS perspective, we found it useful in the analysis to differentiate between large-scale growers of frozen FGLs, large-scale growers of FGLs for fresh market and small-scale growers of FGLs for fresh market owing to differences in their valuing, networks, finances, etc.

Through the sampling (brackets indicate number of interviews), we identified and interviewed a large-scale processer of frozen FGLs (1), large-scale growers of frozen FGLs (3), large-scale growers of FGLs for the fresh market (3), small-scale growers of FGLs for the fresh market (2), seed traders (2), seed conservation organisations (2), a farm machinery operator (1), a farming and horticulture advisor (1), a wholesaler (1), a platform for direct trade between growers and consumers/kitchens (1), retailers (2), chefs (2), a consultant in public kitchens (1), and farming and food interest organisation representatives (2). Starting out with different types of growers, our sampling strategy resulted in an overrepresentation of interviews with actors who cultivate FGLs (see Figure 2). We found that growers (especially those engaged with large-scale production) found difficulties in referring to the actors who buy their products, for example for reasons of confidentiality or limited personal relations. As we were interested in the enactment of the agrifood system, this type of observation provided an early understanding of how a lack of relations also plays a role in valuing processes. In line with the STS perspective, we also acknowledge that if we had begun the sampling from a different starting point, the sample would probably have been different with a potentially greater focus on other relations and differentiation between the other actors involved.

The interviews were conducted face-to-face or online in spring 2022, each lasting for approximately one hour. All interviews were transcribed apart from two, which were not recorded. For these two interviews, the researcher's notes have been used as empirical material. The interviews were semi-structured and explored the actors' thoughts about and experiences of the possibilities and challenges presented by engaging with FGLs. Going through this rich empirical material, we noticed the articulation of different FGL characteristics that were relevant for the actors in their practice of growing, trading, or cooking. We recognised this as a *practice of valuing* [32]. We coded the transcriptions by identifying these values and ended up with a long list ranging from aesthetic, ecological, economic, and cultural to sensory values. In this analysis, we, therefore, focused on those characteristics used by agrifood actors to value FGLs in their everyday lives. To do so, we looked for both *what* and *how* actors value as a way to explore the coming into being of FGLs.

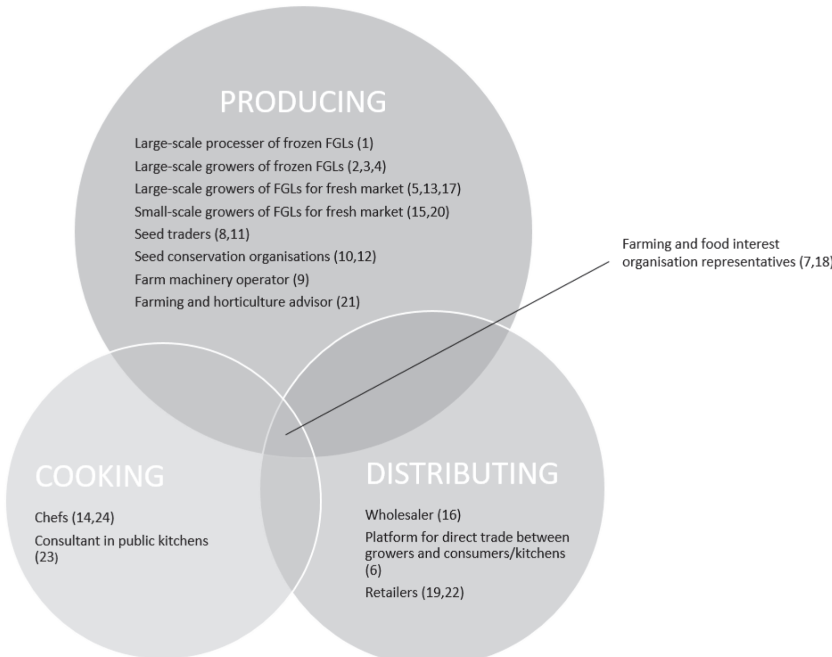

Figure 2. Illustration of the categories of actors interviewed placed in the analytical spheres of producing, distributing, and cooking FGLs. Numbers in brackets indicate the order in which the interviews have been carried out. The *Farming and food interest organisation representatives* have been placed in between spheres as they represent the whole agrifood system. The size of the circles indicates the balance between number of interviews within the three spheres.

Well aware that the agrifood system and its relations are complex, we divided the agrifood system into three spheres representing central activities such as *growing*, *distributing,* and *cooking* [21] in order to create an analytical structure (see Figure 2). We argue that a division of this kind offers interesting insights into the similarities and differences in valuing within as well as across these spheres.

3. Results

In the following section, we illustrate how the value of FGLs is enacted differently through the relations of the actors we interviewed in the agrifood system. By doing so, we encounter the diversity of values at stake and how these can sometimes be contradictory within and between the spheres.

3.1. Growing FGLs: Weighing Price, Stories and Cropping System Benefits

Market price is a common way for growers to value and decide whether growing FGL is a profitable activity for them. The large-scale processer of FGLs explains that many of their growers terminate their contracts for pea production due to low pea prices compared with cereals. Individual growers (large-scale growers of frozen FGLs and FGLs for fresh market) explain that the market price is hard to negotiate with processors, wholesalers, and retailers due to competitive large-scale bulk markets of frozen products and production of peas in pods for the fresh market. In contrast, one small-scale grower selling to a diverse group of customers explains that prices of FGLs vary greatly depending on the kind of network and relation in which they are engaged.

> *"No, it's not the same price. The retailers pay the lowest price, but they also take larger quantities . . . . Then of course there are restaurants and private customers, they of course pay a higher price."* (Small-scale grower of fresh Borlotti beans)

In the interview, the grower elaborates on this differentiation in price. What they sell is a niche product both due to the specific story of their brand and because the specific bean variety is not otherwise available in shops. Similar experiences with price differentiation are raised in other interviews with a small-scale grower and representative of a direct trade platform. Prices are, therefore, linked to quantities, but also to uniqueness and storytelling. Relations to places and stories and between buyers and growers thus create room for flexibility in valuing.

Apart from the price, growers express their appreciation of the plant's contribution to the cropping system, particularly the ability to fix N_2 from the atmosphere for increased N self-sufficiency as well as for the crops that follow.

> *"Peas have always been the dynamo in my crop rotation. It's a huge advantage that we can harvest those fields at the end of July. Then we can keep the soil black, and we can manage the weeds throughout July. And at the end of July we can sow a cover crop . . . So it has accumulated nitrogen over the autumn and winter."* (Large-scale grower of frozen peas)

Large-scale growers of frozen peas also explain that the early harvest time prevents problems with aphids and weeds, which often occur later in the season. Several growers (both small-scale and large-scale) express their appreciation of the contribution made by legumes in diversifying the crop rotation and, thus, stimulating subsequent crop effects. In a complex net of relations with soil, crops, time, machinery, weeds, nutrients, and humans, FGLs come into being as plants that provide ecosystem services. In particular for large-scale growers of frozen peas competing on market terms, the plant and its functions seem to be of greater interest than the product (grain) itself. Thus, the way in which FGLs interact in the broader cropping system is valuable enough for growers to cultivate the plant despite the product carrying a low price. This observation challenges the simplified assumption of price incentives being the primary driver among growers, and illustrates how objects come into being through valuing processes in concrete networks of relations (see also [43–45]).

Some growers value FGLs because they are, as a small-scale grower of different peas and beans for the fresh market says, "the world's easiest vegetable to grow". He appreciates the smaller workload involved with FGLs due to the high manual workload associated with having a diverse range of crops. For large-scale growers of frozen peas as well, the reduced need for fertiliser application means fewer hours spent in the field. Furthermore, frozen pea production is mainly managed by the processor (seeding and harvesting), which allows growers to engage in other activities in busy periods of the season. Again, valuing of FGLs depends on the complete network of relations and practices in which the growers are engaged (e.g., other crops, farm, or off-farm work).

The large-scale processor of frozen FGLs confirms the influence of current networks, explaining that it is too costly and complicated to introduce new FGL species if they are not adaptable to the existing infrastructure and farm machinery. The lack of flexibility within the acquired machinery and the lack of machinery applicable for new FGLs reduce the potential for large-scale growers in particular to value heterogeneity in the size and shape of different FGLs. In contrast, a small-scale grower with less need to use machinery has a flexibility allowing for experiments with different types of FGLs. Thus, the need to use machinery due to the size of production involves large-scale actors in different networks than small-scale actors, thus differentiating between their possibilities for valuing diversity and new FGLs.

The FGL crop is very sensitive to weather conditions, which means that the yield can vary a great deal. One large-scale grower calls it "our lottery ticket", emphasising the risk associated with a lack of yield stability. For another large-scale grower, poor experiences with pea production 25 years ago have discouraged him from taking the risk of growing FGLs for several years:

> *"We actually stopped [growing peas] after 1987 . . . . It literately rained every day in '87 . . . . I don't know how many farmers committed suicide around then . . . . A neighbour of a neighbour of a neighbour was sitting in a field. He had eaten rat poison. No, it was terrible weather. We ploughed 20 hectares down . . . . I must say, in that moment I thought, damn no! We don't want anything [pea plants] lying on the ground anymore."* (Large-scale grower of FGLs for the fresh market)

The personal consequences of yield losses reveal a seriousness about the choices growers make in their everyday lives. The quotation also shows how relations cross time and space [40], and, thus, valuing, are affected by things that have happened and assumptions about what might happen. In this way, *how we know* through personal experiences, feelings, and convictions is part of the practice of valuing. At the same time, these examples of valuing also show how different versions of the object of FGLs are enacted and valued as both 'the world's easiest vegetable to grow' and 'a lottery ticket' and are thus difficult to control.

3.2. Distributing FGLs: Durability, Diversity and Seasonality as Ambivalent Values

Freshness is one of the main values of FGLs articulated by actors in the large-scale distribution sphere of the agrifood system (retail and wholesale). The product needs to be able to stay fresh despite transportation and turnover time in shops. Thus, future consumers, although not yet directly present, become important actors in enacting value as the ability of the product to remain close to its state when harvested ('fresh'). For peas in particular, this can be a challenge. The window for harvesting at the right time of maturity, which gives a *fresh* pea, is only a few days. After harvest, the value, enacted as the freshness of the pea, will decrease in only a few hours. As a small-scale grower of peas in pods explains: " . . . the peas [in the shop] are harvested one week ago. And they're soft in the shell . . . and do not taste of anything". The rapid decline in freshness, which in this quotation affects taste and texture, is a central argument for freezing FGLs as a way to preserve specific values enacted through the qualities and prolong the durability of freshness. In this case, there seems to be a contradiction between the freshness and the actual network of bringing FGLs to consumers through long-distance transportation, bulk handling, and storage. Thus, the example shows that valuing is relative, as a fresh pea (and the associated taste and texture) might be different to a grower than to a costumer who might never have tasted a pea in a freshly picked pod.

Especially for actors within retail, appearance and taste are important qualities. As customers are normally not able to taste the product in the shops before purchase, the importance of appearance is even greater (small-scale grower of fresh peas and beans for the fresh market). Accordingly, a large-scale grower of fresh peas for the fresh market uses the appearance of the pod as one of the main criteria for selecting the varieties that he sells in pods for retail and wholesale. Thus, the look of the *outside* (the pod) becomes a translation of the value of the *inside* (the grain). Another small-scale grower of fresh beans mentions that "when we sell the fresh ones [Borlotti beans], we sell them in the pods. This means that people have to shell them themselves and this is a very exquisite and delicious product". The valuing of FGLs thus depends on *where* and *how* we meet the product and is also related to sensing.

A representative of a wholesaler thinks that he is most able to sell something that is recognisable to his customers (e.g., public kitchens). In order to introduce new FGLs, he argues that the sector should agree on promoting a few specific species or varieties to simplify communication directed at customers. Moreover, retailers emphasise that they need to be sure that they will sell large quantities of each product to avoid them going off in the shops. As noticed with large-scale growers, homogeneous material and large quantities are, therefore, also valued by the mainstream distribution actors. In contrast, an online platform for direct trade between growers and consumers (restaurants, private individuals, etc.) allows growers to decide on both the quantities and kinds of products. It is their experience that the diversity of products (colour, taste, size, etc.) is valued positively as the platform addresses other ways of relating between growers and customers.

Many actors mention the special value of fresh peas in pods in season. The product is associated with a nostalgic summer feeling for which people are willing to pay. Several actors (interest organisation, retail, advisor, small-scale grower) emphasise that the lack of accessibility all year around creates a specific value for FGLs. The seasonal products are often also local products because seasonality mostly presupposes a geographical proximity of production and consumption [46]. Supermarkets and wholesalers experience an increase in demand for local products and try to accommodate this by having local growers' shelves in shops, for example, and investment in local small-scale production by wholesalers, thus adopting what they perceive as valuing practices among their customers.

However, while wholesale and retail are making space for local and seasonal products, they are also extending the Danish season of peas and beans by importing products from other regions the rest of the year and through frozen FGL products. Thus, the provision of seasonal and local products exists alongside, although somehow in opposition to, the concept of constant availability of (local *and* global) products [46]. Despite trying to value local and seasonal qualities, the distribution actors' network of global suppliers affects small-scale local growers, in particular through price competition, which challenges the growers' ability to make a business out of selling to wholesale and retail. This example shows that opposing values can be present simultaneously but may also undermine one another.

Large-scale and small-scale growers explain that the retail sector and wholesalers' requirement for bulk deliveries limits the growers' ability to experiment with new crops or have a range of diverse crops, as the experimental phase requires smaller volumes. Furthermore, as mentioned, representatives from retail and wholesale say that they are only interested in a small number of FGL products because of the very broad selection of products in general that they are offering. Both wholesalers and retailers acknowledge that apart from peas in pods in season, FGLs do not currently have a high priority in their businesses. As retail and wholesale constitute an important link between growers and consumers, the lack of valuing and prioritisation of FGLs by these actors affects the possibilities of producing or accessing FGLs for other actors (see e.g., [47]).

3.3. Cooking FGLs: Knowing and Speaking about Taste, Toxins and Use

Despite working to promote FGLs, we identify different foci of valuing among actors cooking with FGLs. A chef argues that he thinks we ought to eat what is best for the soil, which then becomes an argument for using FGLs in cooking. A consultant in public kitchens argues that FGLs should not be eaten for their environmental function, but rather because of the sensory enjoyment. She explains: " . . . I don't talk about health, I don't talk about nutrition, I don't talk about vegetarians or vegans; I only talk about good food." To her, emphasising the FGLs' ecosystem benefits as the main value might undermine the focus on preparing and eating delicious FGL meals. The quotation thus indicates an actor's awareness about how co-existence of several values (ecological and sensory) can create distraction and accordingly disturb a transition process.

In the interview with actors who work to cook and prepare FGLs, taste is articulated as a core value. However, despite the seeming importance of taste, we find few detailed descriptions of taste in the interviews. This is confirmed by a chef who argues that there is a lack of language to describe the taste of GLs in general. Several actors refer to a *nutty* taste, but sweetness, umami, and bitterness are also mentioned. A consultant in public kitchens explains that she was once involved in a research project to describe the taste of a range of dry GLs. In doing so, she used the smell or taste of something already known, such as elderflower, to explain the taste of GL species and varieties, illustrating how valuing can be linked to something already known. Associations and language are, therefore, also important means of understanding and noticing values. As a breeder describes, the pea varieties on the market today do not apply to the taste qualities that are possible to breed for today. Having a language to describe and thereby make visible the qualities of FGL in all parts of the agrifood system must be the first step to ensure awareness of and be able to communicate the needs and wishes of different actors. In this regard, the study indicates an imbalance between the language available around growing FGLs and the lack of terms referring to taste and other values in the cooking sphere. Such inequalities might indicate a lack of historical and current focus on FGLs in these spheres but may also have consequences for future valuing processes around FGLs.

Despite an unclear definition of the taste of FGLs, the actors still talk about good and bad taste. For peas, a good taste is particularly associated with sweetness. In contrast, when describing a pea with a bad taste, the agricultural advisor associates it with a mealy texture. A large-scale grower of fresh peas for fresh market explains that the larger the pea, the more mealy the taste. In this way, taste is closely related to other sensory experiences and characteristics, such as texture and size:

> *"I think it's about people confusing taste and texture. Because when you eat red beans in chilli con carne, they taste like chilli con carne. And when you eat chickpeas in chicken curry, they taste like curry. But what is unfamiliar to people is the mouthfeel. The slightly floury, mushy consistency."* (Consultant in public kitchens)

Cooking brings FGLs into being through combinations of ingredients in actual meals, where associations and sensing melt together. Valuing is, therefore, also about context and involves confusion, recognition, and preferences. The social aspect of valuing individually (e.g., through preferences and memories) and in communities (e.g., through recipes and traditions) also means that the practice of valuing both carries and shapes a cultural heritage.

Another way of valuing FGLs in the cooking spheres is through their health qualities. In 2021, Denmark's national dietary advice included the recommendation of 100 g of GLs per day [18], a recommendation that public kitchens are expected to mirror in their meals. Protein, fibres, and vitamins in particular are emphasised in the interviews as healthy qualities of FGLs. However, several of the species also contain toxins [48], which require preparation (e.g., soaking, blanching, cooking). The risk associated with the toxins has given rise to regulations about the preparation in public kitchens. According to a consultant in public kitchens, the caution incorporated into food regulations can be a barrier for increased use in kitchens because lengthy preparation, for example, reduces the sensory value and possibilities of variation in meals. The balance between food safety and the potential for a more interesting taste and more diverse use illustrates another dilemma in valuing.

A chef and a large-scale grower (referring to consumer requests from the Middle Eastern immigrant community, with which he has recently established direct contact) express an interest in eating not only the grain but also the pod of FGLs. In this regard, a breeder mentions the potential of breeding a soft and eatable pod (e.g., snow pea and snap pea). In contrast, a large-scale grower of fresh peas in pods explains that due to a lack of workforce, he expects to start harvesting with machinery instead of by hand. This will require new pea varieties with a hard pod to avoid damaging the product while machine harvesting. Thus, for some actors the pod should be robust enough to contain an undestroyed surface since its appearance is the selling point. For others, the pod becomes not the packaging, but the product itself, which calls for quite different values related to digestibility, taste, and texture. The chef explains that being able to use the whole product would make FGLs much more economically attractive to him due to a larger number of eatable parts in relation to price. Thus, looking differently at *what* is valued allows for other enactments of FGLs.

3.4. Clashes between Valuing Practices

As shown above, valuing can be contradictory, and in some cases the practices of valuing involve exclusion of other values. In this way, valuing can also be a matter of power. Below, we use different examples from the interviews to explore clashes between valuing practices, and how this can help us understand how inequalities in valuing practices affect the possibilities for change in the agrifood system.

3.4.1. Promoting Values through Concrete Shaping of Materiality

Breeding of crop species and varieties is a quite concrete practice of valuing. Breeding is primarily handled by large-scale global companies [49] who need a high volume demand in order to start a breeding programme. According to a seed trader for an international seed company, this challenges the development of new varieties for large-scale production of FGLs, which on a global scale is relatively limited. A representative of a seed preservation organisation explains that after 1950 (with the industrialisation of agriculture), breeding criteria for GLs changed to focus specifically on compliance with modern production methods and durability, for example. These are criteria that support and promote specific ways of cultivating and distributing. He argues that distributing through alternative value chains (selling directly and locally) would make some of these breeding criteria (especially those related to transportation and storage) unnecessary, thus illustrating the effects of networks on valuing. Furthermore, the FGLs' ability to cover ground and produce organic material for soil improvement has been *bred away* in order to produce a higher yield and make management with machinery easier (large-scale grower of frozen peas). This shows how the values that breeding companies prioritise has a direct consequence for growers' production. Here, we can ascribe a new meaning to the term *value chain*. Despite perceiving the agrifood system as a network, the FGL travels through different spheres from field to plate. The genetic material of FGLs is a key part of how the plants develop and how they interact with the networks in which they are involved. Thus, there seems to be a power of valuing attributed to those actors positioned in the early parts of the chain, as their valuing practices (e.g., breeding) limit the supply of FGLs and thereby the diversity of potential enactments of FGLs among actors later in the chain. Again, a shortage of concepts concerning the more sense-based qualities appreciated by actors further along the value chain (kitchens, chefs, etc.) makes it hard for breeders to actually take these into consideration when breeding and selecting FGLs.

3.4.2. The Value of Bad Taste

Positioned early on in the value chain, growers choose what species and varieties of crops to grow and consequently bring to market. The values that are part of such choices are described above, including price, N fixation, harvest time, potential for diversification, reduced workload, and risk. However, yet more actors interfere with how values are enacted and re-enacted. Birds present a widespread challenge when growing GLs, as they are quick to embrace FGLs as a valued foodstuff. As a consequence, one large-scale grower of FGLs explains that they choose to grow a specific bean variety, as they observed that birds do not like to eat it, thereby enacting *good taste* as a bad thing, while *bad taste* (from a bird's perspective) becomes a way of valuing FGLs for this grower. Despite the lack of clarity about whether birds and people have the same preferences regarding the taste of beans, the example reveals the grower's lack of prioritisation of taste compared with the risk of losing yield. A farming and horticulture advisor confirms that they focus on yield stability and not on valuing parameters such as taste when giving advice to growers. As in the previous example of selecting breeding criteria, valuing, thus, has actual consequences for which products are brought into being and tells us something about the dominance of some interests over others as part of valuing practices.

3.4.3. Translating as a Way to Promote Some Values over Others

We observed different ways of translating values between actors and how these contain elements of power. Growers and the processing company evaluate the value of the product by a specific T-number, which indicates the dry matter of the pea and, thus, the state of maturity. A large-scale grower of fresh peas in pods for the fresh market values the peas by their juiciness, which he tests by pushing the pea to register the amount of juice released. Both examples are simple indicators of value that can be used to communicate and negotiate the price of the product between actors in the agrifood system. The lack of participation or systematic use of methods by professionals in the cooking sphere in selecting varieties and assessing value in the production sphere excludes a more complex and ambitious valuing of the final FGL product. The risk is that the price fails to reflect the values of the product appreciated by relevant actors and instead reflects the power relations within the agrifood system. As price becomes the authorised norm for value, it has a determining impact on the actors' ability and willingness to grow, trade, or buy FGLs. Having the relations and being in a position to set the price, therefore, represents a power of valuing across the agrifood system.

3.4.4. Reproducing Cultural Meaning as a Barrier for Valuing Differently

GLs have historically been associated with old-fashioned and relatively tasteless dishes or as part of a poor person's diet (see e.g., [50]). This might still be the case, despite its sustainable potential. For example, health authorities have emphasised the importance of legumes in our diets in their recent dietary advice. However, GLs are placed at the bottom of the food pyramid together with other low-price products such as cereal. This is despite the fact that they ought to substitute meat products, which are placed at the top of the pyramid. This indirect ranking of food categories might have an influence on what we perceive to be *high-quality* products, thus creating lock-ins in the agrifood system [26], and again illustrates the power of the valuing processes that lies with health authorities. Studies show that GLs score highly on health and sustainability, but have difficulty competing with meat, which is perceived "as more fun, popular, suitable in diets and for festive occasions, and tastier" [47]. Food is part of our everyday lives of celebration, habits, skills, and entertainment, and carries with it a strong cultural meaning [51–55]. This raises questions about how to change the image or revalue ingredients across the agrifood system. New trends of sustainability and local production might help increase the value of FGLs, not just in monetary terms but also in terms of their meaningfulness among actors in their everyday lives.

4. Discussion

> *"(R)eframing is its own potentially powerful form of intervention, political and otherwise, because it shows that the assumptions embedded in current arrangements could be otherwise"*. [40]

This study illustrates how multiple realities exist in the agrifood system and that some actors or networks have more power than others in their valuing practices. Thus, we argue that understanding actors' practices of valuing (and the decisions that follow it) is part of understanding transition processes. In this regard, relational ontologies allow for new ways of analysing agrifood system change and combining it with everyday socio-material and ecological practices (see also e.g., [45]).

To Mol (2002) it is clear that "if reality is multiple, it is also political" [37]. Undoing the dominance of specific realities is, therefore, not easy, but the multiplicity points to the fact that it is possible [40]. This helps us perceive the agrifood system as less static or fixed than actors might experience in their everyday lives or than it might appear through other theoretical lenses.

This also implies that valuing *in practice* can be an active engagement among actors in changing the agrifood system:

> *"I think it's super interesting because I've started . . . to be interested in how things are developing with climate, sustainability, our nature and so on, and so on. I think it's cool to be a part of it."* (Wholesaler)

As the wholesaler from the interviews explains in this quotation, valuing can include a broad range of parameters beyond price, and noticing this can create meaningfulness in people's everyday lives. Starting to value differently, therefore, represents potential for change. Continuing this, Heuts and Mol (2013) argue that valuing is not just a mere evaluation of qualities, but actors are also playing an active role in creating values through their practices [32]. Breeders are improving FGL varieties, growers provide the conditions for the plants to grow, and chefs are working to provide meals that are valued by those who eat them. Practices to actively engage in making FGLs *good* are, therefore, also an important part of valuing differently. This requires know-how and skills [56,57]. Increasing FGLs role in future agrifood systems must, thus, require acknowledging the importance of the work done to make good FGLs in practice, what Heuts and Mol (2013) describe as *care* [32]. This means being attentive to and supporting learning and valuing processes among all actors in the agrifood system (including the conditions enabling these processes) in political initiatives that aims at supporting transitions towards more production and consumption of FGLs.

Acknowledging the ambitions and potential of FGLs and GLs in general, this study highlights the need to continue to explore how these (new) ingredients can become an interesting and luxury part of our diets in the future. As exemplified in the study, we suggest that the lack of (authoritative) concepts about the taste and sensory qualities of legumes contributes to displacing the balance of power of valuing and provides different conditions for policy in this area than if such language was available. We argue that paying more attention to such concepts could challenge simple indicators and permit exchange of valuing practices between kitchen and field. As Carolan (2015) suggests: "if we wish to maintain agro-biodiversity we must maintain cultural diversity, which means we must maintain a diversity of tastes for food" [58]. Perceiving food professionals as crucial actors in developing new ways of valuing FGLs might support a more just transition towards sustainable and delicious food for both consumers and growers. Doing so can require distribution actors to renegotiate what is perceived as valid value parameters in the distribution sphere and question existing logics and infrastructure. Making new relations across the agrifood system can, thus, disrupt some of the power dynamics that challenge the production and use of FGLs today. Engaging in new relationships and increasing dialogue about the diverse range of qualities appreciated by different actors are some first and important steps towards valuing differently in the agrifood system.

5. Conclusions

The study dealt with understanding the practice of valuing in the agrifood system and how it reveals potentials and barriers in a transition process. The case study of FGLs in Denmark shows that many different actors involved in producing, distributing, or cooking have different ways of valuing FGLs. This includes differences in *what* and *how* FGLs are valued. Contradictory and conflicting values exist alongside each other, and, in some cases, power relations are able to exclude valuing parameters in favour of others. This affects which species and varieties are valued and considered when breeding, cultivating, or promoting future FGLs. The study reveals imbalances in the conceptualisation of values between the production sphere and food professionals. We argue that an extended language about values could generate new understandings between actors along value chains and may even be a prerequisite for the development of new and more sustainable agrifood systems. Action is required in order to redistribute knowledge across established actor positions and build new relations between actors in the agrifood system.

Analysing valuing processes as social and relational practices indicates the importance of analysing changing dynamic interactions and relations of actors in time and space as part of a sustainable transition. It shows that the changes needed are systemic rather than linked to specific parts of the agrifood system. Acknowledging that valuing takes place every day in the agrifood system revels how valuing differently, revaluing, and creating value are ways in which the agrifood system can be changed in both theory and practice.

Author Contributions: Conceptualization, A.K.A., S.R.H., N.H.K., and H.H.-N.; methodology, A.K.A., S.R.H., N.H.K., and H.H.-N.; formal analysis, A.K.A.; investigation, A.K.A.; data curation, A.K.A.; writing—original draft preparation, A.K.A.; writing—review and editing, A.K.A., S.R.H., N.H.K., and H.H.-N.; supervision, S.R.H., N.H.K., and H.H.-N.; project administration, H.H.-N.; funding acquisition, A.K.A., N.H.K., and H.H.-N. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the project Fresh grain legumes for human consumption (GrainLegsGo). The project is part of the Organic RDD 6 programme, which is coordinated by the International Centre for Research in Organic Food Systems (ICROFS). It has received grants from the Green Growth and Development Programme (GUDP) under the Danish Ministry of Environment and Food.

Informed Consent Statement: Written informed consent has been obtained from all actors to publish this paper.

Acknowledgments: We would like to thank all the actors interviewed for sharing their expertise and thoughts. Also, we thank Sofia Martine Løfstrøm, Augusta Christiansen and Katinka Uldum Abrahamsen for transcription of the interviews.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. IPES Food; ETC Group. *A Long Food Movement: Transforming Food Systems by 2045*; IPES Food: Brussels, Belgium, 2021.
2. Willett, W.; Rockström, J.; Loken, B.; Springmann, M.; Lang, T.; Vermeulen, S.; Garnett, T.; Tilman, D.; DeClerck, F.; Wood, A.; et al. Food in the Anthropocene: The EAT-Lancet Commission on healthy diets from sustainable food systems. *Lancet* **2019**, *393*, 447–492. [CrossRef] [PubMed]
3. Lathuillière, M.J.; Johnson, M.S.; Galford, G.L.; Couto, E.G. Environmental footprints show China and Europe's evolving resource appropriation for soybean production in Mato Grosso, Brazil. *Environ. Res. Lett.* **2014**, *9*, 074001. [CrossRef]
4. Garnett, T.; Röös, E.; Little, D. *Lean, Green, Mean, Obscene...? What is Efficiency and Is it Sustainable?* Food Climate Research Network (FCRN): Oxford, UK, 2015; ISBN 1751731111.
5. Hauggaard-Nielsen, H.; Mundus, S.; Jensen, E.S. Nitrogen dynamics following grain legumes and subsequent catch crops and the effects on succeeding cereal crops. *Nutr. Cycl. Agroecosystems* **2009**, *84*, 281–291. [CrossRef]
6. Jensen, E.S.; Hauggaard-Nielsen, H. How can increased use of biological N2 fixation in agriculture benefit the environment? *Plant Soil* **2003**, *252*, 177–186. [CrossRef]
7. The EAT-Lancet Commission on Food, Planet, Health. Healthy Diets From Planet. *Lancet* **2019**. Available online: https://eatforum.org/content/uploads/2019/07/EAT-Lancet_Commission_Summary_Report.pdf (accessed on 1 February 2023).
8. Magrini, M.-B.; Fernandez-Inigo, H.; Doré, A.; Pauly, O. How institutional food services can contribute to sustainable agrifood systems? Investigating legume-serving, legume-cooking and legume-sourcing through France in 2019. *Rev. Agric. Food Environ. Stud.* **2021**, *102*, 297–318. [CrossRef]
9. Mouritsen, O.G.; Styrbæk, K. Design and 'umamification' of vegetable dishes for sustainable eating. *Int. J. Food Des.* **2020**, *5*, 9–42. [CrossRef]
10. Danish Government. Aftale om Grøn Omstilling af Dansk Landbrug. 2021. Available online: https://fm.dk/media/25302/aftale-om-groen-omstilling-af-dansk-landbrug_a.pdf (accessed on 1 February 2023).
11. European Commission Farm to Fork Strategy. *For a Fair, Healthy and Environmentally-Friendly Food System*; DG SANTE/Unit 'Food Inf. Compos. Food Waste'. 2020. Available online: https://food.ec.europa.eu/system/files/2020-05/f2f_action-plan_2020_strategy-info_en.pdf (accessed on 1 February 2023).
12. Belfry, K.D.; Van Eerd, L.L. Establishment and impact of cover crops intersown into corn. *Crop Sci.* **2016**, *56*, 1245–1256. [CrossRef]
13. Constantin, J.; Dürr, C.; Tribouillois, H.; Justes, E. Catch crop emergence success depends on weather and soil seedbed conditions in interaction with sowing date: A simulation study using the SIMPLE emergence model. *Field Crops Res.* **2015**, *176*, 22–33. [CrossRef]
14. Duiker, S.W. Establishment and termination dates affect fall-established cover crops. *Agron. J.* **2014**, *106*, 670–678. [CrossRef]
15. Magrini, M.B.; Anton, M.; Cholez, C.; Corre-Hellou, G.; Duc, G.; Jeuffroy, M.H.; Meynard, J.M.; Pelzer, E.; Voisin, A.S.; Walrand, S. Why are grain-legumes rarely present in cropping systems despite their environmental and nutritional benefits? Analyzing lock-in in the French agrifood system. *Ecol. Econ.* **2016**, *126*, 152–162. [CrossRef]

16. Gylling, M.; Bosselmann, A.S.; Hagelund, A.; Olsen, F.L. Opgørelse over import af soja og andre landbrugsprodukter fra Brasilien Notat vedrørende oplysninger til besvarelse af spørgsmål stillet til ministeren for fødevarer, fiskeri og ligestilling Gylling. IFRO Udredning, No. 2019/25. 2020. Available online: https://static-curis.ku.dk/portal/files/234273377/IFRO_Udredning_2019_25.pdf (accessed on 1 February 2023).
17. Lampe, M.; Sharp, P. *The Land of Milk and Butter: How Elites Created the Modern Danish Dairy Industry*; The University Of Chicago Press: Chicago, IL, USA, 2018.
18. The Danish Veterinary and Food Administration. *The Official Dietary Guidelines—Good for Health and Climate*; Ministry of Food, Agriculture and Fisheries Denmark: Copenhagen, Denmark, 2021.
19. Sonnino, R.; Tegoni, C.L.S.; De Cunto, A. The challenge of systemic food change: Insights from cities. *Cities* **2019**, *85*, 110–116. [CrossRef]
20. Ericksen, P.J. Conceptualizing food systems for global environmental change research. *Glob. Environ. Chang.* **2008**, *18*, 234–245. [CrossRef]
21. Ingram, J. A food systems approach to researching food security and its interactions with global environmental change. *Food Secur.* **2011**, *3*, 417–431. [CrossRef]
22. Lamine, C.; Dawson, J. The agroecology of food systems: Reconnecting agriculture, food, and the environment. *Agroecol. Sustain. Food Syst.* **2018**, *42*, 629–636. [CrossRef]
23. Bui, S.; Cardona, A.; Lamine, C.; Cerf, M. Sustainability transitions: Insights on processes of niche-regime interaction and regime reconfiguration in agri-food systems. *J. Rural Stud.* **2016**, *48*, 92–103. [CrossRef]
24. Garnett, T. Food sustainability: Problems, perspectives and solutions. *Proc. Nutr. Soc.* **2013**, *72*, 29–39. [CrossRef]
25. Eakin, H.; Connors, J.P.; Wharton, C.; Bertmann, F.; Xiong, A.; Stoltzfus, J. Identifying attributes of food system sustainability: Emerging themes and consensus. *Agric. Hum. Values* **2017**, *34*, 757–773. [CrossRef]
26. Meynard, J.M.; Jeuffroy, M.H.; Le Bail, M.; Lefèvre, A.; Magrini, M.B.; Michon, C. Designing coupled innovations for the sustainability transition of agrifood systems. *Agric. Syst.* **2017**, *157*, 330–339. [CrossRef]
27. Lamine, C. Introduction. In *Sustainable Agri-Food Systems: Case Studies in Transitions Towards Sustainability from France and Brazil*; Bloomsbury Publishing Plc: London, UK, 2020; ISBN 9781350101135.
28. Geels, F.W.; Kemp, R. Dynamics in socio-technical systems: Typology of change processes and contrasting case studies. *Technol. Soc.* **2007**, *29*, 441–455. [CrossRef]
29. Geels, F.W. From leadership to followership: A suggestion for interdisciplinary theorising of mainstream actor reorientation in sustainability transitions. *Environ. Innov. Soc. Transit.* **2021**, *41*, 45–48. [CrossRef]
30. Shove, E.; Walker, G. Governing transitions in the sustainability of everyday life. *Res. Policy* **2010**, *39*, 471–476. [CrossRef]
31. Law, J. On sociology and STS. *Sociol. Rev.* **2008**, *56*, 623–649. [CrossRef]
32. Heuts, F.; Mol, A. What Is a Good Tomato? A Case of Valuing in Practice. *Valuat. Stud.* **2013**, *1*, 125–146. [CrossRef]
33. Helgesson, C.-F.; Muniesa, F. For What It's Worth: An Introduction to Valuation Studies. *Valuat. Stud.* **2013**, *1*, 1–10. [CrossRef]
34. Mol, A. Care and its values Good food in the nursing home. *Care Pract.* **2010**, 215–234. [CrossRef]
35. Ren, C. Non-human agency, radical ontology and tourism realities. *Ann. Tour. Res.* **2011**, *38*, 858–881. [CrossRef]
36. Yates-Doerr, E.; Mol, A. Cuts of Meat: Disentangling Western Natures-Cultures. *Camb. J. Anthropol.* **2012**, *30*, 48–64. [CrossRef]
37. Mol, A. *The Body Multiple: Ontology in Medical Practice*; Duke University Press: Durham, UK, 2002; ISBN 9780822329176.
38. Harbers, H.; Mol, A.; Stollmeyer, A. Food Matters. *Theory Cult. Soc.* **2002**, *19*, 207–226. [CrossRef]
39. Mol, A. Ontological Politics. A Word and Some Questions. *Sociol. Rev.* **1999**, *47*, 74–89. [CrossRef]
40. Law, J. Material Semiotics. *Heterogeneities* **2019**, 1–19. Available online: http://www.heterogeneities.net/publications/Law2019MaterialSemiotics.pdf (accessed on 1 February 2023).
41. Bryman, A. *Social Research Methods*, 2nd ed.; Bryman, A., Ed.; Oxford University Press: Oxford, UK, 2004; ISBN 0199264465.
42. Goodman, L.A. Comment: On respondent-driven sampling and snowball sampling in hard-to-reach populations and snowball sampling not in hard-to-reach populations. *Sociol. Methodol.* **2011**, *41*, 347–353. [CrossRef]
43. Hijbeek, R.; Pronk, A.A.; van Ittersum, M.K.; ten Berge, H.F.M.; Bijttebier, J.; Verhagen, A. What drives farmers to increase soil organic matter? Insights from the Netherlands. *Soil Use Manag.* **2018**, *34*, 85–100. [CrossRef]
44. Gosnell, H. Regenerating soil, regenerating soul: An integral approach to understanding agricultural transformation. *Sustain. Sci.* **2021**, *17*, 603–620. [CrossRef]
45. Seymour, M.; Connelly, S. Regenerative agriculture and a more-than-human ethic of care: A relational approach to understanding transformation. *Agric. Hum. Values* **2022**. [CrossRef]
46. Vargas, A.M.; de Moura, A.P.; Deliza, R.; Cunha, L.M. The role of local seasonal foods in enhancing sustainable food consumption: A systematic literature review. *Foods* **2021**, *10*, 2206. [CrossRef]
47. Röös, E.; de Groote, A.; Stephan, A. Meat tastes good, legumes are healthy and meat substitutes are still strange—The practice of protein consumption among Swedish consumers. *Appetite* **2022**, *174*, 106002. [CrossRef]
48. Hove, E.L.; King, S.; Hill, G.D. Composition, protein quality, and toxins of seeds of the grain legumes *Glycine max*, *Lupinus* spp., *Phaseolus* spp. *Pisum sativum*, and *Vicia faba*. *N. Z. J. Agric. Res.* **1978**, *21*, 457–462. [CrossRef]
49. Howard, P.H. *Concentration and Power in the Food System: Who Controls What We Eat?* revised ed.; Bloomsbury Publishing Plc: London, UK, 2021; ISBN 9781350183094.

50. Röös, E.; Carlsson, G.; Ferawati, F.; Hefni, M.; Stephan, A.; Tidåker, P.; Witthöft, C. Less meat, more legumes: Prospects and challenges in the transition toward sustainable diets in Sweden. *Renew. Agric. Food Syst.* **2020**, *35*, 192–205. [CrossRef]
51. Frank, J. Meat as a bad habit: A case for positive feedback in consumption preferences leading to lock-in. *Rev. Soc. Econ.* **2007**, *65*, 319–348. [CrossRef]
52. Murcott, A. The cultural significance of food and eating. *Proc. Nutr. Soc.* **1982**, *41*, 203–210. [CrossRef] [PubMed]
53. Rozin, P. Food is fundamental, fun, frightening, and far-reaching. *Soc. Res.* **1999**, *66*, 9–30.
54. Visser, M. Food and Culture: Interconnections. *Soc. Res.* **1999**, *66*, 117–130.
55. Rozin, P. The meaning of food in our lives: A cross-cultural perspective on eating and well-being. *J. Nutr. Educ. Behav.* **2005**, *37*, S107–S112. [CrossRef]
56. Huyard, C. Sustainable food education: What food preparation competences are needed to support vegetable consumption? *Environ. Educ. Res.* **2020**, *26*, 1164–1176. [CrossRef]
57. Sørensen, L.B.; Germundsson, L.B.; Hansen, S.R.; Rojas, C.; Kristensen, N.H. What skills do agricultural professionals need in the transition towards a sustainable agriculture? A qualitative literature review. *Sustainability* **2021**, *13*, 13556. [CrossRef]
58. Carolan, M. Affective sustainable landscapes and care ecologies: Getting a real feel for alternative food communities. *Sustain. Sci.* **2015**, *10*, 317–329. [CrossRef]

sustainability

MDPI

Article

When the Sugar Runs Out: Transitioning Agricultural Systems and Their Effect on Dietary Diversity in Yaguajay, Central Cuba

Victoria Constanza Ramenzoni [1,2,*], Vanessa Vázquez Sánchez [3], Diana Valdés Massó [4], Armando Rangel Rivero [3], Daily Yanetsy Borroto Escuela [5] and Daniel J. Hoffman [2,6]

1 Department of Human Ecology, School of Environmental and Biological Sciences, Rutgers University, New Brunswick, NJ 08901, USA
2 Center for Childhood Nutrition Research, New Jersey Institute for Food, Nutrition, and Health, Rutgers University, New Brunswick, NJ 08901, USA; dhoffman@sebs.rutgers.edu
3 Museo Antropológico Montané, Universidad de La Habana, La Habana 10400, Cuba; vanevaz@fbio.uh.cu (V.V.S.); rangel@fbio.uh.cu (A.R.R.)
4 Hospital Miguel Enríquez, La Habana 10700, Cuba
5 Caguanes National Park, Simón Bolívar, Yaguajay 62100, Cuba; dborroto76@gmail.com
6 Department of Nutritional Sciences, School of Environmental and Biological Sciences, Rutgers University, New Brunswick, NJ 08901, USA
* Correspondence: victoria.ramenzoni@rutgers.edu

Abstract: The past years have shown the widespread vulnerability of agro-food systems and rural diets to external perturbations such as wars, climate events, and pandemics. Experiencing numerous obstacles, Cuba constitutes an example of success in the transition to agroecological sustainability models. This article characterizes how processes of agricultural change, local development, and industrial degrowth have impacted food availability and dietary diversity among rural livelihoods in the municipality of Yaguajay, Sancti Spíritus, for the past forty years (1980s–2020s). It integrates findings from focus groups, repeated nutritional surveys, and interviews carried out between 2016 and 2022 among residents of the towns of Yaguajay and La Picadora. The goal is to identify effects and response strategies within agro-food systems of rural populations. Distinguishing between periods of abundance and shortage, our findings show two counterpoints: intensive sugar monocrop cultivation, which resulted in high dietary variety; and economic crises in the 1990s and during the last period of the pandemic, which have led to significant dietary adjustments. The article concludes by underscoring the importance of comprehensive assessments of dietary strategies to elicit what agroecological transitions mean for local realities and of the value of food consumption and small-holder production experiences to understand the limits to sustainable transformations.

Keywords: sustainability transitions; diets; agroecology; food system resilience; climate change

Citation: Ramenzoni, V.C.; Vázquez Sánchez, V.; Valdés Massó, D.; Rangel Rivero, A.; Borroto Escuela, D.Y.; Hoffman, D.J. When the Sugar Runs Out: Transitioning Agricultural Systems and Their Effect on Dietary Diversity in Yaguajay, Central Cuba. *Sustainability* **2023**, *15*, 13073. https://doi.org/10.3390/su151713073

Academic Editors: Hamid El Bilali, Tarek Ben Hassen, Marian Rizov and Carola Strassner

Received: 18 April 2023
Revised: 27 July 2023
Accepted: 27 August 2023
Published: 30 August 2023

1. Introduction

The year 2003 saw the closing of the last sugar mill in Yaguajay, Central Cuba. Once a lively municipality with over one-third of its population directly employed by the sugar industry, the region was swiftly transitioned into livestock farming, including small-scale, organic, and commercial production operations [1–3]. The shift in agricultural practices was nothing short of revolutionary for thousands of households, which saw their livelihoods profoundly changing in under two years. Beyond a reconversion of the working force and the introduction of sustainable development programs, local communities once again experienced instabilities and swings in dietary practices. The sugar-productive conglomerate, locally known as complejo agroindustrial azucarero, was the primary and often unique source of income for most families. With its disappearance, food provisioning programs stopped operating, and communities lost secure access to food supplies. While changes in diets are an expected after-effect of any agricultural transition process, scarce attention has been paid in rural studies to the nature of dietary strategies among Cuban farmers. This is a surprising outcome for numerous reasons.

In a developing nation such as Cuba, which has been signaled as an example to follow toward the adoption of agricultural sustainability models under strenuous political and economic circumstances, scarcity is frequently documented by the government as a direct result of the long-standing embargo [4]. Lack of access to foreign markets has severely impaired the country's capacity to obtain key agricultural staples, such as seeds, fertilizers, spare parts, and diesel, which are crucial for self-sufficiency in food production. As a result, Cubans have seen severe food shortages in the 1990s and early 2000s. More presently, with events such as the Coronavirus-19 pandemic, the strengthening of sanctions by the Unites States government in the mid to late 2010s, and the loss of tourism, families are enduring a new set of challenging conditions.

In fact, retrospective studies of weight changes and morbidities from 1980 to early 2010s discovered an average loss of 4 to 5 kg across the adult population as an aftermath of the economic crisis that followed the dissolution of the Soviet Union in 1991 [5]. The reduction of foreign trade during the years 1991–1995 resulted in a 75% contraction of imports to the values of 1989. During the same period in the early 1990s, agricultural production saw a decline of 47%. Decreases in the availability of fuel and food items inaugurated multiple cycles of inflation and led to a 34 to 36% dip in consumption at the household level for the last decade of the twentieth century [6]. Franco et al. showed that, between 1988 and 1993, per capita daily energy intake decreased from 2899 to 1863 calories. Other authors indicate that the impact was immediate and grave, with a reduction in protein intakes between 37% and 42% in the early 1990s, and important deficits in vitamin B1 [6–8]. Simultaneously, the proportion of physically active adults increased from 30 to 67% [9]. Driven by the shortages in diesel, public transportation receded. People resorted to horses, bikes, and carts for transport, and to the walking of long distances when none of these were available. Sustained weight losses and changes in activity levels in the 1990s were considered important factors explaining changes in the prevalence of diabetes and coronary pathologies towards the early 2000s. Most importantly, findings reflected a change in the composition of diets, suggesting a shift in nutritional strategies in the population. In comparison to 1980, at the beginning of the crisis in 1991 through 1994, dietary profiles showed a higher proportion of carbohydrates originating in sugar cane and rice. Profiles also exhibited reductions in the proportion of fat and protein due to the lower consumption of animal products [9]. To substitute for the scarcity of animal protein, the state instituted new rations, with 7 eggs and 2 pounds of fish granted per adult each month [6]. To many Cubans, state solutions remained insufficient. Thus, the last decade of the twentieth century became known as the "special period", the time when food security emerged as a strategic issue of concern not just for the revolutionary government, but also for the people [8].

Overall, and despite the many challenges, Cuba was able to recover its economy by the early to mid-2000s. The country exhibited in 2009 a prevalence of population malnourishment well below 3% and no presence of severe or chronic child malnourishment, a fact that distinguishes the nation from other Latin America countries. Whereas diets have been described as meeting nutritional goals according to the United Nations, food practices show a comparatively low dietary breadth and an ample reliance on private outlets to meet household demands [10]. Faithful to its socialist values, throughout the past several decades, Cuba has made significant investments in resources and capacity development to attain alimentary sufficiency. Numerous policies centering on food security such as the rationing and broad-scale distribution of key food groups to vulnerable populations have been the norm. Yet, some of these policies have remained unsuccessful. In this context, an understanding of the trade-offs faced by rural households during the economic and agricultural production transitions can shed important insights for public health and nutritional experts. This is a task that remains pending within rural populations in Cuba and that we seek to explore through this article.

Dietary Studies and Agricultural Production in Cuba in the Context of Sustainable Models of Agriculture

Until very recently, studies of dietary trade-offs in Cuba have been mostly conducted at a national scale with detailed descriptions only covering major urban centers such as Havana [11–15]. The latest 2010–2011 National Survey of Risks Factors and Prevention Activities of Non-Transmissible Diseases coordinated by the National Institute of Hygiene, Epidemiology, and Microbiology (Instituto Nacional de Higiene, Epidemiología y Microbiología INHEM), The National Bureau of Statistics (Oficina Nacional de Estadísticas, ONE), and the National Institute of Nutrition and Dietary Hygiene (Instituto de Nutrición e Higiene de los Alimentos, INHA), however, has included a study of rural populations [16]. Detailed findings are not accessible, restricting knowledge of rural diets to general comparisons and outdated reports. For example, at the regional level, some information can be obtained for six clusters of provinces in the Ethnographic Atlas of Cuba, which was compiled between 1980 and 1990. The latter document sought to assess the changes brought by the Revolution in traditional diets and habits by contrasting two rural surveys, one from 1957 and another from 1988 [17]. Although rich in details, this and other works do not inform on the specific strategies that farmers rely upon to deal with periods of scarcity or increased availability. Household strategies refer here to the deliberate set of planned actions to address changes in socioeconomic and environmental conditions imperiling the survival of a domestic unit [11,18]. Strategies capture practices adopted to procure resources during times of crises and to secure the reproduction of the family [19,20].

In addition to concerns about dietary sufficiency, over the past few years, the urgency to foment societal transformations that can support economic, social, and ecological sustainability in food production practices across developed and developing countries has become dire [21,22]. Within calls for change, agricultural production systems which are responsible for a third of total greenhouse gas emissions [23,24] have been at the center of discussions [25,26]. Modifications in agricultural techniques include changes in land use, fertilization, and crop selection to increase the amount of carbon stored in soil and vegetation. Organic agriculture and agroecological practices, which do not rely on industrial pesticides or agrochemicals and employ small-scale farming strategies such as crop rotation and minimum soil tillage, have been found to have a stronger potential for climate change mitigation when compared to conventional cultivation methods [27–29]. However, organic production can result in lower yields per hectare for some crops, creating the need for extensive land use to meet agricultural demand [30,31]. It can also increase production costs and, ultimately, consumer prices as it is more labor-intensive. Yet, this is only one among several socioeconomic concerns pertaining to the broad-scale adoption of sustainable organic practices, which may encompass certification issues and export dynamics [32,33].

Forced to transition its agricultural production to organic farming due to a complex sociopolitical scenario, Cuba has been one of the preferred case-studies among scholars of sustainability [4,34,35]. With the decline of the Soviet bloc in the early 1990s, the island lost access to export markets for its single most important commodity: sugar. Most significantly, Cuba was no longer able to procure key utilities such as chemical fertilizers, animal feed, and essential technology to support its agricultural sector. The sudden transition was heralded as a success in terms of social, ecological, and economic standards. Captured by sustainability indicators such as the Human Dimension Index or the Sustainable Society Index, the wide-scale adoption of organic policies has been seen by scholars and practitioners as largely positive [36]. To some, Cuba has become “an antidote to the hyper-commercialized and industrial food systems of the Global North” [37]. The success behind this shift has been attributed to the particular mix of strong institutional and policy frameworks that continue to scaffold Cuban development priorities [38,39].

A more nuanced view of the agricultural sector, however, illuminates other dimensions of the transition that can escape broad-scale policy analyses [40,41]. For example, even when the country embraced organic regimes to an unprecedented historical extent, the growth in smallholder farming, peri-urban and urban agriculture, and state-sponsored production cooperatives were not without obstacles [42,43]. The process of decentralization and reconversion was very gradual, requiring the implementation of numerous territorial development programs over the past thirty years that have only recently gained momentum. The shift in production was disruptive of former local practices, requiring extensive participation of social movements and external actors such as universities, and the spearheading of a grassroots approach to development [37,44,45]. In addition, the transformation of the agricultural system only seems to have gained traction after the deactivation of the sugar monocrop industry in the early to mid-2000s [35,46]. As sugar factories were compulsorily shut down and the island lost access to food imports from other socialist countries, a large section of the population reverted to small-scale farming and ranching as a way of sustenance. It was indeed a strategic decision for agricultural workers at the lowest levels. The shifting from technological agriculture to sustainable production reflected a new reality: virtually inexistent industrial inputs such as oil for mechanized activities, decreasing imports of food items and prohibitive prices, and a complete lack of access to financial markets. Rather than a choice, the transition to organic and agroecological practices was made out of necessity and often required careful strategizing within households [4]. The expansion of smallholder farms was only attained in 2008, after the introduction and incentivization of usufruct policies that transferred state-idled lands to private individuals and cooperatives [2]. In 2013, about 70.8% or 4.5 million hectares of Cuba's arable land were in the hands of non-state parties, with roughly half of the land under cultivation [47]. By 2016–2017, the percentage of land under non-state tutelage increased to 80%. Of this proportion, 49% of the distribution fell under three types of cooperatives (Unidades Básica de Producción or UBPC; Créditos y Servicios, or CCS; and, Producción Agropecuaria or CPA), and 29% was held by individual farmers under usufruct contracts [48]. Presently, the process of political transformation of the agricultural system continues. Significant steps were introduced in 2012 and 2019 as a result of the new Cuban constitution, and more recently, with the Coronavirus-19 pandemic [49].

Because family-based agriculture is the largest producer of foodstuffs [50], exploring this sector further in terms of strategies and trade-offs becomes crucial to understanding the challenges to food security. Unfortunately, rural household experiences and decisions among Cuban farmers are not often documented in the academic literature (but see [37,51]). A small number of studies have looked at smallholder properties in Sancti Spíritus, the province where the current research takes place [1,50]. Machado and Fernandez as well as Moon et al. have also generally characterized some of the challenges seen in La Picadora, one of the communities focused on our long-term research program [37,52,53]. None of these works, however, have delved into the complexity behind household dietary trade-offs, a shortcoming that reflects the paucity of data in terms of rural nutrition beyond state publications and the national 2010–2011 census of risk factors, and the challenges of conducting long-term fieldwork. These challenges have increased in the past year, with the impacts of the Ukrainian invasion and the ongoing U.S. treasury embargo producing dire shortages of food and commodities and high prices [54]. Scarcity and the loss of the tourism industry, the main source of revenue for the state, has once again forced thousands to migrate in record numbers [55,56].

In this article, we aim to investigate the impacts of recent agricultural transformations in food availability, dietary composition, and food-nutrition-related labor and activities within two different population clusters: La Picadora, a rural farming community, and a group of urban fishermen from the town of Yaguajay in Central Cuba. Part of a transdisciplinary approach including ecologists, social scientists, and biological anthropologists, we rely on longitudinal data collected between 2016 and 2022 to interpret previous findings with more recent information to better explore nutritional strategies for these two clusters. To that end, the article describes the main dietary conditions, trade-offs, and challenges experienced by households in an ongoing agroecological transition that began in the early 1990s. We focus on this region due to its former importance in agricultural and industrial sugarcane production, its distance from major urban centers such as Santa Clara or Havana, and its high level of reliance on manual labor for subsistence.

2. Materials and Methods

2.1. Study Site

The rural community of La Picadora is in the municipality of Yaguajay, province of Sancti Spíritus, Central Cuba. Comprising about 80 households (215 people), up until the early 2000s most inhabitants worked in the three sugar mills and a fertilizer plant, with only a small fraction of the population completely devoted to small-scale agriculture [57–60]. The community relies primarily on farming, ranching, and tourism as sources of employment. Like elsewhere in Cuba, there are different modalities that organize agricultural production in La Picadora, including CCS, CPA, and the UBPC [37]. There are also private smallholders who do not take part in any of the cooperatives. Despite some farmers concentrating on a particular crop such as sorghum for large-scale production, each household grows a set of diverse cultigens, including tubers and root vegetables (boniato, malanga, and yuca), grains (maize, rice, beans, and coffee), fruit trees (papaya, guayaba, mango, avocado, and bananas), and produce (garlic, onions, cucumbers, squash, tomatoes, carrots, and green leafy vegetables) [60]. An agricultural calendar, which has seen important alterations due to climate-related events such as drought, flooding, hurricanes, and changes in average temperatures, loosely systematizes activities [57]. The recent pandemic did not affect farming operations and sanitary provisions such as social distancing were followed.

The town of Yaguajay, about 20 km northwest of La Picadora, is located in proximity to coastal lagoons and shallow bays. With a population exceeding 6500 residents, its inhabitants are predominantly employed in a host of different occupations ranging from government and educational services to transport and agricultural tasks [61–63]. Unlike La Picadora, where most households work on farms, households in Yaguajay have mixed economic portfolios. For example, a small percentage of households within the town also rely on artisanal fishing as a complementary source of sustenance [58,61]. There is an association that congregates about 47 active fishers that operate in nearshore areas out of Playa Vitoria, Yaguajay's docking pier, and occasionally beyond the northern cays. The level of dependence on fishing varies, with only a handful of individuals fully dedicated to commercial fishing activities and much of the sample self-defined as opportunistic fishers. Because of their higher level of dependence on natural resources in comparison to other inhabitants, and their living proximity to fishing areas, we narrowed our study focus to this set of fishing households.

Over the past forty years, the towns of La Picadora and Yaguajay, have been at the center of rapid agricultural change [58,60]. Because most residents in both communities participated in the large-scale sugarcane industry, they were equally vulnerable to agricultural policies that regulated production and suffered major transformations in their way of living. In the next subsections, impacts from two agricultural transitions are identified at the domestic level. Complemented by historical sources, interviews and focus group discussions provide direct evidence of the effect of these transitions in diets and activities.

2.2. Ongoing Research

Part of a larger project seeking to explore rural adaptation in rapidly changing environments, the study was designed to develop a long-term comparison of the communities of La Picadora and Yaguajay to observe variations in dietary and energetic patterns among different households given the diversity of occupations. The research team includes researchers from Montané Anthropological Museum at Universidad de La Habana, Caguanes National Park, and Rutgers University. Ongoing activities began in 2016 and were interrupted during 2017 due to the passage of hurricane Irma, which brought significant damage [57]. While research was reestablished in 2018, the Coronavirus-19 pandemic restricted travel to the region between 2020 and 2021.

Participants for the study were recruited in both groups through snowball sampling. Given the small size of these clusters, we used a purposive approach to identifying individuals based on their residence location and engagement in subsistence activities. Following responsible research practices and ethical protocols from Universidad de La Habana, consent was requested before survey administration and to participate in discussions, interviews, and anthropometric or energetic measurements. When possible, discussions and interviews were recorded. Each group discussion had a duration of approximately 75 min and took place in the town hall of La Picadora or in the offices of Caguanes National Park in Yaguajay. Interviews lasted anywhere from 10 to 60 min. All recorded exchanges were later transcribed and analyzed with NVivo 12.

Repeated nutritional surveys, carried out initially in 2017 and 2018, and then in 2022, sought to assess diet composition among both populations and across time. The survey tool accompanied anthropometric measurements (not reported here) and was designed after the questionnaire used by the former Cuban National Institute of Nutrition and Dietary Hygiene (INHA). The adapted instrument considers weekly consumption patterns of seven basic food groups (grain and tubers; vegetables; fruits; animal protein, meats, and beans; dairy; fats or other sources of fat; and sugars). The other two modules within the instrument included the assessment of food frequency consumption for the past week for breakfast, lunch, and dinner, and ways of preparing, consuming, and storing food as well as cultural practices such as parties and food sharing. In the first implementation in 2017, a total of 19 male farmers and 14 male fishers participated in the survey. In March 2018, following the passage of Hurricane Irma in 2017, 28 individuals from the previous dietary survey repeated the nutritional assessment and participated in a reduced form of IPAQ, the international physical activity questionnaire. In 2022, we repeated dietary and physical surveys as described below, and conducted focus groups and interviews.

2.3. Research Design

The article complements previous findings reported elsewhere [16,58–60] with new information obtained through informal interviews, additional dietary surveys, and 2 focus groups conducted in 2022 (see Table 1 for details). To that end, we focus on findings from 2022 and reanalyze previous datasets from 2017 and 2018 to further enrich the interpretation of results. The combination of quantitative and qualitative methods seeks to create a holistic representation of the dietary practices, potential strategies, and health in these smaller subgroups. Yet, it is important to indicate that the external validity of the findings presented here is constrained by the small sample sizes that characterize the project. Whereas generalization is challenging, there are important initial results that paint a picture of the potential transitions undergone by these subgroups. Therefore, this study has substantial value in guiding research priorities in the area and underscores the need to expand future work. Ethical practices for research were followed as described above in data collection in 2022, with consent to continue participation requested among participants.

A dietary survey was re-administered in 2022 among 16 male farmers from La Picadora and 10 male fishers from Yaguajay who participated in the prior 2017 surveys. Findings have informed the development of more precise instruments to assess energetics in November 2022. An expanded sample of 40 rural workers participated in a physical activity 48-h recall and wore accelerometers to measure energetic expenditure. These results will be discussed in depth in future publications. However, we rely on anthropometric data from this activity to characterize the population in 2022 and assess potential changes in comparison to 2017 through non-parametric tests. Survey data on diets and 48-h activity recalls from 2017 and 2018 were re-analyzed for comparisons with the 2022 survey through parametric and non-parametric statistical techniques.

Finally, two focus groups (*n*: 16) and interviews (*n*: 25) were also administered in late 2022 to explore issues related to environmental change, extreme events exposure and impacts, agricultural activities and fishing, dietary availability, and, more recently, dietary changes, the nature of physical activities, and labor. We relied on interview transcriptions and content analysis to elicit important themes and further complement survey data.

Table 1. Detail of research activities.

Activity	Year	Sample Size	Themes	Location	Full Reference
Interviews (exploratory)	2016	7	Fishing and agriculture	La Picadora and Yaguajay	[58,61]
I. Focus Group Discussion	2017	15	Climate change, environmental threats, agricultural calendar	La Picadora	[57–59,61]
II. Focus Group Discussion	2017	15	Climate change, environmental threats, fishing calendar	Yaguajay	[57–59,61]
Nutritional Surveys	2017	35	Dietary composition and frequency; anthropometry.	La Picadora (19) and Yaguajay (14)	[16,62]
Interviews	2018	7	Extreme events (post hurricane impacts on fishing and agriculture)	La Picadora and Yaguajay	[59,63]
III. Focus Group Discussion	2018	21	Extreme events (post hurricane impacts on fishing)	Yaguajay	[59,60,63]
Physical Activity Survey (IPAQ)	2018	28	Labor intensity post hurricane, anthropometry.	La Picadora (18) and Yaguajay (10)	[64]
Interviews	2022	11	Extreme events recovery	Yaguajay	
Nutritional Surveys	2022	26	Dietary composition and frequency, anthropometry.	La Picadora (16) and Yaguajay (10)	
IV. Focus Group Discussion	2022	8	Dietary change and physical labor	La Picadora	
V. Focus Group Discussion	2022	8	Extreme events, environmental impacts, agricultural and fishing changes	La Picadora	
48-h Activity Recall Surveys and Energetic expenditure measurements [1]	2022	40	Activity recall 48 h, physical activity measurement with accelerometers	La Picadora	

[1] Not presented in this article.

3. Results

3.1. General Population Statistics

On average, interviewed households in 2017 had a median of 3 inhabitants, with ranges between 1 and 5 individuals per home. Given our interest in energetic expenditure on arduous activities, anthropometry and measurement of activity levels were carried out with male subjects. Sampled individuals had all completed primary education, and had an age mean of 49.56 years (SD = 5.36) for fishers and 43.26 years (SD = 11.34) for farmers (see Table 2 for a characterization of the sample). No significant differences in Body Mass Index (BMI) calculations between groups (Wilcoxon Two Sample Test, Z = 1.54, $p = 0.12$) or in weight were found. Yet, when classified according to Cuban standards from the National Health Institute and the World Health Organization [65,66], fishers displayed a higher number of individuals possessing BMIs with values suggesting potential overweight or obesity [16,64]. For example, out of 14 individuals, 8 were found to have BMIs above 25, the cutoff for healthy weight. However, self-reports of activity indicated that fishers spent 8.2 ± 2.7 h a day carrying out agricultural labor tasks, on average 1 more hour of work per day in relation to farmers.

Table 2. Basic characteristics of the population in 2017 and 2022.

	2017		2022	
Measure	**Farmers (19)**	**Fishers (14)**	**Farmers (16)**	**Fishers (10)**
Weight (kg)	71.20 ± 13.38	75.48 ± 12.58	72.33 ± 15.63	71.21 ± 11.31
Height (cm)	172.83 ± 6.73	170.12 ± 5.72	170.88 ± 6.73	170.76 ± 5.72
BMI (kg/m^2)	23.78 ± 3.91	26.18 ± 3.53	24.69 ± 4.61	24.39 ± 3.33

Beyond attrition in sample sizes, repeated measurements from 2022 showed fluctuations with different levels of statistical significance. For example, the median number of household inhabitants decreased for farmers to 2 and increased for fishers to 4. This suggests modifications in a household's capacity to support dependents or processes of migration. Weight increased for farmers by approximately 1 kg and decreased among fishers by a total of 4 kg. Changes in weight are also captured in an increase in average BMIs for farmers and a decrease among fishers. In 2022, the difference between BMIs for both populations shrunk, with a higher dispersion in BMIs observed among farmers indicating more variability. Differences in weight and BMI were not significant statistically for farmers in a matched pairs T-test. However, they were statistically significant in the case of fishers for weight, $p = 0.02$, and for BMI, $p = 0.02$. Unfortunately, given the small sample sizes, it is very difficult to infer whether these modifications between 2017 and 2022 are applicable to the whole population, and further research is needed to evaluate the potential implications of the findings.

3.2. Diets

Reflecting a mix of Spanish, African, and Caribbean influences, the composition of rural Cuban diets shows a relatively low level of variation in terms of ingredients and types of preparation [67]. The revolution, while creating important changes in the consumption of items such as tasajo, dried salted beef, or fish, and introducing other less common items such as yogurt or butter, did not essentially alter the character of traditional cuisine [68]. As a result, daily meals in rural areas such as Yaguajay are predominantly characterized by rice, black beans, and pork, the latter when available, which are complemented with a small portion of viandas, including tubers, root vegetables, and green beans, and salad. The most important meals are breakfast, lunch, and dinner, with occasional snacks in the afternoon.

Access to foodstuffs is mostly determined by seasonality and income as well as the existence of family plots, gardens, and/or livestock. In La Picadora, most households have a long history of farming along with lime production and timber extraction. Sharing and exchanges of food items are very common among neighbors and extended family members. As of recent, there is a farmer's market that has begun operating by the side of the main municipal road on Saturdays. In Yaguajay, on the other hand, respondents do not necessarily consider themselves as farmers, but as salaried workers with different occupations. Food is usually obtained from the local state-run markets or stores, from the local *organopónicos* or urban organic farms, by the cultivation of home gardens, or through bartering. As is the case for all Cubans, the state guarantees access to basic foods through a rationing program known as "la libreta". Depending on age, each Cuban citizen can get essential food items at subsidized prices in monthly or even bi-monthly installments. Items include rice, sugar, bread, beans, and some sort of animal protein such as eggs, chicken, or fish. Rich protein foodstuffs such as milk, meat, and eggs are also provided to individuals who require special diets due to medical conditions. The list of foods subsidized has, however, decreased over time along with the quantities that can be purchased. Availability of certain products is also tied to general macroeconomic conditions and general demand, making some of the items in la libreta virtually inexistent. In fact, many respondents mentioned that the quantities that are guaranteed through the system barely meet the needs of a family over a ten-day period and that products like fish have not been available for years. It is no surprise, then, that the sharing and exchange of foods has such an important role in both communities. Discussions about the availability of certain foods or their scarcity are elements of normal conversation, with respondents often narrating the difficulties and obstacles they must surmount in their search for food. The situation has deteriorated further in the past year with the war in Ukraine and the continuous pressure of the blockade creating shortages in items like oil and flour, animal protein, and dairy. Unfortunately, environmental factors tied to climate change and extreme events are also posing significant challenges to the nutrition of rural households. In addition to an increase in the frequency of tropical storms and episodes of salinity intrusion, farmers must contend with extended drought, higher temperatures, and floods, which have resulted in the loss of crops, fruit trees, and cattle.

3.3. Diets Transition

Interviews and conversations with participants in both groups allowed us to reconstruct two major historical moments or transitions in the implementation of agricultural programs. The first transition comprised sugar monocrop intensification and state centralization and occurred from the late 1970s to the early 1990s. During this period, the region saw an expansion and mechanization of its three complejos azucareros Obdulio Morales (Narcisa), Aracelio Iglesias (Nela), and Simón Bolívar (Vitoria). Along with industrialization, the area experienced losses in agricultural diversity and deforestation. In the 1980s, hydrological changes and the drainage of the final residual swamp forests extended cane fields to the line of coast. The second transition began in the 1990s with the Third Agrarian Reform, which led to the decentralization and diversification of agricultural practices. The process was decanted in the dismantling of sugar mills in the early 2000s and the expansion of agroecological and local development models in the municipality [69,70]. As a result, a highly qualified working force of more than 3000 engineers, mechanics, and specialists along with the permanent agrarian workers who tended to the sugar plantations lost their jobs [71]. Whereas a large proportion of those unemployed turned to agriculture, close to one-quarter of the working-age population found employment in the tourism sector [72]. To facilitate the finding of alternative means of subsistence, the Cuban state maintained average salaries for up to six or seven years after the closing of the mills incentivizing education at all levels. The process of reorganization of sugar production was known as "Tarea Álvaro Reynoso". Former sugar workers completed their elementary or high school diplomas and became lawyers, accountants, technicians, teachers, and agricultural engineers. Once the Álvaro Reynoso program came to an end, many found employment in agriculture. Old sugar cane fields were turned into rangelands and cooperatives were established to organize production. Furthermore, access to higher education created an outflow of migration of the available and now highly qualified working force to other provinces. New jobs in tourism and migration contributed negatively to the aging group of agricultural smallholders in Yaguajay who continued to produce essential foodstuffs for the district. Nowadays, La Picadora produces a myriad of different crops including rice, beans, produce, tubers, and coffee, and seasonal vegetables such as tomatoes, lettuce, carrots, and onions.

Matching the two agricultural transitions outlined above, interviewees and focus group participants from both locations made a clear distinction in the quality of dietary diversity between the time during which complejos ran agricultural production in the district before the fall of the Soviet Union and what followed to the closing of the mills in the mid-2000s and the incentivization of usufruct in non-cultivated state lands. They also recognize episodes of scarcity brought about by the 1990s economic crisis and the changes introduced by the adoption of agroecological policies. More recently, interviews mentioned food shortages because of climate-related factors such as hydrological drought, flooding, and hurricanes.

3.4. Periodization of Agricultural Transitions and Dietary Oscillations

1. Diets and labor before 1989/1990

The period that followed the revolution, and specifically, the 1980s was described by interviewees as a time of bounty. The USSR provided an extensive market for sugar, financing the transformation of the sector into a modern agrotechnical industry. As part of these technological exchanges with socialist countries such as Bulgaria, Czechoslovakia, and Mongolia, Cubans received items ranging from fridges, engines, and cars to canned fruits and meats. The island provided in return sugar, citric products, and nickel, along with non-skilled and qualified workers and medical professionals. Thus, it was not unusual to find Cubans working in Eastern Germany and Czechoslovakia or touring Moscow, Hungary, and Bulgaria as part of cultural programs. During these years, sugar factories in Yaguajay were complex conglomerates that included, beyond extensive cane fields, living quarters, mechanical workshops, and agricultural and ranching lands. This was termed a "distrito cañero" and referred to the agglomeration of population settlements with industrial buildings. Workers were divided into different teams according to their tasks and received a salary and incentives. This type of organization of production activities was not unique to the municipality, it was also replicated with some minor adjustments in other provinces.

As part of an arrangement with the groups of labor known as "centros de trabajo", the workers had arduous days of planting, tending, harvesting, transporting, and processing cane. The central had its own food production groups known as "brigadas de autoconsumo" (self-sufficiency brigades) responsible for farming, processing, and obtaining the necessary food for all employees. The central also provided access to workers to what was known as the "cuota cañera", a big sac of products that included rice, canned products, rum, cigars, and even soap that operated as an incentive and allowed households to buy subsidized foods at a marginal price. In fact, some of the respondents described the sac as "una salvajada", an excess of items that were shared beyond close family, friends, and neighbors. As a result of exchanges and their work in the sugar sector, rural households became acquainted with the famous Russian meat, a can of boiled beef that sometimes included pork or ham, along with sardines and anchovies, black bread, borscht, candied peaches, lichi, boiled vegetables, and milk from local producers. In some cases, the cuota was calculated to last for the most intensive periods of labor such as the harvest. However, because the availability and variability of products were determined by foreign trade relations, there was a list of more common items that were locally consumed and could not be bought through the program, such as tubers, vegetable roots, or butter. In those cases, households exchanged products, bartered, or purchased desired foodstuff in informal markets. Respondents also mentioned that during agricultural labor they received breakfast, lunch, and snacks. The food in the fields was very good and reflected what was available at the time. The tradition of cultivating sugar introduced an important habit among farmers and salaried workers: the consumption of sugar in all diverse variants such as guarapo (sugarcane juice), molasses, and even stalks from the plant. The stalks, which were frequently chewed while conducting field labor, left a permanent imprint in the form of tooth decay and wear. Among interviewees, for example, 75% of farmers mentioned that they had regularly consumed sugarcane stalks throughout their childhood and as adults. Some of them also recalled the habit of skinning the stick of cane with their teeth (pelar la caña con los dientes), which explains observed dental deterioration. In all, rural households had several sources or means to access low-price foodstuffs: through small-scale production or barter, through the national ration system, by purchasing independently in state markets, and the cuota cañera. As a farmer indicated, "se comía bien... uno trabajaba mucho pero siempre había... se vivía como ricos" (they lived like wealthy people, work was hard but there was always food, they ate well).

2. The Special Period (1990–1999)

The year 1989 marks the beginning of a change in diets, with canned goods replaced by fresh meat and produce when available. This period lasted until 1991 when the crisis deepened and access to foodstuffs became arduous. Items such as milk, chicken, beef, and oil completely disappeared from local bodegas, also known as state stores [73]. The cuota cañera shrunk and other rationing systems considerably reduced their inventory and the proportion subsidized to a handful of products. Despite challenges, farmers and sugar industry workers found alternative strategies to survive. After a long shift in the central, many reverted to agricultural labor, extending crops and planting surfaces. They began cultivating in the little land that could be found around their houses, in gardens, and in former wastelands. They bartered and sold whatever excess they produced in informal markets. Clothes and goods were also traded, long-term storage facilities were built, and food processing and conservation techniques such as preserves were improved. Some ventured into manufacturing their own laundry and toiletry products. Other strategies among farming households included policultivation and crop diversification, the planting of short-term crops, the joining of production cooperatives, the cultivation of animal fodder, and the participation in agricultural fairs. Not surprisingly, the implementation of strategies depended on access to land among other resources. As one of the respondents indicated, despite adversity, they still managed to eat. The days of past bounty seemed like they never happened.

In the meantime, in late 1992 and 1993, the state introduced a process of reorganization of the sugar industry into smaller farms or UBPCs (Unidades Básicas de Producción Cooperativa), representing about 10 to 15% of the original extension [74]. In this new form, farms were in charge of managing production through the liberalization of the ownership of agricultural means, with the exception of the land [75]. The UBPC had now the tasks of securing total production goals as well as attaining self-sufficiency in food, implementing agroecological techniques, and growing a wider variety of seasonal crops [76]. A similar process of destatization of livestock production was introduced in former rancherias, vaquerías, and dairy centers, which now became small farms holding 10 to 60 cows, or 1.2 to 2 cattle per hectare. The decline in productivity experienced in those years meant a decrease of almost 60% in total crops. With scarcity endangering the health of the population, thousands of dairy cows were re-directed to slaughter. Almost half of all grasslands on the island were covered by invasive species like marabú (*Dichrostachys cinerea*) and the average daily production of liters of milk per cow fell from 6.1 in 1990 to 3.1 in 1992 [75], a value that has not yet improved according to respondents. To recover the sector, more attention was paid to the generation of alternative production inputs such as organic pesticides and fodder, along with a revitalization of organopónicos or urban farms. However, as some respondents indicated, the solutions that were implemented were to a large extent of a centralized nature and disregarded local particularities.

For example, some of the variants that self-sufficiency brigades were responsible for growing in complejos did not match dietary habits. As a result, produce was sent elsewhere or left to rot. It would take several more years before the country was able to bounce back to production levels modestly approaching those of the late 1980s. In this light, the record crop of tubers in 1999 indicated the change in agricultural varieties [74]. Progressively, as the situation improved and with the deactivation of the industrial conglomerates, rural households began applying for newly available agricultural parcels. Access to land was recognized by respondents as a key buffer to scarcity, allowing for the cultivation of staples that could be traded for essential items. Simultaneously, the country invested significant effort in developing the tourism and services sector in a bid to increase the inflow of foreign capital and currency [77]. Changes affected the municipality when the neighboring province of Villa María opened an international tourism hub in the early 2000s that offered salaried jobs.

As it was noted, the special period had a remarked effect on women who were historically responsible for household nutrition [73,78]. In urban areas such as Havana or Santiago, the need for resources led many to open paladares and small restaurants, which are increasingly run by women. In addition, women adopted new strategies to diversify their income. For example, they began preparing and selling snacks on the street or in their houses, working as vendors going door-to-door and trading key foodstuffs, or even commercializing the bolsa negra, a gathering of items bought directly from state workers at discounted prices [51,79]. According to interviewees and accounts from the literature, this return to the domestic sphere of production remained to a large extent informal. Shortages in electricity and scarcity of petrol and kerosene resulted also in prolonged domestic tasks [80]. Women had to rely on timber or wood, coal, and diesel to cook. As water pumps stopped working, women had to contend with obtaining clean water for preparing food, drinking, bathing, laundry, and cleaning. The absence of common ingredients, and the shutting down of state-sponsored diners, cantinas for workers, and cafeterias in schools, also created stressors for household heads who had to devise inventive ways of coming together with a complete meal. In the countryside, while options for alternative employment were limited and tourism virtually inexistent, women had access to gardens and orchards that helped provide for family needs. Beyond food, the lack of goods extended to hygiene and cleaning products, linens and clothes, shoes, sanitary towels, toothpaste, and domestic appliances.

To meet these needs, households became creative and deployed a set of ingenious tactics. For instance, lemon juice was used for toiletries and shampoo. Support among neighbors and friends allowed households to cook together, exchange items such as coffee for beans or rice for medication, or even collaborate in production activities. The high level of solidarity in agricultural labor distinguishes La Picadora from other towns in the region [70,81]. In fact, many respondents mentioned the importance of working together and helping each other beyond the formed cooperatives as a key strategic factor in overcoming challenges. Considering these arrangements, during this time, participants alluded to the high prices of foods that made any purchase in markets almost prohibitive. Local networks of neighbors and family would constantly share information regarding the availability of products in local stores or among other households to facilitate access. Beyond the search for better prices, in private domestic settings, strategies also included the careful planning and reallocation of resources to primary needs such as food, the prioritization of the nutrition of elderly, children, and sick, the skipping or reduction in portions in meals, and the fixing of wardrobe items and shoes.

3. Post-Sugar Monocrop (2000–2020).

In the early 2000s when activities from the sugar industry largely ended, the municipality put forth a strategy to achieve nutritional self-sufficiency, boost agricultural production, and expand forestry programs. New plans were launched to develop the dairy industry, which included the introduction of water buffaloes along with traditional livestock. The strategy sought to increase the production of fruits and vegetables by about one-third in comparison to the previous years, with other staples like rice and grain crops expected to grow between 4 and 5% [82]. As a result, 3 state-run empresas were created with 9 cooperatives specifically focused on agriculture and livestock (CPAs) and 21 UBPCs also concentrated on food production. Infrastructure was built to optimize pig rearing as a source of animal protein, and smaller farms were dedicated to poultry. The Cuban Food Ministry also incentivized freshwater aquaculture providing support for species like Claria (Claridaee family) and Tilapia (Cichlidae family) to be grown in dikes and ponds throughout the province. Finally, the community of La Picadora collectively made the strategic decision to open an agrotourism business in 2015 that houses foreign tourists on a regular basis. Most households participate in the effort by providing services such as cooking or sharing agricultural resources to support the visitors. Earnings are shared equally.

In terms of dietary diversity, our surveys from 2017 showed that ingestion of rice occurred among farming households every day (see Table 3). Bread and crackers were consumed by approximately 80% of the sample daily, and viandas by 60% of respondents. Close to 40% of households made use of other vegetables such as spinach or lettuce, and 42% also consumed fruits. These figures are roughly similar among fishing households in Yaguajay, which reported a higher use of vegetables and fruits. However, differences arose when observing the sources of animal protein in both diets. Only 33.3% of fishing households consumed pork between two to three times a week. Comparatively, among farmers, the proportion was 81.2% for pork in the same frequency, with 50% of the sample also consuming chicken and processed meats twice or three times weekly. The latter were rarely consumed among fishing households. On the other hand, fish was seldom eaten in La Picadora. Yet, close to 82% of the households in Yaguajay relied on fish at least once a week, with 31% of homes consuming this food daily. Differences are highly significant with a Fisher Exact Test for consumption between groups of pork, $p < 0.01$; chicken, $p < 0.02$; and fish or shellfish, $p < 0.00$. Eggs were also used daily in preparations by 47% of farming households and 36% of fishing households. Although not statistically significant, there was also a relatively higher consumption of dairy, about twice the amount, for products such as milk and cheese among respondents in Yaguajay. In addition, fishing households relied on vegetable fat, while farmers relied on animal fat in their preparations (Fisher Exact Test for consumption between groups of animal fat, $p < 0.01$; and vegetal fat, $p < 0.00$). The whole sample exhibited a high ingestion of sugary drinks like sodas on a daily frequency.

Table 3. Diet comparison between residents of La Picadora and Yaguajay in 2017.

Yaguajay (N: 14 Fishing Households)						La Picadora (N: 19 Farming Households)							
Never	**Rarely**	**1 Wk**	**2/3 Wk**	**4/5 Wk**	**Daily**	**Never**	**Rarely**	**1 Wk**	**2/3 Wk**	**4/5 Wk**	**Daily**	**Item**	**Food Group**
0	0	0	0	0	100	0	0	0	0	0	100	Rice	Group 1
21	43	21	7	0	7	21	37	5	32	0	5	Maize	
0	14	7	0	0	79	0	5	0	0	11	84	Bread	
7	43	29	21	0	0	0	21	32	42	0	5	Pasta	
0	7	7	36	7	43	0	0	6	11	22	61	Vianda	Group 2
7	7	0	29	14	43	5	16	11	21	5	42	Vegetables	
0	21	0	14	7	57	0	5	5	11	37	42	Fruits	Group 3
0	15	23	38	8	15	0	0	5	74	21	0	Pork **	Group 4
64	36	0	0	0	0	68	26	0	5	0	0	Rabbit	
0	21	14	50	0	14	5	0	37	42	16	0	Chicken **	
43	21	29	7	0	0	16	11	21	42	11	0	Processed Meat	
7	7	7	21	29	29	16	58	21	0	5	0	Fish **	
21	57	14	7	0	0	84	16	0	0	0	0	Shellfish **	
57	29	14	0	0	0	32	21	32	11	5	0	Entrails/Viscera	
0	14	0	36	14	36	0	0	5	26	21	47	Eggs	
0	0	0	0	7	93	0	0	0	5	5	89	Grains/Beans	
29	0	0	0	7	64	42	5	5	5	11	32	Milk	Group 5
43	21	7	7	0	21	26	5	5	32	11	21	Yogurt	
21	21	7	21	0	29	21	11	5	42	11	11	Cheese	
0	0	7	7	0	86	42	0	5	21	11	21	Vegetable Fat **	Group 6
29	36	0	0	0	36	5	5	0	5	11	74	Animal Fat **	
14	7	7	29	14	29	5	11	21	16	11	37	Sweets/cakes	Group 7
0	0	0	14	21	64	16	5	0	0	5.5	68	Sodas/Drinks	

All values expressed in percentages. **: indicates significance in a Fisher's Exact test for comparing non-parametric samples, with alpha level set at $p < 0.05$.

In all, despite the higher use of marine and coastal products, fishing household diets captured a mix of traditional rural cuisine. For example, the preferred food for parties and special events continued to be pork both slow-roasted or in different kinds of preparations such as fricassee; in conjunction with a small portion of raw vegetables, boiled yucca with a garlic and vinegar dressing, and congris (a mix of black beans and rice). Regarding cooking techniques, vegetables and viandas tended to be consumed raw or boiled. Like pork and different meats, fish were fried, baked, or roasted. There was also consumption of highly processed meats such as sausages or croquettes, which can also be made of chicken and fish. The availability of these kinds of preparations varied depending on what is sold at the state Acopio store or available through the market. The same is to be said for flour-based products such as bread and crackers.

4. Most Recent Years (2020–2022).

Nowadays, as elsewhere on the island, rural households are experiencing food shortages. Despite government efforts, agricultural and aquaculture outputs remain insufficient to meet local needs and imports have dwindled [83–85]. During recent conversations, farmers discussed the low level of milk productivity that is reported among livestock and shortages in the availability of animal protein, flour, and grain. While international sanctions continue to severely limit access to global markets, some of the difficulties affecting the agricultural sector, in the long run, are to be found in the interaction of low government investment, anthropogenic degradation, and climate-related pressures such as extreme events and prolonged droughts. Heat stress, water scarcity, and hurricanes have particularly affected cattle, fruit trees, and rice. Over the next century, the region is expected to experience significant losses in hydrological resources [86,87], which may aggravate the current economic situation.

In comparison to 2017, our repeated survey from 2022 (see Table 4) elicited some potential modifications in diets in La Picadora reflecting the new conditions. Preliminary findings show overall decreases in the frequency of consumption of a total of fifteen food items, including pork, meat-derived products, viscera and entrails, eggs, dairy, maize, sweets, and flour-based products, such as bread, pasta, and crackers. This finding matches what was reported during conversations in focus groups and interviews. Although not statistically significant, a decrease in the consistent use of vegetables and an increase in the daily consumption of fruits was mentioned by participants and is also observed in the dataset. Probably, the most important finding is the decline in the consumption of pork and its partial replacement by chicken and/or fish. For example, a matched samples Wilcoxon Signed Rank test for pork use between 2017 and 2022 for both groups combined was highly significant in evaluating the difference in consumption ($Z = -3.30$, $p = 0.00$). The decline in pork is also seen as a decrease in the use of viscera ($Z = -2.04$, $p = 0.04$) and an increase in the use of vegetable fat ($Z = 2.56$, $p = 0.01$), which has become the staple for food preparation, showing processes of substitution as well as changes in the frequency of previously marginally employed items. For instance, even when not statistically significant, fish has become consumed more frequently during the week. The lack of statistical significance in this case may result from the small sample size and the redistribution of responses along broader categories. Whereas, in 2017, more than half of the sample rarely ate fish, in 2022, the proportion decreased to a third with individuals reporting an increase in use of at least two or three times a week or weekly. Moreover, while not statistically significant, in the case of viandas, fruits, and chicken, these items are now consumed with a higher weekly frequency, indicating processes of replacement of more expensive foods. Thus, even when some important decreases in foodstuffs dominate findings, increments in the use of items such as produce, tubers, and processed meats are also observed. To sum up, while in 2017 the most predominantly used items included grain and pork, in 2022, the composition of meals changed to grain, fish, and chicken along with other less popular foodstuffs. Furthermore, there is a decrease in store-bought items such as pasta ($Z = -2.64$, $p = 0.00$) and sodas ($Z = -3.08$, $p = 0.00$), alluding to a reshifting of monetary resources at the household level.

Table 4. Diet comparison between 2017 and 2022 among farming households in La Picadora.

La Picadora (N: 16 Farming Households) 2022						La Picadora (N: 19 Farming Households) 2017							
Never	**Rarely**	**1 Wk**	**2/3 Wk**	**4/5 Wk**	**Daily**	**Never**	**Rarely**	**1 Wk**	**2/3 Wk**	**4/5 Wk**	**Daily**	**Item**	**Food Group**
0	0	0	0	0	100	0	0	0	0	0	100	Rice	Group 1
29	21	14	36	0	0	25	38	6.2	31	0	0	Maize	
13	0	0	6.2	6.2	75	0	6.2	0	0	13	81	Bread	
6.2	44	25	19	6.2	0	0	19	31	44	0	6.2	Pasta **	
0	6.2	0	13	6.2	75	0	0	6.7	13	27	53	Vianda	Group 2
6.2	25	19	25	6.2	19	6.2	19	13	19	6.2	38	Vegetables	
0	19	6.2	19	0	56	0	6.2	6.2	6.2	38	44	Fruits	Group 3
6.2	25	25	44	0	0	0	0	6.2	81	13	4.5	Pork **	Group 4
100	0	0	0	0	0	75	19	0	6.2	0	0	Rabbit	
6.2	6.2	6.2	69	13	0	6.2	0	21	50	13	0	Chicken	
13	19	38	31	0	0	19	13	13	50	6.2	0	Processed Meat	
25	31	31	13	0	0	19	56	25	0	0	0	Fish	
94	6.2	0	0	0	0	94	6.2	0	0	0	0	Shellfish	
56	38	6.2	0	0	0	38	19	31	13	0	0	Entrail/Viscera **	
6.2	0	0	50	25	19	0	0	6.2	31	19	44	Eggs	
0	0	0	6.2	0	94	0	0	0	6.2	0	94	Grains/Beans	
56	6.2	0	13	0	25	44	6.2	6.2	6.2	13	25	Milk	Group 5
31	25	13	19	0	13	31	6.2	6.2	31	6.2	19	Yogurt	
19	25	19	25	13	0	25	6.2	0	50	13	6.2	Cheese	
0	0	0	0	0	100	44	0	6.2	25	6.2	19	Vegetable Fat **	Group 6
6.2	6.2	0	0	0	88	6.2	6.2	0	6.2	6.2	75	Animal Fat **	
38	0	0	31	25	6.2	6.2	6.2	19	19	6.2	44	Sweets/cakes	Group 7
56.2	12.5	12.5	18.8	0	0	18.8	0	6.2	0	6.2	68	Sodas/Drinks **	

All values expressed in percentages. **: indicates significance in a Wilcoxon Matched Pairs Signed Rank test comparing 2017 to 2022, with alpha level set at $p < 0.05$.

The replacement of what are seen as culturally important items like pork with lesser valuable ones is a necessary yet negative strategy as discussed by interviewees. According to respondents, the observed dietary changes are not just explained by preferences or environmental stressors, but by the domestic economic situation, the deacceleration in tourism visits due to the pandemic, financial volatility, and by the lack of access to foodstuffs in general. In fact, a reduction in alimentary imports and mounting economic deficit produced by low export levels [88] may account for the diminished consumption of dairy products such as powdered milk, deserts, and milk-based puddings, and store-bought foods such as sugary drinks, cookies, and sweets as shown in the survey. It is important to observe that respondents compared the special period to present days, with current conditions being described as a bit worse than in the past ("estamos más apretados", we are more pressed). Despite difficulties, some rural households were still able to maintain a traditional "Cuban" diet including pork two or three days of the week. Such a finding is not necessarily surprising given the relatively low variation in foodstuffs that characterize this cuisine and the high level of internalization that certain ingredients have in culinary practices. On a positive note, the continuation of the traditional rural cuisine that is to a large extent homogeneous across the Cuban provinces provides mechanisms to implement nutritional programs in a cost-effective and uniform way [89]. On the other hand, the persistence of this traditional "Cuban" diet may suggest the thesis that this constitutes a population with high levels of consumption of sugars and carbohydrates when animal protein availability decreases. Without government support and protection of key foodstuffs like milk in rationing programs, the country may place below recommended standards for dairy or micronutrient ingestion. Continuous research is needed to evaluate this hypothesis and the role of what is known as the "Cuban" cuisine in undermining new government-led strategies that seek to introduce alternative dishes and preparations.

Overall, we observe that current strategies, the set of deliberate actions seeking to maintain the family unit during times of stress, vary according to access to land, foreign currency, collective work, participation in cooperative groups, and partaking in state-funded ration systems beyond la libreta. Most actions are centered around securing the necessary resources to meet household needs and comprise the substitution and replacement of culturally valuable items by more economical ones. Some of these changes result in the consumption of foods of lower nutritional value but may also underscore the use of less preferable yet protein-rich items such as viscera or fish. The search for better prices for subsistence items dominates most of the daily chores at the household level, with values for produce and animal products much lower in the countryside or in rural areas. A significant amount of time and energy is invested in attaining what are perceived as dietary needs, with exchanges of information and partnerships acquiring strategic importance. The ability to trade and barter has become essential, which explains the more recent opening of an agricultural market in La Picadora. Strategies, however, are not just reduced to dietary adjustments, food procurement activities, or additional cultivation of new varieties. In these two clusters, they also involve issues related to improving living conditions such as housing and access to basic items of necessity like hygiene products, fuel, and reliable transportation to and from working sites or in maintaining agricultural labor at valuable production outputs. The latter constitutes a significant impediment that is scarcely considered in current nutritional initiatives in this region that emphasize sustainability above the reality of energetic demands.

4. Discussion

The article presents a detailed exploration of rural diets among two clusters of residents (farmers and fishers) in two communities of Yaguajay, Sancti Spíritus, Cuba. It is important to indicate that the external validity of the results discussed below is constrained by the small sample sizes that characterize the project. Yet, findings provide valuable insights to be further explored. In short, analysis of interviews, focus groups, surveys, and additional historical sources may indicate that rural communities in this region, and to some extent in central Cuba, have undergone two different transitions in the adoption of agroecological practices. The first period comprised sugar monocrop intensification and state centralization (1970s to early 1990s), while the second transition began in the 1990s with decentralization and diversification of agricultural practices. As a result of these changes and a forbidding economic blockade, households have suffered different instances of nutritional vulnerability. To improve conditions, the Cuban state has responded through numerous policies that have fostered industrial degrowth in the sugar sector and have scaffolded the expansion of an organic agricultural and ranching system through education and rural development. Yet, it is in the nature of self-constituted cooperatives, small-holder state support, and social reciprocity that coping and adaptation strategies are to be found. As suggested by cultural studies of food and dietary practices, familiarity with how local actors may access, produce, and exchange food stuffs can provide essential knowledge on the inner workings of societies, creating avenues for intervention [90]. Most importantly, within the Cuban context, such information can help elicit limitations or shortcomings in state-driven agroecological policies. As many insular Caribbean countries are engaging with climate-resilient development frameworks, rural coping strategies adopted in Cuba can also shed light on the need to adopt precautionary or mitigating measures that can increase the success of proposed adaptations [91]. To that end, in this section, we analyze the diversity of tactics or strategies adopted and what they mean in terms of reforming a traditional agricultural production system into a sustainable sector.

Beginning as early as the 1600s, sugar cultivation has constituted one of the most important economic undertakings in Yaguajay. Also known as a livestock-producing region, sugar monocrops came to dominate all agricultural activities after the revolution, with long-standing influences on dietary habits and culinary practices. Whereas conditions were highly satisfactory in the 1980s according to interviews, political and economic crises largely compromised households' sufficiency in the 1990s. The triumph of the revolution in attaining better living conditions, including major housing and health programs for all Cubans, was tested for the first time by widespread shortages. Memories of the challenges and strategies that households adopted in the early 1990s remain very much present among interviewees. For example, some of the actions discussed included the careful planning and reallocation of resources to meet essential needs, the prioritization of vulnerable population sectors, meal reduction, skipping collective work practices, and information sharing. The economic crisis led the government to the adoption of agroecological solutions, with some recoveries observed towards the end of the twentieth century.

After sugar mills and other industrial centers were discontinued in the early 2000s, the population of Yaguajay began to feel additional economic pressures that led to the reintroduction of small-scale diversified agriculture, house gardens, ranching and livestock practices, and tourism. Changes in production in the mid-2000s and 2010s had additional consequences for dietary habits, with increases in the use of green leafy vegetables, seasonal crops, and fish in comparison to traditional cuisine. These modifications are shown in the first 2017 survey. More recent instabilities brought in by hydrological drought, extreme events, the Coronavirus pandemic, and the war have also led to significant alterations in consumption patterns, with decreases in the use of pork and the introduction of dietary substitutions.

In all, nutritional oscillations in the past four decades speak of the challenges faced by rural households. Most importantly, dietary changes paint a picture of how processes of agroecological transitions rely heavily on individual ingenuity and flexibility to achieve success. The abilities of small actors, such as household heads, work groups, and cooperative leaders, to adjust or to innovate under uncertain conditions are in this specific case supporting and accommodating major transformations. To some extent, the Cuban state has been able to recognize the significance of empowering these smaller actors through educational policies and extension activities. However, state support has not been enough to buffer some of the costs associated with agroecological models that may require substantial changes in the productive sector. In conjunction with economic and financial barriers that limit options, high levels of precarity have compounded perceptions of insecurity among rural homes as interviews elucidate.

As an illustration of the increasing importance of individual actors, the type of strategies adopted during the special period and more recently suggest the progressive involvement of household members in income-generating activities independent from state employment. The ability to juggle between different sources of money allows some households to improve the likelihood of meeting their needs; however, it is subjected to both external and internal factors beyond their control. In the first case, macroeconomic conditions and state policies can create very unstable configurations that have difficult access to food. For example, the reduced variety of imports in the context of rationing, with fixed schedules and distribution stores, results paradoxically in unpredictable timing and locations for the supply of eclectic items. In the municipality of Yaguajay, we observed during the weekend, long queues at gas station stores not just to buy gas but also to purchase chicken or a handful of other products such as beer or diapers. While items trickle down through the distribution chain like a broken faucet, as some respondents voiced, the ability to prepare a full meal depends on long-distance travel and money. Referenced by Moon et al., economic pressures critically shape access as well as consumption patterns in La Picadora [53]. Despite individual or cultural preferences and continuous efforts at procuring a "decent meal", farmers eat what is available, indicating that subjective appreciations are subordinate to concrete productive realities. And even when agricultural production may dictate what is available, other needs may cause households to forfeit consumption of desirable items to address more pressing needs related to economic contraction and isolation from the world market. Thus, in a municipality that has been devoted to agricultural and livestock production for at least five centuries, some of the common shortages include pork meat, eggs, butter, oil, and flour along with locally grown items such as boniato.

In addition to identified strategies, findings regarding the persistence of the Cuban cuisine mirror what other researchers have discovered elsewhere on the island [11,13,51]. The rationing system, which provides citizens with subsidized foods according to what is available at the time, has helped in the long run to homogenize cuisines, ultimately weakening local food production systems with a higher variety [51,53]. This is captured in our interviews and conversations with household members from La Picadora describing the need to consume non-traditional products such as fish croquettes, instead of chicharrones and roasted pork, as a negative experience. It also signals an interesting byproduct of the special period, where culinary preferences and local cultural identities associated with food reemerged after two decades of revolutionary policies that sought the standardization of alimentary practices [78].

As discussed among respondents, the decline in dietary diversity that is experienced now is probably felt more keenly in urban centers where agricultural cultivation is limited in its capacity (urban gardens are reduced to 0.25 hectares per person) to offset scarcity. Despite repeated efforts by the Cuban government to implement nutritional substitution policies and liberalize non-commercial imports of foods and medication [49,92,93], in early August 2022, it was estimated that close to 80% of the food consumed on the island was imported [94]. This ranks Cuba as the second largest importer behind Panama, a position of high vulnerability to price fluctuations and disruptions in logistics and transport [54]. Recent analyses have suggested that shortages and high prices are the result of a stale underdeveloped food production system that cannot provide for all [95]. The current loss of revenues associated with weakened tourism due to the pandemic restriction also underscores important limitations in the Cuban industrial system and provides a glimpse of the structural crisis permeating agricultural production [95]. The concentrated focus on service industries and construction to the detriment of agriculture and manufacturing capacities—between 2017 and 2021, state investment in agriculture was a mere 2.8% while hotel and real estate received 50% of the budget—has contributed to both food insecurity and scarcity [96]. Most importantly, it has aggravated the energetic crisis that has affected mechanized labor in the municipality. With frequent blackouts and interruptions in the flow of electricity that last between 6 to 8 h per day, farmers have increasingly relied on animal traction for agricultural labor. In this same light, many have observed a worrisome inflation trend throughout Latin America, and especially in Cuba, that endangers nutritional health among lower-income households [97]. The slow recovery perceived in labor markets and the economic degrowth experienced due to the Coronavirus pandemic interact with food insecurity to create the conditions for migration [55]. Compounded with this situation is an aging population that has very limited access to foreign capital [46,74] and must rely on manual labor to meet essential needs.

As this exploratory case study seeks to illustrate, comprehensive mixed methods assessments of dietary strategies are key tools to elicit the local realities of agroecological transitions. Experiences of food consumption and production, oscillations in food sufficiency, and nutritional vulnerability among rural households are clear examples of how challenges in adopting sustainable transformation models may evolve over time in a process of fits and starts. It is important that climate-resilient development programs take into account the dynamic nature in which adaptation decisions are made, and how many of these coping strategies are not only a result of perturbations but are the foundation in which transformational change happens [98–100]. Unpacking the decisions made at the smallest scale of production, comprehending the trade-offs and limitations that the most vulnerable experience in the struggle to make a worthy living on a damaged planet, is an essential task in designing an inclusive future [91].

5. Conclusions

Distinguishing between periods of abundance and shortage, our findings show two counterpoints: a wider variety of dietary options available during intensive sugar monocrop cultivation and the scarcity experienced during the early 1990s, and more recently, during the last period of the pandemic, which has resulted in nutritional and activity adjustments. Constrained by the small sample sizes that characterize this project, findings present an initial picture that must guide research in the region. They underscore the need to expand future work. In all, comprehensive assessments of dietary strategies are key to eliciting what agroecological transitions mean for local realities and the value of experiences of food consumption and production to better understand the limits to sustainable transformation models.

Author Contributions: Conceptualization, V.C.R., V.V.S. and D.J.H.; methodology, V.C.R. and V.V.S.; formal analysis, V.V.S. and D.V.M.; investigation, V.C.R., V.V.S., D.V.M., D.Y.B.E. and A.R.R.; resources, V.C.R. and V.V.S.; writing—original draft preparation, V.C.R.; writing—review and editing, V.C.R., V.V.S., D.V.M., A.R.R., D.Y.B.E. and D.J.H.; visualization, V.C.R.; supervision, V.C.R., V.V.S. and D.J.H.; project administration, V.C.R. and V.V.S.; funding acquisition, V.C.R. and D.J.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially funded by Rutgers University Global Programs, Gaia Global Grant, Project Number 301431, including data collection and APC.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and following Universidad de La Habana's ethical and research approval processes.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy concerns.

Acknowledgments: We want to thank community leaders from La Picadora and Caguanes National Park for their support in conducting the research.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Domínguez González, A.Z.; Torres Martínez, M.; Puerta de Armas, Y.G. *Experiencias En La Protección de La Biodiversidad y El Desarrollo Sostenible En La Provincia de Sancti Spíritus*; Ministerio de Ciencia, Tecnología y MedioAmbiente: La Habana, Cuba, 2012; ISBN 978-959-287-033-8.
2. Nova González, A. *El Modelo Agrícola y los Lineamientos de la Política Económica y Social en Cuba*; Nuevo Milenio: Batangas, Philippines, 2020; ISBN 978-959-06-1948-9.

3. Ramenzoni, V.C. Co-Governance, Transregional Maritime Conventions, and Indigenous Customary Practices Among Subsistence Fishermen in Ende, Indonesia. *Front. Mar. Sci.* **2021**, *8*, 1011. [CrossRef]
4. Rudel, T.K. Cuba: Agro-Ecological Farming After the Soviet Collapse. In *Shocks, States, and Sustainability*; Oxford University Press: Oxford, UK, 2019; pp. 91–112, ISBN 978-0-19-092101-9.
5. Franco, M.; Bilal, U.; Orduñez, P.; Benet, M.; Morejón, A.; Caballero, B.; Kennelly, J.F.; Cooper, R.S. Population-Wide Weight Loss and Regain in Relation to Diabetes Burden and Cardiovascular Mortality in Cuba 1980–2010: Repeated Cross Sectional Surveys and Ecological Comparison of Secular Trends. *BMJ* **2013**, *346*, f1515. [CrossRef] [PubMed]
6. López Gonzalez, M.E.L. A 30 Años del Periodo Especial en Cuba y las Enseñanzas de la Historia-Intervención y Coyuntura. 2020. Available online: https://www.cubaperiodistas.cu/2020/08/a-30-anos-del-inicio-del-periodo-especial-en-cuba-y-las-ensenanzas-de-la-historia-iii/ (accessed on 18 April 2023).
7. Álvarez, A.G.; Cruz, B.A. El Modelo Agropecuario y Su Vínculo Con El Acceso a Los Alimentos: La Experiencia Cubana (1959–2019). *Int. J. Cuban Stud.* **2020**, *12*, 76–96. [CrossRef]
8. Nayeri, K. *Book Review: Sustainable Agriculture and Resistance: Transforming Food Production in Cuba Fernando Funes, Luis García, Martin Bourque, Nilda Pérez, and Peter Rosset*; Food First Books: Oakland, CA, USA, 2002; p. 307.
9. Franco, M.; Orduñez, P.; Caballero, B.; Tapia Granados, J.A.; Lazo, M.; Bernal, J.L.; Guallar, E.; Cooper, R.S. Impact of Energy Intake, Physical Activity, and Population-Wide Weight Loss on Cardiovascular Disease and Diabetes Mortality in Cuba, 1980–2005. *Am. J. Epidemiol.* **2007**, *166*, 1374–1380. [CrossRef] [PubMed]
10. Cruz, B.A. Acceso a Los Alimentos En Cuba: Prioridad, Dificultades y Reservas Para Mejorar. *Econ. Desarro.* **2020**, *164*.
11. Escalante Lara, Z.B. *La Economía Doméstica Cubana Frente al Período Especial: Estrategias Económicas y Diversificación Ocupacional Frente a la Crisis*; Tesis de Licenciatura; Faculta de Filosofía y Letras, Universidad Autónoma de México: Coyoacán, México, 2006.
12. Juárez, N.H. Cambios en la producción y consumo de viandas en Cuba. *Rev. D'ethnoécol.* **2013**, *3*, 1–27. [CrossRef]
13. Mulet Pascual, M. Alimentación y Análisis Nutricional En La Habana Bajo El Prisma de La Etnocontabilidad: El Caso Comparativo de Las Familias Vázquez y López. *Cah. Am. Lat.* **2017**, *84*, 125–146. [CrossRef]
14. Palomino, M.L.; Ambrós, Z.A.; Amable, O.G.; Fuentes, A.J.M. Estado de los conocimientos y comportamientos sobre alimentación de las personas atendidas en un consultorio del Programa del Médico de Familia. *Rev. Cuba. Aliment. Nutr.* **2018**, *28*, 463–471.
15. Porrata-Maury, C. Consumo y Preferencias Alimentarias de La Población Cubana Con 15 y Más Años de Edad. *Rev. Cuba Aliment. Nutr.* **2009**, *19*, 87–105.
16. Vázquez Sánchez, V.; Rangel Rivero, A.R.; Alcolea, S.P.; Rodríguez, Y.A.D.; Ramenzoni, V. Estado nutricional y composición corporal de campesinos y pescadores ocasionales del municipio Yaguajay, Sancti Spíritus, Cuba. *Nutr. Clín. Diet. Hosp.* **2018**, *38*, 134–139.
17. Núñez González, N.; González Noriega, E. Algunas transformaciones en las comidas tradicionales de la población rural cubana. *Rev. Cuba Aliment. Nutr.* **2001**, *15*, 139–145.
18. Ellen, R.F. *Modern Crises and Traditional Strategies: Local Ecological Knowledge in Island Southeast Asia*; Berghahn Books: Oxford, UK, 2007; ISBN 978-1-84545-312-1.
19. Comas, G.; Poy, S. Capacidades de subsistencia y estrategias económicas de los hogares durante etapas de expansión y crisis. Una mirada dinámica de la pobreza. *Entramados Perspect.* **2020**, *10*, 35–63.
20. Selby, H.A.; Murphy, A.D.; Lorenzen, S.A.; Cabrera, I.; Castañeda, A.; Selby, H.A. (Eds.) *La Familia en el México Urbano: Mecanismos de Defensa Frente a la Crisis (1978–1992)*; Consejo Nacional para la Cultura y las Artes: México City, México, 1994; ISBN 978-968-29-6020-8.
21. Gomiero, T. Organic Agriculture: Impact on the Environment and Food Quality. In *Environmental Impact of Agro-Food Industry and Food Consumption*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 31–58, ISBN 978-0-12-821363-6.
22. Sijpestijn, G.F.; Wezel, A.; Chriki, S. Can Agroecology Help in Meeting Our 2050 Protein Requirements? *Livest. Sci.* **2022**, *256*, 104822. [CrossRef]
23. FAO. *Emissions Due to Agriculture. Global, Regional and Country Trends 2000–2018*; Food and Agriculture Organization: Rome, Italy, 2021.
24. USDA. Climate Change. Available online: https://www.ers.usda.gov/topics/natural-resources-environment/climate-change/ (accessed on 18 April 2023).
25. Firbank, L.G. Commentary: Pathways to Global Sustainable Agriculture. *Int. J. Agric. Sustain.* **2012**, *10*, 1–4. [CrossRef]
26. Gomiero, T.; Pimentel, D.; Paoletti, M.G. Is There a Need for a More Sustainable Agriculture? *Crit. Rev. Plant Sci.* **2011**, *30*, 6–23. [CrossRef]
27. Goh, K.M. Greater Mitigation of Climate Change by Organic than Conventional Agriculture: A Review. *Biol. Agric. Hortic.* **2011**, *27*, 205–229. [CrossRef]
28. Gomiero, T.; Pimentel, D.; Paoletti, M.G. Environmental Impact of Different Agricultural Management Practices: Conventional vs. Organic Agriculture. *Crit. Rev. Plant Sci.* **2011**, *30*, 95–124. [CrossRef]
29. Scialabba, N.E.-H.; Müller-Lindenlauf, M. Organic Agriculture and Climate Change. *Renew. Agric. Food Syst.* **2010**, *25*, 158–169. [CrossRef]
30. Lorenz, K.; Lal, R. Environmental Impact of Organic Agriculture. In *Advances in Agronomy*; Elsevier: Amsterdam, The Netherlands, 2016; Volume 139, pp. 99–152, ISBN 978-0-12-804773-6.

31. Verdi, L.; Marta, A.D.; Falconi, F.; Orlandini, S.; Mancini, M. Comparison between Organic and Conventional Farming Systems Using Life Cycle Assessment (LCA): A Case Study with an Ancient Wheat Variety. *Eur. J. Agron.* **2022**, *141*, 126638. [CrossRef]
32. Crowder, D.W.; Reganold, J.P. Financial Competitiveness of Organic Agriculture on a Global Scale. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 7611–7616. [CrossRef]
33. Meemken, E.-M.; Qaim, M. Organic Agriculture, Food Security, and the Environment. *Annu. Rev. Resour. Econ.* **2018**, *10*, 39–63. [CrossRef]
34. Acevedo-Suárez, J.; Gómez Acosta, M.I.; Joy, T.; Pérez, B. Agricultura Urbana y Periurbana En Cuba. In *Agricultura Urbana Integral: Ornamental y Alimentaria. Una Visión Global e Internaciona*; Editorial Agrícola Española S.A.: Madrid, Spain, 2014; pp. 323–339, ISBN 978-84-92928-36-1.
35. Altieri, M.A.; Funes Monzote, R. The Paradox of Cuban Agriculture. *Mon. Rev.* 2012. Available online: https://monthlyreview.org/author/fernandorfunesmonzote/ (accessed on 18 April 2023).
36. Cabello, J.J.; Garcia, D.; Sagastume, A.; Priego, R.; Hens, L.; Vandecasteele, C. An Approach to Sustainable Development: The Case of Cuba. *Environ. Dev. Sustain.* **2012**, *14*, 573–591. [CrossRef]
37. Moon, K.R.; Ward, J.R.; Rodriguez, J.V.; Foyo, J. La Picadora: A Case Study in Cuban Agroecotourism. *Int. J. Cuban Stud.* **2021**, *13*, 8–42. [CrossRef]
38. Anonymous. Draft. Proyecto de plan estratégico para Cuba (2021–2024) 2020. World Food Programme. 2020. Junta Ejecutiva, Roma, Italia. Available online: https://docs.wfp.org/api/documents/WFP-0000117572/download/ (accessed on 18 April 2023).
39. Luna, M.V.; Alfonso, A.C. El Derecho Alimentario en Cuba. *Rev. Cuba. Aliment. Nutr.* **2008**, *18*, 84–93.
40. Fernandez, M.; Williams, J.; Figueroa, G.; Graddy-Lovelace, G.; Machado, M.; Vazquez, L.; Perez, N.; Casimiro, L.; Romero, G.; Funes-Aguilar, F. New Opportunities, New Challenges: Harnessing Cuba's Advances in Agroecology and Sustainable Agriculture in the Context of Changing Relations with the United States. *Elem. Sci. Anthr.* **2018**, *6*, 76. [CrossRef]
41. Saunders, A.; Luukkanen, J. Sustainable Development in Cuba Assessed with Sustainability Window and Doughnut Economy Approaches. *Int. J. Sustain. Dev. World Ecol.* **2022**, *29*, 176–186. [CrossRef]
42. de los, A. Arias Guevara, M. Cuba: Reforma y transformación agraria. La crisis de los noventa y el proceso de desestatalización de la agricultura. *Rev. IDeAS* **2009**, *3*, 6–29.
43. Joseph, T.W.R.; Joseph, L.C.R. La cuestión agraria cubana aciertos y desaciertos en el período de 1975-2013: La necesidad de una tercera reforma agraria. *Polis Rev. Latinoam.* **2017**, *16*, 107–135.
44. Nelson, E.; Scott, S.; Cukier, J.; Galán, Á.L. Institutionalizing Agroecology: Successes and Challenges in Cuba. *Agric. Hum. Values* **2009**, *26*, 233–243. [CrossRef]
45. Rosset, P.M.; Machín Sosa, B.; Roque Jaime, A.M.; Ávila Lozano, D.R. The Campesino-to-Campesino Agroecology Movement of ANAP in Cuba: Social Process Methodology in the Construction of Sustainable Peasant Agriculture and Food Sovereignty. *J. Peasant. Stud.* **2011**, *38*, 161–191. [CrossRef]
46. Funes Monzote, R. *Farming Like We're Here to Stay: The Mixed Farming Alternative for Cuba*; Wageningen Universiteit: Wageningen, The Netherlands, 2008.
47. Nova González, A.; González-Corzo, M.A. Cuba's Agricultural Transformations. *J. Agric. Stud.* **2015**, *3*, 175. [CrossRef]
48. Nova González, A. *La Agricultura en Cuba: Transformaciones, Resultados, y Retos*; Association for the Study of the Cuban Economy: Havana, Cuba, 2018.
49. Rodríguez, A. El agro Cubano aún no se Recupera Pese a Reformas Económicas. Available online: https://apnews.com/article/noticias-af655f3a3b09c02e17c83096b8038fda (accessed on 24 September 2022).
50. Borràs Escayola, M.; Fernández, L.; Suárez-Hernández, J. Evaluation of Socioecological Resilience in Six Farms of the Sancti Spiritus Province, Cuba. *Pastos Forrajes* **2021**, *44*, 1–11.
51. Garth, H. Alimentary Dignity: Defining a Decent Meal in Post-Soviet Cuban Household Cooking. *J. Lat. Am. Caribb. Anthropol.* **2019**, *24*, 424–442. [CrossRef]
52. Machado, M.R.; Fernandez, M. Orion Magazine—This Cuban Town Has a Sustainability Lesson to Share. Available online: https://orionmagazine.org/article/cuba-la-picadora-agroecology-sustainability/ (accessed on 24 September 2022).
53. Moon, K.R.; Ward, J.R.; Rodriguez, J.V.; Foyo, J. Food Access, Identity, and Taste in Two Rural Cuban Communities. *Gastronomica* **2022**, *22*, 66–78. [CrossRef]
54. CEPAL, U. *Balance Preliminar de las Economías de América Latina y el Caribe 2022*; Comisión Económica para América Latina y el Caribe (CEPAL), Naciones Unidas: Santiago, Chile, 2022; p. 177.
55. Augustin, E.; Robles, F. *'Cuba Is Depopulating': Largest Exodus Yet Threatens Country's Future*; The New York Times Company: New York, NY, USA, 2022.
56. Nodarse Venancio, M.U.S. *Cuba Relations: The Old, the New and What Should Come Next*; WOLA: Warsaw, Poland, 2022.
57. Ramenzoni, V.C.; Besonen, M.R.; Yoskowitz, D.; Sánchez, V.V.; Rangel Rivero, A.; González-Díaz, P.; Méndez, A.F.; Escuela, D.B.; Ramos, I.H.; López, N.V.H.; et al. Transnational Research for Coastal Wetlands Conservation in a Cuba—US Setting. *Glob. Sustain.* **2020**, *3*, e19. [CrossRef]
58. López Castañeda, L.; Vázquez-Rodríguez, J.; Ramenzoni, V.; Yoskowitz, D.; Rangel Rivero, A.; González-Díaz, P.; Vázquez-Sánchez, V.; Delgado-Pérez, A.; Borroto, D. Cambios Ambientales Percibidos Por Pescadores Artesanales Residentes En Yaguajay, Sancti Spíritus, Cuba. In *Pescadores en México y Cuba: Retos y Oportunidades Ante el Cambio Climático*; Urrea Mariño, U., Alcalá, G., Eds.; Instituto Politecnico Nacional, Unas Letras Industria Editorial: Merida, Spain, 2020.

59. Ramenzoni, V.C.; Borroto Escuela, D.; Rangel Rivero, A.; González-Díaz, P.; Vázquez Sánchez, V.; López-Castañeda, L.; Falcón Méndez, A.; Hernández Ramos, I.; Valentín Hernández López, N.; Besonen, M.R.; et al. Vulnerability of Fishery-Based Livelihoods to Extreme Events: Local Perceptions of Damages from Hurricane Irma and Tropical Storm Alberto in Yaguajay, Central Cuba. *Coast. Manag.* **2020**, *48*, 354–377. [CrossRef]
60. Vázquez Sánchez, V.; Rangel Rivero, A. (Eds.) *La Picadora: People and Nature in a Rural Cuban Community*; Montané Anthropological Museum, Fernando Ortiz Foundation, University of Havana: Havana, Cuba, 2018; ISBN 978-959-7249-09-2.
61. Ramenzoni, V.C.; López Castañeda, L.; Vázquez, J.; Vázquez Sánchez, V.; Rangel Rivero, A.; González Díaz, P. Pesquerías Artesanales En Cuba. Breve Recorrido de Su Evolución, Características, y Posibles Desafíos Futuros. In *América Profunda. Visiones y Convergencias en la Oceanografía Social del Continente*; Narchi, N.E., Beitl, C.M., Eds.; El Colegio de Michoacán: Michoacán, México, 2022; pp. 117–137, ISBN 978-607-544-166-5.
62. Vázquez Sánchez, V.; Rangel Rivero, A.; Peña Alcolea, S.; Díaz Fuentes, Y.A.; Ramenzoni, V. Hábitos alimentarios de un grupo de pescadores ocasionales del municipio Yaguajay, Sancti Spíritus, cuba: Un enfoque ecológico. *Rev. Investig. Mar.* **2018**, *38*, 130–138.
63. Borroto-Escuela, D.Y.; Ramos, I.H.; Méndez, A.F.; Sánchez, V.V.; Rivero, A.R.; Ramenzoni, V.C.; López-Castañeda, L.; González-Díaz, P.; Besonen, M.; Yoskowitz, D.W. Educación Ambiental Con Pescadores de Yaguajay Desde La Perspectiva Del Manejo Integrado de Zonas Costeras. *Rev. Investig. Mar.* **2021**, *41*, 158–170.
64. Vázquez Sánchez, V.; Rangel Rivero, A.; Peña Alcolea, S.; Díaz Rodríguez, Y.A.; Ramenzoni, V.C.; Ojeda Martínez, D.A. Estilos de Vida de Campesinos y Pescadores Ocasionales Residentes En Yaguajay, Sancti Spíritus, Cuba. *Rev. Argent. Antropol. Biol.* **2020**, *22*, 017. [CrossRef]
65. Weir, C.B.; Jan, A. BMI Classification Percentile and Cut Off Points. In *StatPearls*; StatPearls Publishing: Treasure Island, FL, USA, 2023.
66. Noda, M.F.; Aleaga, Z.G.; Hernández, M.C.R.; Rodríguez, L.E.M.; Braojos, I.M.P.; Varela, I.S.; del Pozo, Z.V.; Díaz, R.R. Índice de masa corporal y características clinicopatológicas de pacientes con cáncer de mama. *Rev. Cuba Endocrinol.* **2016**, *27*, 45–62.
67. Ramírez, I.S. Del Funche al Ajiaco: La Dieta Que Los Amos Imponen a Los Esclavos Africanos En Cuba y La Asimilación Que Éstos Hacen de La Cocina Criolla. *An. Mus. Am.* **2009**, *16*, 127–154.
68. Núñez González, N.; González Noriega, E. Antecedentes etnohistóricos de la alimentación tradicional en Cuba. *Rev. Cuba. Aliment. Nutr.* **1999**, *13*, 145–150.
69. Boffill Vega, S.; Calcines Díaz, C.M.; Sánchez Cid, A. Modelo De Gestión Para Contribuir Al Desarrollo Local, Basado En El Conocimiento Y La Innovación En Cuba. *Ing. Ind.* **2009**, *30*.
70. de la, C. Zorio González, E.; Massip, A.M. Las redes de innovación agrícola. Una vía para el desarrollo productivo y sostenible en Cuba. *Agrisost* **2019**, *25*, 1–8.
71. Morales Rodríguez, G. La zafra del turismo. Cuba Profunda. 2015. Available online: https://cubaprofunda.wordpress.com/2015/08/05/la-zafra-del-turismo/ (accessed on 18 April 2023).
72. Morales Rodríguez, G. Centrales en tiempo muerto. Cuba Profunda. 2015. Available online: https://cubaprofunda.wordpress.com/2015/07/29/centrales-en-tiempo-muerto/ (accessed on 18 April 2023).
73. Holgado Fernández, I. *Encuentro*; Heinemann Educational Books: Portsmouth, NH, USA, 1998; pp. 221–228.
74. Funes Monzote, R. *Sustainable Agriculture and Resistance: Transforming Food Production in Cuba*; Food First Books: Oakland, CA, USA, 2002.
75. Pérez, R. La Ganadería Cubana En Transición. *Catauro Rev. Cuba Antropol.* **2012**, *13*, 30–44.
76. Álvarez Sarduy, J. El proceso de redimensionamiento de la agroindustria azucarera cubana y su impacto en las cooperativas cañeras. Master's Thesis, Universidad de La Habana, Habana, Cuba, 2005.
77. Spagnolo, L.; Munevar, D. Inequidad salarial en Cuba durante el Período Especial. *Am. Lat. Hoy* **2008**, 48. [CrossRef]
78. Bobes, V.C. Las Mujeres Cubanas Ante El Periodo Especial: Ajustes y Cambios. *Debate Fem.* **2001**, *23*, 67–96.
79. Garth, H. *Food in Cuba: The Pursuit of a Decent Meal*; Stanford University Press: Redwood City, CA, USA, 2020.
80. Pérez Izquierdo, V. Impacto Del Período Especial En La Vida Cotidiana de La Mujer Cubana, En La Década de Los Años 90. In Proceedings of the Mujeres Contra el Bloqueo, Havana, Cuba, 21 March 2002.
81. Martínez Massip, A. Innovar Redes de Difusión de Innovación para la Productividad Agropecuaria del Municipio Camajuaní. Ph.D. Dissertation, Departamento de Sociología, Universidad de La Habana, Habana, Cuba, 2018.
82. Boffill, S.; Suárez, J.; Reyes, R.M.; Luna, C.; Prado, D.; Calcines, C. Programa Integral Para La Producción de Alimentos En El Contexto Del Desarrollo Local: La Experiencia Del Municipio Yaguajay, Cuba. *Pastos Forrajes* **2009**, *32*, 1.
83. Anonymous. En Yaguajay Hoy No se Puede Comer Pescado Fresco del Mar. Available online: https://www.cibercuba.com/noticias/2019-05-13-u196554-e42839-s27061-yaguajay-hoy-no-puede-comer-pescado-fresco-mar (accessed on 28 September 2022).
84. Anonymous. Incumplen Plan de Captura de Pescado en Embalses de Sancti Spíritus. Available online: https://www.cibercuba.com/noticias/2022-11-24-u1-e199370-s27061-incumplen-plan-captura-pescado-embalses-sancti-spiritus (accessed on 28 December 2022).
85. Anonymous. Piden Esfuerzos a Ganaderos Tuneros Para Suplir Déficit de Leche en Polvo. Available online: https://www.cibercuba.com/noticias/2022-01-07-u1-e43231-s27061-piden-esfuerzos-ganaderos-tuneros-suplir-deficit-leche-polvo (accessed on 9 September 2022).
86. Alcolado, P.M.; Arellano, D. Lecciones Aprendidas En La Implementación Del Manejo Integrado Costero: Las Experiencias Demostrativas Del Ecosistema Sabana-Camagüey, Cuba. *Rev. Comun. Cient. Técnol.* **2016**, *1*, 1–7.

87. Cutié Cancino, V.; Lapinel Pedroso, B. *La Sequía En Cuba, Un Texto de Referencia; Monografía Proyecto 1/0P-15/GEF*; Instituto de Meteorología, Centro del Clima, Centros Meteorológicos Provinciales: Sancti Spíritus, Cuba, 2013; ISBN 978-959-300-053-6.
88. Anonymous. Cuba Es El País Más Dependiente de Las Importaciones de Alimentos, Después de Panamá. Available online: https://embed.tumblr.com/widgets/share/button?notes=right&locale=es_ES&canonicalUrl=http%3A%2F%2Ftumblr.com%2Fwidgets%2Fshare%2Ftool%3FcanonicalUrl%3Dhttps%3A%2F%2Fwww.14ymedio.com%2Feconomia%2FCuba-dependiente-importaciones-alimentos-Panama_0_3438256147.html& (accessed on 30 December 2022).
89. Porrata-Maury, C.; Hernández-Triana, M.; Abuin, A.; Huergo, C.C.; Pianesi, M. Caracterización y evaluación nutricional de las dietas macrobióticas Ma-Pi. *Rev. Cubana Investig. Bioméd.* **2008**, *27*. Available online: http://scielo.sld.cu/scielo.php?script=sci_arttext&pid=S0864-03002008000300000 (accessed on 18 April 2023).
90. Contreras Hernández, J.; Gracia Arnaiz, M. *Alimentación y cultura: Perspectivas antropológicas*; Ariel España: Madrid, Spain, 2005; ISBN 978-84-344-2223-0.
91. Pörtner, H.-O.; Roberts, D.; Tignor, M.; Poloczanska, E.S.; Mintenbeck, K.; Alegría, A.; Craig, M.; Langsdorf, S.; Löschke, S.; Möller, V.; et al. *Climate Change 2022: Impacts, Adaptation and Vulnerability Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2022.
92. Anonymous. Importación de alimentos a Cuba. *Cubatrámite 2023.* Available online: https://www.cubatramite.com/importacion-de-alimentos-a-cuba/ (accessed on 18 April 2023).
93. Delgado, D. El Gobierno Cubano Presenta Un Plan de Soberanía Alimentaria | Protección Del Medio Ambiente. Available online: https://www.greentechcuba.com/es/el-gobierno-cubano-presenta-un-plan-de-soberania-alimentaria (accessed on 30 December 2022).
94. EFE, R. Cuba Flexibiliza la Importación de Alimentos con Fines no Comerciales. Available online: http://quepasamedia.com/noticias/vida-y-estilo/bolsillo/cuba-flexibiliza-la-importacion-de-alimentos-con-fines-no-comerciales/ (accessed on 30 December 2022).
95. de Miranda Parrondo, M. Cuba: Entre los Vaivenes de una Política Económica Fallida y los Problemas Irresueltos. Available online: https://jovencuba.com/vaivenes-politica-economica-fallida/ (accessed on 30 December 2022).
96. de Miranda Parrondo, M. La Crisis Estructural de La Industria No Azucarera En Cuba. *La Joven Cuba.* **2022**. Available online: https://jovencuba.com/crisis-estructural-industria/ (accessed on 18 April 2023).
97. Capote, R.A. Perspectivas para la Economía de América Latina y el Caribe en 2023 y Crecerán-Cuba en Resumen. 2022. Available online: https://cubaenresumen.org/2022/12/28/perspectivas-para-la-economia-de-america-latina-y-el-caribe-en-2023-y-creceran/ (accessed on 18 April 2023).
98. Balvanera, P.; Calderón-Contreras, R.; Castro, A.J.; Felipe-Lucia, M.R.; Geijzendorffer, I.R.; Jacobs, S.; Martín-López, B.; Arbieu, U.; Speranza, C.I.; Locatelli, B.; et al. Interconnected Place-Based Social–Ecological Research Can Inform Global Sustainability. *Curr. Opin. Environ. Sustain.* **2017**, *29*, 1–7. [CrossRef]
99. Fazey, I.; Moug, P.; Allen, S.; Beckmann, K.; Blackwood, D.; Bonaventura, M.; Burnett, K.; Danson, M.; Falconer, R.; Gagnon, A.S.; et al. Transformation in a Changing Climate: A Research Agenda. *Clim. Dev.* **2017**, *10*, 197–217. [CrossRef]
100. Sharpe, B.; Hodgson, A.; Leicester, G.; Lyon, A.; Fazey, I. Three Horizons: A Pathways Practice for Transformation. *Ecol. Soc.* **2016**, *21*, 47. [CrossRef]

MDPI AG
Grosspeteranlage 5
4052 Basel
Switzerland
Tel.: +41 61 683 77 34

Sustainability Editorial Office
E-mail: sustainability@mdpi.com
www.mdpi.com/journal/sustainability

MDPI

Academic Open
Access Publishing

mdpi.com

ISBN 978-3-7258-3966-7