

Special Issue Reprint

Sustainability in the Global Dairy Sector

Challenges and Opportunities

Edited by
Rajeev Bhat

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Sustainability in the Global Dairy Sector: Challenges and Opportunities

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Guest Editor

Rajeev Bhat



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Guest Editor

Rajeev Bhat

Food Science & Technology,

The Institute of Veterinary Medicine &

Animal Sciences

Estonian University of Life Sciences

Tartu

Estonia

Editorial Office

MDPI AG

Grosspeteranlage 5

4052 Basel, Switzerland

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About the Editor

Rajeev Bhat

Rajeev Bhat is a Professor of Food Science at the Institute of Veterinary Medicine & Animal Sciences, Estonian University of Life Sciences. He is an outstanding academic and researcher with more than two decades (25 years) of experience in agri-food technology, with an expertise in '*Sustainable Food Production*' and '*Food Security*.' To date, he has authored more than 250 research articles published in ISI-WOS-based journals and as refereed book chapters; has edited 13 books and authored 1 book; is on the editorial board of multiple leading international journals; and has been a scientific committee/advisory board member and an invited keynote speaker at various international conferences and symposiums. Over the past five years, Bhat has been ranked among the world's top 2% of scientists in the field of Food Science & Technology (as reported by Stanford University). He has served as an expert in 'Meat Alternatives' under the EASAC Biosciences of the European Academies Science Advisory Council (EASAC), and presently he provides expertise as an appointed member of the 'Guideline Development Group' (Traditional Food Markets) of the World Health Organization (WHO/UN). Prof. Bhat has been a visiting professor at many recognized universities and is a recipient of several prestigious international awards/recognitions conferred by various institutions of higher learning and research establishments.

Preface

The global dairy sector plays a dynamic role in maintaining rural livelihoods, safeguarding food security, and supporting overall socioeconomic development. As the demand for dairy products continues to rise alongside the global population and changing dietary preferences, this sector faces unprecedented sustainability challenges. These may arise from environmental pressures such as greenhouse gas emissions, extensive water usage, and land abuse/degradation, or from socioeconomic concerns, including animal welfare, fair labor practices, and community well-being. In today's world, sustainability in the dairy sector is no longer an option, but rather has become a necessity. A holistic approach that balances productivity with environmental stewardship, economic viability, and overall social responsibility is therefore vital. This entails adopting innovative technologies, improving resource efficiency, enhancing animal health and welfare, and promoting equitable practices across the entire dairy value chain.

The future of the global dairy sector is poised for a dynamic transformation, influenced by various challenges and opportunities. With the rapid expansion of the global population and urbanization, the demand for dairy products will undoubtedly increase; however, the pathways to meeting this demand may vary significantly across regions. Globally, the dairy sector must evolve through collaborative efforts promoting sustainability and resilience. Fostering collaboration between farmers, the research community, policymakers, and consumers, the global dairy sector can evolve to meet the needs of present and future generations. Bridging the gap between low-, middle-, and high-income countries via knowledge transfer, capacity building, and fair trade can foster an equitable and robust dairy industry. Adopting climate-smart practices, circular economy models, and digital technologies can contribute to nutrition and maintaining livelihoods.

This Special Issue aims to provide a comprehensive overview of various sustainable practices, emerging trends, and policy frameworks that can guide stakeholders towards a more resilient and responsible dairy industry. It is anticipated that this SI will inspire meaningful actions and encourage ongoing dialogs to advance sustainability in the global dairy sector. Also, this second edition of this Special Issue ("Sustainability in the Global Dairy Sector: Challenges and Opportunities") follows on from the first successful installment, "Dairy Sector: Opportunities and Sustainability Challenges." As the Special Issue editor, I sincerely thank the Editor-in-Chief, the handling editors, the members of the MDPI publishing team (particularly the *Sustainability* journal staff), my institute director at the University (Toomas Tiirats), and to all the contributing authors.

Rajeev Bhat
Guest Editor

The Path to Sustainable Dairy Industry: Addressing Challenges and Embracing Opportunities

Rajeev Bhat ^{1,*} and Federico Infascelli ²

¹ Chair in Food Science and Technology, The Institute of Veterinary Medicine and Animal Sciences, Estonian University of Life Sciences, Kreutzwaldi 56/5, 51006 Tartu, Estonia

² Department of Veterinary Medicine and Animal Production, University of Naples Federico II, 80100 Napoli, Italy; infascel@unina.it

* Correspondence: rajeev.bhat@emu.ee

Precipitous transition has been documented in the global dairy sector in the past few years with a range of challenges. Opting for a justifiable state of the art-based research approach has become critical. There are numerous repetitive sustainability challenges witnessed across the entire dairy production and supply chain that have put intense pressure on the system. This, in turn, has precipitated the need to develop and implement innovative technological solutions, such as innovative cost-effective processing and preservation technologies, prediction models, life cycle analysis, artificial intelligence, IoT, digitalization, and much more. These innovations must benefit and meet the demands of the consumers, producers, and dairy industry stakeholders.

The global dairy industry is under aggregated pressure to address sustainability challenges, and there is an urgent need for innovation, regulatory action, and meeting consumer demand for more sustainable practices. Some of the challenges faced by the dairy industry that have impacted the environment, the economy and the society, and the feasible solutions offered include the following: (i) Greenhouse gas emissions (GHG) or methane emissions from dairy cows during digestion (enteric fermentation) and the decomposition of manure that releases methane and nitrous oxide, contributing to climate change. One solution could be the use of advanced feed additives and breeding for lower methane-emitting cattle, which could have an impact on reducing the climate impacts. (ii) Water use: Being water-intensive, significant amounts of water are required for both animal hydration and crop irrigation (for feed). In regions facing water scarcity, this can impose pressure on local water resources. Hence, efficient water management practices are vital. Innovative technologies focusing on efficient water use, including rainwater harvesting and wastewater treatments could significantly reduce the pressure imposed on local water sources. (iii) Land use and deforestation: Excessive land requirements for grazing and growing animal feed can contribute to deforestation wherein the conversion of natural ecosystems to agricultural land can deplete biodiversity and contribute to carbon emissions through soil disturbance and vegetation loss. In addition, monoculture farming for animal feed can deplete soil health and biodiversity. Moreover, there are widespread concerns that overgrazing and extensive land use to accommodate dairy production can disintegrate natural habitats. In addressing these issues related to land health and biodiversity, rotational grazing, regenerative farming, and agroforestry are potentially viable solutions. (iv) Animal Welfare: The intensity of some dairy operations can lead to poor animal welfare, such as inadequate access to pasture and physical stress from the milking process. Of late, there has been increased pressure from regulatory bodies to

improve the conditions where dairy cows are maintained. (v) Pollution issues: Dairy farms produce enormous volumes of waste via wastewater, manure, and packaging materials. Deprived of proper management, this waste can pollute nearby water resources, as well as the land and the air. In the majority of countries worldwide, one of the major concerns comes from the nitrate contamination of groundwater from excessive fertilizer/manure usage. In addition, most of the dairy products are sold in plastic or non-biodegradable multilayer packaging that, unless properly recycled, contributes to plastic pollution. Hence, pollution reduction, improved recycling, and transition to more sustainable materials are required. (vi) Energy consumption: Dairy farms often rely on energy-intensive processes (e.g., milking, refrigeration, transportation) that increase the carbon footprint, and this needs to be addressed through the adoption of appropriate, cost-effective technologies. (vii) Climate resilience: Dairy farms are highly vulnerable to the impact of climate change and extreme weather events (e.g., droughts, floods, heat waves) that can affect animal health, feed production, and water availability. Hence, understanding climate resilience in the dairy industry with respect to the capacity of dairy farms and supply chains and preparing for, or responding to the challenges posed by climate change are issues of high importance. The global dairy industry must develop strategies that not only minimize negative effects but also help farmers adapt to the new realities of a changing climate. (viii) Sustainable nutrition: Nutritional sustainability is focused on ensuring that dairy production delivers essential nutrients for human health while addressing socioeconomic and environmental impacts. Today, there is a developing market trend, and consumers are shifting towards using plant-based alternatives. Alternative proteins, or the rise of plant-based and lab-grown dairy alternatives, can offer more sustainable options to consumers.

- (i) With this as the background, this second Special Issue (SI) “Sustainability in the Global Dairy Sector: Challenges and Opportunities” (https://www.mdpi.com/journal/sustainability/special_issues/Dairy_Opportunities_Sustainability_II, accessed on 13 April 2025) follows on from the successful issue “Dairy Sector: Opportunities and Sustainability Challenges” (https://www.mdpi.com/journal/sustainability/special_issues/Dairy_Opportunities_Sustainability accessed on 12 April 2025).
- (ii) The focus of this second SI was on identifying sustainability challenges and future opportunities in the global dairy sector. A Web of Science search with keywords such as “innovative technologies in the dairy industry”, “sustainable production”, “valorization strategies”, “circular bioeconomy”, “climate change”, “carbon footprint functional products”, “blockchain technology”, “IoT”, “digitalization and supply chain management”, “regulatory and safety issues”, “food security”, “education”, and “energy crisis” were considered. This SI comprises original articles and reviews focusing on various issues about the dairy sector.
- (iii) Two interesting reviews have been published. The first one focuses on the One Health approach for improved sustainability in dairy farming (Noble Method®) and highlights the nutritional properties of dairy products, improving animal welfare, human health, and environmental sustainability. The second review systematically covers the sustainable management and valorization of agri-food wastes/by-products and the opportunities to develop animal feed/feed supplements (for ruminants, non-ruminants, and poultry feed). In addition, this review covers safety and regulatory aspects. Regarding the research articles, we received very intriguing research reports covering much of this diverse field. The articles published were on the sustainable utilization of hemp press cake flour in ice cream production; the influence of psychological factors on dairy farmers’ intentions to adopt environmental sustainability practices; the optimization of ultrasonic-assisted extraction of antioxidants in apple

pomace, using RSM to develop a potential feed supplement or feed ingredient; digital technology; factor allocation and the environmental efficiency of dairy farms; predicting raw milk prices based on in-depth time-series features for consumer behaviour analysis; Tasmanian dairy farmers' attitudes towards using e-extension methods; strengthening the dairy extension system for a sustainable dairy industry; the influence of functional feed supplements on milk production efficiency; feed utilization, blood metabolites, and health of Holstein cows during mid-lactation; and qualitative study on Irish dairy farmers' values with respect to sustainable grass-based production practices using the concept of "good farming".

Moreover, the global dairy system displays great diversity, ranging from subsistence farms, where small numbers of low-yielding animals address the household's basic needs, to large-scale, market-oriented farms with large numbers of high-yielding animals. Regardless of the production model, several concerns have been raised with respect to the dairy sector: (i) the aging demographics among dairy producers, with relatively few young farmers and a notable gender imbalance; (ii) high degree of specialization, where farm revenues are reliant on a single output, increasing producers' vulnerability to income fluctuations; or, on the contrary, the lack of resources in small-scale farms, which heightens their exposure to adverse market conditions; (iii) environmental concerns, including improper manure disposal or the excessive utilization of fertilizers for forage production; (iv) the impact of climate change: high temperatures and humidity negatively affect animal welfare, milk yield, and milk fat content, particularly in pasture-based systems, whereas housed cattle may benefit from technologies designed to mitigate heat; (v) unfair trading practices, with the dairy farmers being in a weak position in the food supply chain compared to the large operators in the chain, making them more susceptible to market fluctuations; (vi) conflicting demands by consumers, who seek high environmental standards and animal welfare standards, and market interests, which prioritize affordability; and (vii) growing interest in plant-based milk substitutes [1].

Therefore, both the ecological and the economic sustainability of dairy systems present a complex and multifaceted challenge that encompasses significant issues across different scales, regions, and management practices that require integrated proposals, concerted efforts, and original solutions [2].

Due to the world population growth, the demand for dairy products has progressively increased, yet this growth needs to be achieved sustainably in order to guarantee productive supply chains with minimal environmental impact. The identification of the most sustainable production model, whether intensive or extensive, remains challenging as each system exhibits distinct benefits and detriments. While some research attributes a better environmental performance to low-input systems, others associate highly intensive systems with a lower environmental impact. In general, the improvements in production efficiency have been associated with a reduced environmental impact per kilogram of milk due to the dilution of the environmental cost associated with an individual animal over a larger output. Additionally, high-yielding cows usually receive low-fiber rations, which results in lower methane emissions per kilogram of milk. However, increased productivity also heightens other environmental pressures, including greater demand for feed, energy, and water production. Furthermore, the use of highly productive breeds can positively affect the environmental efficiency of milk production when assessing the impact per unit of milk produced.

The intensive genetic selection has resulted in the reduced longevity of the animals, leading to a reduction in the number of lactation cycles despite an increase in productivity. This, in turn, increases the speed at which heifers are replaced, which inevitably entails

higher costs for the farmer and extends periods of unproductivity, as well as contributing to greenhouse gas emissions and manure production, further intensifying the environmental and economic burden of dairy farming. Conversely, grazing systems typically rely on local or more resilient breeds, which are better adapted to diverse environmental conditions. The rational use of pastures, through the nutritional assessment and the careful selection of suitable breeds, can support high production efficiency while maintaining superior product quality [3]. It is also important to point out that with the use of permanent pastures, characterized by natural grasses, which are particularly present in marginal areas, zootechnical activities ensure the safeguarding of territories facing abandonment and enable access to food of animal origin with a high nutritive value in marginal areas. In addition, the emissions associated with the production of animal feed represent a significant contributor to the environmental impact of dairy ruminants, largely due to the widespread reliance on concentrated feedstuffs such as soybeans. Conversely, the use of locally available resources or agricultural by-products can positively affect the impact generated by the dairy supply chain, as in other animal production systems. Feeding management has been identified as one of the most effective strategies for reducing CH₄ and NH₃ emissions [4]. A promising approach for mitigating the environmental footprint of the dairy sector involves the replacement of concentrate feed with by-products. Several studies have demonstrated that the incorporation of by-products into dairy cattle diets does not compromise milk production, feed intake, or diet digestibility, while it has been associated with a reduction of methane emission. This effect is attributed to the higher content of plant secondary compounds, such as tannins and isoflavones, which are able to reduce rumen methanogenesis. In addition, the inclusion of such phenolic compounds in animal diets enriches the milk with antioxidant molecules, thereby providing additional health benefits. In addition, the common agricultural policy (CAP) provisions producers' organisations to use bargaining options to stabilize price, thus facilitating increase in farm milk prices and overcome price fluctuation [5].

In conclusion, some of the additional key considerations for ensuring a sustainable dairy sector includes:

- An efficient and transparent traceability system has become essential due to the rising incidence of adulteration and toxic substances. A robust traceability system ensures compliance with ethical standards that promote consumer trust and strengthen collaboration among related stakeholders. Furthermore, it enhances the efficiency of dairy operations, yielding economic benefits while enabling the comprehensive tracking and monitoring of production processes. By optimizing the resource utilization and reducing waste, such a system supports the principal objectives of sustainable development by promoting reliability and constant advancements [6].
- The milk matrix and the chemical and physical interactions among its components play a crucial role in determining the storage stability, safety, sensory attributes, and health properties of dairy products. A more holistic approach is required that considers the impact of macro-, micro-, and nano-structural elements within food, as opposed to a reductionist perspective that limits nutrition to the analysis of individual nutrients. In this context, there are huge opportunities for further research on the relationship between the structure and function of foods. Such advancements will reinforce the benefits of dairy consumption and support the development of new dairy products and food formulations incorporating dairy ingredients. Beyond nutrition and health considerations, those new foods will need to align with consumers' expectations regarding taste, convenience, affordability, and ethical values, including sustainable production practices and their broader implications. In this regard, the development of

- foods with a lower environmental footprint will represent an opportunity rather than a necessity [7]. Furthermore, the customization of dietary solutions for individuals across different stages of life and with distinct lifestyle preferences is intricately linked to food structuring. For instance, probiotics emerge as a promising avenue for dairy product innovation given their capacity to modulate the microbiome by reducing potentially harmful bacterial species while promoting the growth of beneficial ones, particularly in the context of the microbiome-mediated effects of diet on health.
- Although technological advancements and digitalization offer significant potential benefits for the dairy industry, there are still several challenges to be addressed to completely harness these opportunities. These comprise issues related to digital infrastructure and connectivity, the high cost of implementing new technologies, the demand for skilled workforce, and the need for greater collaboration among supply chain stakeholders.
 - Consumer preferences and willingness to pay for sustainable dairy products are driving global market demand, thereby shaping industry practices and influencing sustainability outcomes within the dairy sector. Understanding consumer attitudes toward sustainability, environmental responsibility, and ethical sourcing is vital for dairy producers, retailers, and policymakers seeking to meet consumer expectations and attract value in competitive markets. By aligning the development of products, marketing strategies, and supply chain practices with consumer values and preferences, the dairy industry can enhance both economic and ecological sustainability while effectively responding to the evolving needs of global consumers [8].
 - Policy frameworks and institutional planning play a vital role in supporting the transition towards sustainable dairy systems by providing guidelines and promoting sustainable practices, thus generating positive socioeconomic and environmental impacts.

Nevertheless, challenges related to food security and sustainable food production in the entire agri-food sector are envisaged to remain elevated; hence, recognizing their importance and embracing the revolution along the entire supply chain via modern-day innovative production technologies, information technologies (ICTs), and digitalization are vital, especially in the rural and semi-urban set-up [9].

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Review

Sustainability Assessment Tools for Dairy Supply Chains: A Typology

Rita Paçarada ^{1,*}, Stefan Hörtenhuber ¹, Torsten Hemme ², Maria Wurzinger ¹ and Werner Zollitsch ¹

¹ Department of Sustainable Agricultural Systems, Institute of Livestock Sciences, University of Natural Resources and Life Sciences, 1180 Vienna, Austria; stefan.hoertenhuber@boku.ac.at (S.H.); maria.wurzinger@boku.ac.at (M.W.); werner.zollitsch@boku.ac.at (W.Z.)

² International Farm Comparison Network—IFCN, 24118 Kiel, Germany; torsten.hemme@ifcdairy.org

* Correspondence: rita.pacarada@boku.ac.at

Abstract: The dairy sector faces increasing pressure to adopt sustainable practices. Various tools have been developed to evaluate sustainability of the dairy supply chain. This paper provides an overview of these tools, highlighting their strengths and limitations regarding sustainability dimensions, indicators, and system boundaries. A systematic literature search identified 27 tools that were then categorized into a typology based on dimensions of sustainability, geographical applicability, and accessibility. In-depth analysis was conducted on six tools: Sustainability Assessment of Food and Agriculture (SAFA), Sustainability Monitoring and Assessment RouTine (SMART), Response-Inducing Sustainability Evaluation (RISE) 3.0 version, Swiss Agricultural Life Cycle Assessment (SALCAsustain), MOnitoring Tool for Integrated Farm Sustainability (MOTIFS), and Technology Impact and Policy Impact CALculations (TIPICAL). Assessment focused on the relevance of covered sustainability dimensions to the dairy sector, level of supply chain coverage, type of indicators, accessibility, and practicability. The review identified tools which integrate multiple sustainability aspects in a comprehensive way (SAFA and SMART) and tools offering accurate quantification of the impact on sustainability dimensions of the production system (SALCAsustain, RISE, MOTIFS, TIPICAL). Only two tools extend assessment past the farm gate (SAFA, SMART). Future users should select tools based on the specific objectives of measuring sustainability in dairy systems. This review contributes to the literature by addressing various aspects of sustainability assessment tools, by addressing the need for an integrated and comprehensive view, and by considering the entire dairy supply chain.

Keywords: dairy sector; sustainability dimensions; sustainability indicators; comprehensiveness; sustainability evaluation; sustainability themes

1. Introduction

In recent decades, many frameworks and tools have been developed to measure, evaluate, and improve agricultural production practices [1–3], yet variations in definitions and components still exist due to diverse disciplines, political viewpoints, and values [1]. Addressing this contextual challenge involves establishing an understanding of the notion of sustainability and a universally recognized benchmark of what sustainable food production comprises [1]. Historically, the notion of sustainability has integrated environmental, social, and economic aspects, known as the “triple bottom line” of sustainability [4] or the three-pillar conception [5]. Governance was formally established as the fourth pillar by the United Nations Commission on Sustainable Development [6].

While the concept of sustainability has been long recognized, it has only begun to be actively discussed in the dairy sector since 2011, with many sustainability-related initiatives being implemented [7]. Assessing sustainability is a complex process, as the dairy sector involves a range of stakeholders, from farmers to consumers, and impacts

multiple sustainability dimensions [3]. Actors from different societal groups, including the food industry, contribute to the transformation of food systems towards environmental friendliness, economic feasibility, and the provision of access to affordable food [8]. The dairy sector is facing major challenges in adopting sustainable practices and providing responsibly produced food [9–11]. External societal pressure and internal company pressure have driven components of dairy supply chains worldwide to start various initiatives and pledges to sustainability. Consumers also prioritize sustainability when selecting dairy products [12]. Taking this into account, retailers and large dairy processors are becoming the main initiators of implementing sustainability programs [13].

Globally, greenhouse gas emissions from the dairy sector increased by 18% between the years 2005 to 2015 [14]. Dairy production has also been strongly linked to acidification, eutrophication, the monotony of landscapes, and low biodiversity [10,11,15,16]. This generic statement is in line with findings on dairy production's impact on individual categories [9–11,16]. This has led to the majority of sustainability assessment studies focusing on environmental issues and process efficiency [7], which in turn has led to an emphasis on the environmental dimension of sustainability assessment tools [17,18].

For a comprehensive supply chain assessment, the added dimension of governance is important [19]. Dairy farming is regulated at the national as well as international level, giving importance to the governance dimension when it comes to examining sustainability within the dairy context [17]. This particular dimension should garner attention to sustainability assessment due to the unfairness exhibited in terms of dairy farmers and their relation to the entire supply chain [19] and the demand in production and delivery transparency from consumers [20]. Equally important, economic sustainability focuses both on natural and economic capital, and ensures its sustainable use [17].

Sustainability assessment tools utilized for different food systems are often criticized for inadequately addressing the social sustainability dimension [21], while the economy and environment dimensions are commonly included [3,18,22–24]. This is partly because, in this context, social concepts are not sufficiently comprehensive and specified, let alone measured [25,26]. SAFA guidelines provide an integrated framework for assessing sustainability [1], through detailed consideration of all four dimensions as mentioned before. Therefore, industry stakeholders and major dairy producers need to establish frameworks in order to develop sustainability practices that take the focus beyond the environmental aspects.

Over the years, a vast array of methods, tools, and frameworks has emerged by which to assess sustainability at the levels of individual farms, farming systems, or supply chains [2]. Simultaneously, these tools have undergone review in terms of relevance, applicability, and ease of implementation. Scientists have systematically compared and categorized these tools through different schemes, as shown in Table 1. Díaz De Otálora et al. [3] identified the tool's level of integration of three main sustainability pillars. This was also undertaken by Schader et al. [2], who explained the distinct perspective on sustainability and classified tools according to their scope and precision. Many of these integrated three pillars of sustainability [5]. Gasparatos and Scolobig categorized sustainability assessment tools into three main types: monetary tools, biophysical tools, and indicator tools [27]. Others have assessed tools based on their definition and their operationalization of specific sustainability dimensions, such as the social dimension [24]. Their applicability in certain regions was also analyzed and categorized [28], along with their normative systemic and procedural dimensions [23], object and temporal focus [22], scientific soundness, utility, and applicability [29], as well as the methodology, data, time, and budgetary constraints they imposed [30].

Table 1. Literature background. Previous reviews with a focus on sustainability assessment tools and their limitations.

Publications	Focus	Methodology	Limitations
Schader et al. [2]	Sustainability assessment tools	Compared and categorized tools by scope, precision, relevance, applicability, and ease of implementation.	(a) No dairy sector-specific focus. (b) Not addressing sustainability in the context of dairy. (c) Evaluation of tool effectiveness for dairy
Díaz De Otálora et al. [3]	Sustainability assessment tools	Identified the integration level of three main sustainability pillars in tools applied to the dairy sector.	(a) No wider range of tools considered. (b) Lack of dairy-specific sub-themes of sustainability. (c) Three pillar sustainability dimensions.
Ness et al. [22]	Sustainability assessment tools	Assessed tools based on their object and temporal focus.	(a) No dairy sector-specific focus. (b) Lack of dairy-specific indicators (c) Application to dairy sector challenges. (d) Evaluation of tool effectiveness for dairy
Binder et al. [23]	Sustainability assessment tools	Analyzed tools based on their normative, systemic, and procedural dimensions.	(a) No dairy sector-specific focus. (b) Lack of dairy-specific indicators. (c) Evaluation of tool effectiveness for dairy
Janker and Mann [24]	Sustainability assessment tools	Reviewed tools based on their definition and operationalization of social sustainability dimension.	(a) No dairy sector-specific focus. (b) Evaluation of tool effectiveness for dairy. (c) One dimension considered.
Gasparatos and Scolobig [27]	Sustainability assessment tools	Categorized sustainability assessment tools into three main types: monetary tools, biophysical tools, and indicator tools.	(a) No dairy sector-specific focus. (b) Not addressing sustainability in the context of dairy. (c) No practical implementation for dairy sector
Ndambi et al. [28]	Sustainability assessment tools	Analyzed and categorized tools that apply to the dairy sector based on their applicability in east Africa.	(a) Geographical limitation. (b) Limited discussion on social sustainability dimension. (c) Evaluation of tool effectiveness for dairy.
Byomkesh et al. [29]	Methods to assess agricultural sustainability	Evaluated tools based on the methodology, data requirements, time, and budgetary constraints they imposed.	(a) No dairy sector-specific focus. (b) Limited discussion on social sustainability dimension. (c) Lack of dairy-specific indicators.

Sustainability assessment is undertaken using qualitative and quantitative indicators, and a holistic and integrated approach [31] has been deemed successful for the sustainability assessment of agricultural systems [30]. In the context of the dairy sector, the majority of sustainability assessment studies have primarily focused on environmental issues and process efficiency [7], which has led to an emphasis on the ecological dimension of sustainability. Because overall sustainability of the dairy sector is an outcome of all four dimensions, our research utilizes the SAFA guidelines to evaluate selected dairy sustainability assessment tools and their coverage of the four dimensions. The motivation for this work was to offer a review that does not only investigate the thoroughness of the tools in terms of sustainability dimensions, but also investigates the way in which tools are suited for the dairy sector's specific challenges. While numerous reviews have focused on sustainability assessment tools for food systems, they have not systematically examined the sustainability aspects relevant to the dairy sector. Considering the scarcity in comprehensive tool coverage in the context of the dairy sector, this work contributes to the literature by addressing various aspects of sustainability and considering the entire dairy

supply chain. The tools are analyzed for thematic relevance to the dairy sector, supply chain coverage, comprehensiveness of sustainability dimensions, type of indicators, accessibility, and practicability.

The overall aim of this review is to offer guidance for actors along the dairy value chain who are beginning to engage in a comprehensive sustainability analysis on the choice of an accessible and appropriate tool by which to assess sustainability in the dairy supply chain. It also seeks to address the questions regarding what sustainability themes and sub-themes are covered in accessible dairy sustainability assessment tools and how different parts of the supply chain are accounted for in the assessment process, while also taking into consideration the type of indicators used.

2. Materials and Methods

2.1. Methodological Framework

Prior to conducting the search and analysis, a methodological framework was established based on the Preferred Reporting Items for Systematic Review and Meta-Analysis (Prisma) method [32]. This method provides a transparent, complete, and accurate account of the review's purpose, methodology, and findings [32].

A comprehensive search strategy was applied by focusing on terms such as “sustainability”, “assessment”, “analysis”, “method”, “tool”, “indicator”, “dairy sector”, and “dairy farm”, to capture a broad spectrum of tools relevant to the study objectives. Based on the research question, a search string was developed: (sustainability AND (assessment OR analysis*) AND (method OR tool) AND indicator AND (dairy sector OR dairy farm OR cow OR milk)). The search was conducted in the scientific databases Scopus and Web of Science. The latter yielded 135 results, while the former yielded 6525 results. Prior to full-text screening, duplicates (68 publications) were removed manually. The remaining entries (6592 publications) were selected for screening in ASReview [33]. ASReview, an AI tool from the University of Utrecht, supports literature reviews by sorting search results for relevance. Users upload search results with abstracts and identify relevant and irrelevant publications. The AI learns from these selections, continuously re-evaluating and prioritizing the list, iteratively presenting the next best options to the user. It was arbitrarily decided to stop the review after reaching 7.33% of the total number of papers (i.e., 483 publications). Due to this, 1.52% (i.e., 100 publications) of the total number were deemed irrelevant following the last relevant paper addressing the research question. Of 483 publications, 388 were excluded as they did not focus on sustainability assessment and did not consider any sustainability assessment tools, methodologies, or frameworks. This ensured that 95 potentially relevant publications were to be analyzed individually.

During the individual analysis of the 95 publications, 76 were excluded due to (1) not offering detailed information on the sustainability assessment tool, methodology, or framework; because they were (2) case-specific methodological applications; and (3) because the tool/methodology/framework could not be applied to the dairy sector. This yielded 19 relevant publications in total. Additionally, 8 relevant records were identified from websites following expert consultation, amounting to 27 total entries relevant to the study. Figure 1 shows a flow diagram of the research process.

Specific criteria were applied for manually selecting tools for in-depth analysis from the total of 27. These criteria included accessibility, coverage of at least three dimensions of sustainability, and utilization of indicator-based assessment methodologies. This process is further elaborated in the next section.

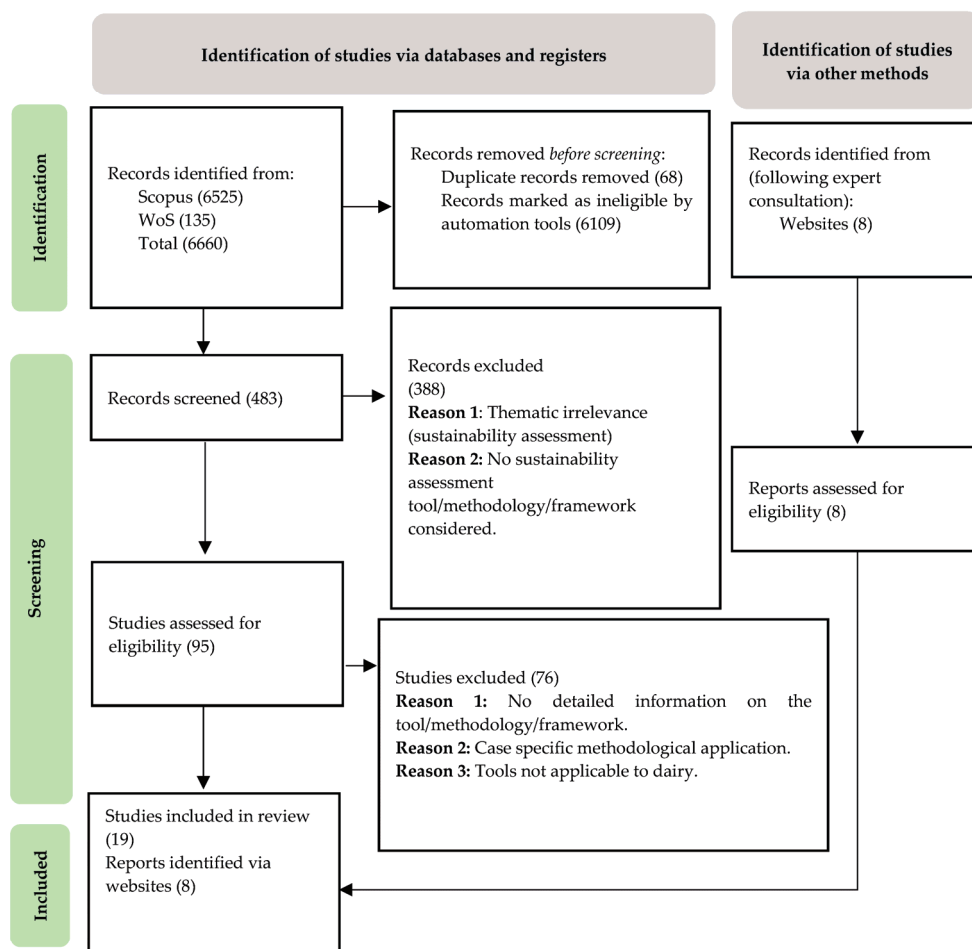


Figure 1. Research process flow. Authors own elaboration based on PRISMA2020 [32].

2.2. Development of Typology and Selection for In-Depth Analysis

Based on the works of Schader et al. [2], and by utilizing the selected tools, a typology was constructed to categorize the tools based on their sustainability dimensions, geographical applicability, and accessibility. Although the focus was on tools covering three dimensions of sustainability, tools with a strong dominance of environmental aspects were not excluded, for the sake of comparison. Geographical applicability indicates the intended geographical scope of the tools, while accessibility defines whether the tools were fully accessible for use or if information on the tools was retrieved from other sources.

Subsequently, six tools were selected for further analysis, guided by the predefined selection criteria: Sustainability Assessment of Food and Agriculture “SAFA Sustainability Monitoring” and Assessment RouTine (SMART), Response-Inducing Sustainability Evaluation (RISE) 3.0 version, Swiss Agricultural Life Cycle Assessment “SALCAsustain”, MOnitoring Tool for Integrated Farm Sustainability “MOTIFS”, and Technology Impact and Policy Impact CALculations “TIPICAL”. All six of these tools cover all three of the following sustainability dimensions: environmental integrity (EI), economic resilience (ES), and social wellbeing (SW), while SAFA and SMART also cover good governance (GG). The indicators of each sub-theme of sustainability used by each tool were counted and compared. Additionally, a critical discussion was conducted regarding whether the predefined sub-themes by SAFA guidelines [1] were addressed by the tools through the specifically tailored indicators. All six tools could be used in a wider geographic scope, and descriptions of their methodology and indicator type were available. Tools were then analyzed according to (1) sustainability dimensions covered, (2) level of supply chain coverage, and (3) type of indicators and accessibility. The level of supply chain coverage defines the extent to which the tools address different elements of the dairy supply chain,

from the production of raw materials to retail. A special section is dedicated to the type of indicators and accessibility criterion.

3. Results and Discussion

The results are presented and discussed in the following section. The typology, as the first part of the review, was applied to 27 tools in total (see Table 2). The second part includes the in-depth analysis of the six tools that were selected from the typology.

Table 2. Categorization of sustainability assessment tools that apply to dairy according to the set criteria.

Tool Name	Dimensions of Sustainability	Geographical Applicability	Accessibility	Reference
Caring dairy	EI, ER, SW	Transnational	-	[34]
COOL FARM	EI	Global	Accessible *	[35]
DAIRY SAT	EI	National	-	[15,36]
DairyGEM	EI	Global	Accessible *	[9]
Delta	EI, ER, SW	National	-	[37]
DSI	EI, ER, SW	Transnational	-	[38]
FARMIS	EI, ER	National	-	[39,40]
GAMEDE	EI, ER, SW	Global	-	[41]
IDEA	EI, ER, SW	National	Accessible *	[42,43]
IFSC	EI, ER, SW	National	-	[44]
INSPIA	EI, ER, SW	Transnational	-	[45]
MASFDD	EI, ER, SW	National	-	[46]
MODAM	EI, SW	National	-	[47,48]
MOnitoring Tool for Integrated Farm Sustainability MOTIFS	EI, ER, SW	Transnational	Accessible *	[49]
Public Goods Tool	EI, ER, SW	Transnational	-	[50]
Response-Inducing Sustainability Evaluation (RISE)	EI, ER, SW	Global	Accessible *	[51,52]
Sustainability Assessment of Food and Agriculture (SAFA)	GG, EI, ER, SW	Global	Free	[1]
Swiss Agricultural Life Cycle Assessment (SALCAustain)	EI, ER, SW	Transnational	Accessible *	[53,54]
SIMS Dairy	EI, ER, SW	Transnational	-	[55]
Sustainability Monitoring and Assessment RouTine (SMART)	GG, EI, ER, SW	Global	Accessible *	[56,57]
SSP	EI, ER, SW	Transnational	-	[58]
Technology Impact and Policy Impact CALculations (TIPICAL)	EI, ER, SW	Global	Accessible *	[28,59]
WLGP	EI, ER, SW	National	-	[60]
GLEAM	EI	Global	Free	[61]
SAI platform	EI, ER, SW	Global	-	[62]
SEEBalance	EI, ER, SW	Transnational	-	[63]
Dairy Sustainability Framework (DSF)	EI, ER, SW	Global	-	[64]

GG—good governance, EI—environmental integrity, ER—economic resilience, SW—social wellbeing. “-” represents tools where information was not available. “Free”—represents tools that were fully accessible without a fee. “Accessible *”—represents information of tools that was accessible through academic papers, while tools were accessible for a fee.

3.1. Categories and Characteristics of Tools

Tools were categorized from the perspective of the dairy sector rather than the sector for which they were primarily intended. Of all 27 tools (see Table 2), four covered only the

environmental dimensions (COOL FARM, DAIRY SAT, DairyGEM, and GLEAM). Two tools (SAFA and SMART) also covered good governance in addition to the three pillars of sustainability. Except for the six tools mentioned above, the other tools covered the environmental and social dimension. Overall, the selected tools can be categorized as (i) indicator-based assessment tools (IDEA, MOTIFS, RISE, SAFA, SMART, SALCAsustain, IFSC, DSI, Dairy Sustainability Framework-DSF, SPA, INSPIA, Caring dairy, SEEBalance, SSP, Public Goods Tool, and TIPICAL), (ii) dynamic models offering an impact-related and quantitative assessment (Delta, GAMEDE, SIMS Dairy, FARMIS, and WLGP) and (iii) life cycle assessment tools (COOL FARM, Dairy SAT, DairyGEM, and GLEAM). The latter tools extensively focused on the environmental dimension. Of the selected tools, two could not be assigned to any of the categories above: MODAM, an on-farm cost-calculating tool, which also considers the environmental and social dimensions, and FARMIS, which considers the environmental and the economic dimensions.

Concerning the geographical scope, nine tools can be applied globally (DairyGEM, COOL FARM, GAMEDE, GLEAM, RISE, SAI, SMART, TIPICAL and DSF), nine tools were intended for, and applied at, the national level so far (DAIRY SAT, DELTA, FARMIS, IFSC, IDEA, MASFDD, MODAM, Public Goods Tool, and WLGP) and eight tools were intended for transnational use (Caring dairy, DSI, INSPIA, MOTIFS, SALCAsustain, SIMS Dairy, SSP, and SEEBalance).

Of all 27 of the tools, two labeled as “Free” (Table 2) were fully accessible (SAFA, and GLEAM). The tools categorized as “Accessible *” were those for which the authors needed to be contacted or for which information could be retrieved from scientific articles. For most of the tools, information on their accessibility could not be found. Some tools among those selected for in-depth review were accessible through scientific papers or reviews, reports on tools instructions, or through the retrieval of information directly from the developers or people responsible for the tool’s maintenance and update. Some of the tools were created in recent years, while RISE, though created in 1999, has been updated continuously in terms of its thematic relevance and applicability.

Six tools were selected for further in-depth analysis, which covered at least three dimensions of sustainability, and which were accessible entirely or through information given in academic papers, with a wider geographical scope (regional or global). Selected tools (see Table 3) were further reviewed according to their (I) thematic relevance (sustainability dimensions/themes/sub-themes covered), (II) level of supply chain, and (III) input data type and accessibility.

Table 3. Assessment of tools: sustainability dimensions, level of supply chain, type and count of indicator, and accessibility.

	Environmental Integrity	Economic Resilience	Social Wellbeing	Good Governance	Upstream Activities	Farm	Processing	Retail	Qualitative Indicators	Quantitative Indicators	Semi-Quantitative Indicators	Accessibility
SAFA	✓	✓	✓	✓	✓	✓	✓	✓	76/116	16/116	24/116	✓
SMART	✓	✓	✓	✓	✓	✓	✓	✓	199/327	15/327	89/327	✓ *
RISE	✓	✓	-	✓	✓	✓	-	-	17/46	11/46	18/46	✓ *
SALCAsustain	✓	✓	✓	-	✓	✓	-	-	9/28	19/28	0/28	✓ *
MOTIFS	✓	✓	-	✓	-	✓	-	-	10/22	12/22	0/22	✓ *
TIPICAL	✓	✓	✓	-	✓	✓	-	-	0/10	10/10	0/10	✓ *

“✓”—applicable; “-”—not covered; “*” —tools that were accessible through contacting the authors/developers or through scientific (review) papers.

3.1.1. SAFA

The SAFA Tool (version 2.2. 40) is a freely accessible software. The tool has a wide scope and covers the entire dairy supply chain, including upstream and downstream impacts. It is a comprehensive tool for assessing sustainability and can be used free of charge by any assessor or relevant stakeholder [1]. The themes, sub-themes, and indicators provided in the SAFA guidelines serve as a basis for evaluating the integration of themes in other tools. SAFA allows for contextualization of the assessment, allowing the assessor to tailor the sub-themes and indicators to the entity being assessed [1], and provides 116 indicators in total.

3.1.2. SMART

SMART is a comprehensive sustainability assessment tool, based on SAFA guidelines, that has been successfully applied to various farming systems [2,57,65]. It consists of up to 327 indicators for farm applications in a custom-built database. Some of these indicators can also be used in different stages of the supply chain. SMART adjusts the SAFA dimensions, themes, sub-themes and objectives to the entity being assessed, selecting only relevant indicators. It is important to note that similar indicators are used several times within a sub-theme. The tool is not intended for the farmer as the end user, but rather as an assessment and advisory tool for the entire supply chain [56]. However, it is still applicable to the farm level as it accounts for the impact of farm activities on the upstream parts of the supply chain.

3.1.3. RISE

RISE is a farm advisory tool that uses an interview-based method to assess the sustainability performance of on-farm production across all three dimensions of sustainability [2,52]. It is intended for use by farmers and farm advisors and has been widely applied globally, including in the dairy sector [2]. RISE emphasizes indicators within the environmental dimension and generates a farm sustainability profile based on calculated parameters and scores derived from normalized data. The tool is useful for identifying areas of good vs. poor sustainability performance on a farm and offers 46 indicators in total, though its software does not offer free access.

3.1.4. SALCAsustain

The need for a comprehensive indicator-based sustainability assessment tool that incorporates more quantitative indicators motivated Roesch et al. [53,54] to develop SALCAsustain. This tool, although not exclusively created and used for the dairy sector, presents a feasible on-farm sustainability assessment tool that focuses on the transnational level. This model presents another comprehensive approach, which estimates the environmental, social, and economic impact of farms with the use of indicators. In addition to its use at farm level, SALCAsustain has also proven to be a robust method by which to assess product level, which presents as an important overall differentiation feature from other reviewed tools.

3.1.5. MOTIFS

MOTIFS stands for MOnitoring Tool for Integrated Farm Sustainability, and represents a comprehensive tool for sustainability assessment [49]. This model is also indicator based, with a focus on the environmental and social dimensions. Although its sector scope is wide, so far it has only been used to assess sustainability in Flemish dairy farms [2]. Important consultants and stakeholders have taken part in the development of the model, especially in regard to the social dimension. The tool offers a total of 22 indicators. The tool does not offer its own software but comprises a specifically created database.

3.1.6. TIPICAL

The Technology Impact Policy Impact CALculations (TIPICAL) model is a farm level tool that enables its user to analyze a farm's impact not only in the scope of the economic dimension, but also regarding social and environmental issues [66]. It has been designed specifically to offer a comprehensive sustainability assessment of the dairy sector. This is a key differentiation feature from other reviewed comprehensive assessment tools. TIPICAL is an excel sheet-based database and provides farm benchmarking, sensitivity analysis and forecast.

3.2. Thematic Coverage, Input Data Requirements and Accessibility

The quality of the tool is dependent on the tool's relevance regarding themes, sub-themes, and aspects of sustainability. This, among many other attributes, indicates the tool's future usage. Focus was placed on the number of indicators used and if they are designed to truly capture the main environmental and socio-economic issues for which the dairy sector has a high impact.

The SAFA guidelines present four key dimensions: good governance, environmental integrity, economic resilience, and social wellbeing. In this study, assessment was made regarding the number of indicators that the tools consist of in regards to the sub-themes listed in the SAFA guidelines. In good governance, the sub-themes include corporate ethics, accountability, participation, rule of law, and holistic management. Environmental integrity includes sub-themes such as atmosphere, water, land, biodiversity, materials and energy, and animal welfare. Economic resilience covers sub-themes like investment, vulnerability, product quality and information, and local economy. Lastly, social wellbeing comprises sub-themes such as decent livelihoods, fair trading practices, labor rights, equity, human health and safety, and cultural diversity. In Figure 2, the information provided in Table 2 is examined, specifically the dimensions of sustainability and the extent of coverage of the sub-themes. A hierarchical categorization is devised in Figure 2, with five distinct levels. Level (-) indicates the lack of indicators for the respective sub-theme, all the way to level (V) which denotes that more than 50 indicators address that theme in the respective tool. This shall provide an overview of whether certain sub-themes are addressed by the respective tool but does not depict whether the sub-themes are covered adequately, nor whether a certain tool should be considered as "the ideal tool".

Substantial gaps were witnessed for certain sub-themes of good governance and especially the social wellbeing and good governance dimensions in most tools. Environmental sub-themes were addressed by all tools, albeit rather differently. This variety between tools in terms of addressing the sustainability dimensions is also presented in Figure 3. This visual presentation offers a key to also understanding the level of detail of each tool and coverage of the dairy supply chain compared with one another.

Category levels range from "low" to "high" in terms of detail or indicator type (where high denotes that the tool consists of more quantitative indicators and low of more qualitative indicators) and thoroughness (sustainability aspects included). Supply chain coverage includes "farm", "upstream level", and "upstream and downstream". Upstream level consists of farm plus the input supply, while the downstream goes beyond the farm gate.

3.2.1. Good Governance

The SAFA tool covers good governance with a set of 19 indicators [1]. The designed indicators aim at measuring an enterprise's mission transparency, the responsible stakeholder's participation, continuous improvement of regulatory frameworks in the context of sustainability and more. In addition, having a sustainability management plan is considered to be the starting point of aligning with sustainability practices, in the context of good governance [1]. Indicators for this dimension can be applied across the entire supply chain but would need different measures included to be applicable to the farm.

-	no indicators							
I	up to 2							
II	up to 10							
III	up to 30							
IV	up to 50	SAFA	SMART	RISE	SALCA	sustain	MOTIFS	TIPICAL
V	>50							
Good Governance	Corporate ethics	I	IV	I	-	-	-	
	Accountability	I	V	-	-	-	-	
	Participation	II	IV	I	-	-	-	
	Rule of Law	II	IV	-	-	-	-	
	Holistic Management	I	III	I	-	-	-	
Environmental Integrity	Atmosphere	II	V	I	I	I	I	
	Water	II	V	II	II	I	I	
	Land	II	V	II	III	III	-	
	Biodiversity	III	V	III	III	III	-	
	Materials & Energy	III	V	II	I	III	I	
	Animal Welfare	II	V	II	-	III	I	
Economic Resilience	Investment	II	V	I	I	II	I	
	Vulnerability	II	V	II	II	II	II	
	Product Quality & Information	II	V	II	-	-	-	
	Local Economy	II	III	-	-	-	-	
Social Wellbeing	Decent livelihood	II	V	II	I	II	I	
	Landscape	II	IV	II	-	-	-	
	Fair Trading Practices	I	III	-	-	-	-	
	Labour Rights	II	V	-	-	-	-	
	Equity	II	III	-	-	-	-	
	Human safety and health	II	V	II	-	-	-	
	Cultural diversity	I	III	-	-	-	-	

Figure 2. Visual representation of the extent of thematic coverage in selected tools based on numbers of indicators.

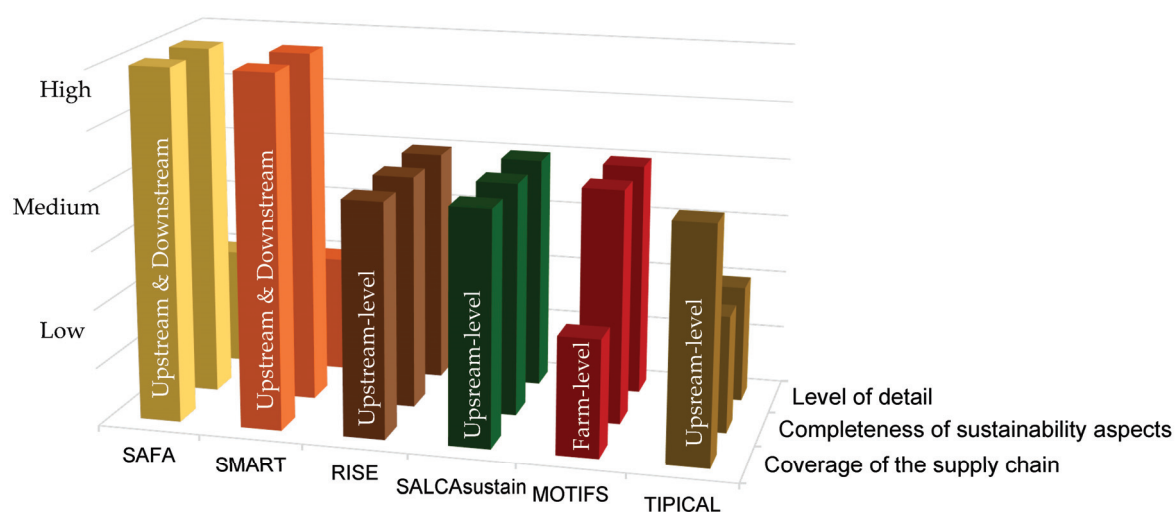


Figure 3. Comparison of tools in terms of level of detail, completeness of sustainability aspects, and coverage of the dairy supply chain.

Aspects of good governance, such as responsibility, transparency, and rule of law, stand for open-access reliable information for the public, social responsibility towards all stakeholders, and their protection, respectively [1]. In the context of the dairy sector this also refers to regulations on milk safety, traceability and transparency [20] throughout the whole dairy supply chain. These aspects are covered extensively in SAFA and SMART. RISE has indicators that could fit within the scope of transparency, in the form of available information about a farm and its financial situation. In RISE, there are also indicators that cover the impact of farm management on sustainability dimensions, namely the expected impact on economic, environmental, and social aspects. A dairy farmer's management strategies are assessed based on how they prioritize impacts on and off the farm in terms of sustainability standards. In dairy and other agriculture supply chains, good governance indicators also consider the rights of less engaged stakeholders. This is particularly important for dairy, as farmers need to be engaged and to ensure their participation as stakeholders within the supply chain in order to have bargaining power, which is also important for economic resilience. SMART also emphasizes a farmer's civic responsibility and their duty to engage with their local communities on social and environmental issues [56].

Corporate social responsibility (CSR) is a key determinant of competitive advantages in dairy supply chains [13] and is emphasized in both the SAFA and SMART tools through various indicators. Well-established CSR ensures efficient dairy production and quality of dairy products [13]. In an exclusive dairy sustainability assessment tool, the quality assurance aspect should garner special attention, not only to the scope of good governance but also in relation to the environment and the product. SMART and SAFA both employ indicators when measuring responsibility and transparency in the context of the farm and the farmer. SMART offers indicators that also account for farm inputs and their suppliers, like information on an input supplier's origin and traceability, how much of the input is externally sourced, and many more issues that are accounted for through a range of indicators. RISE, SAFA, and SMART also place importance on resilient relationships and conflict resolution aspects, giving these tools advantages in good governance assessment. SALCAsustain, and MOTIFS do not incorporate indicators that could pertain to the alignment of a farm's strategy and management with the mentioned good governance dimension principles and goals. TIPICAL does not offer indicators within the good governance scope.

3.2.2. Environmental Integrity

The environmental dimension is quite extensively accounted for in most of the tools, as seen in Table 2 and Figures 2 and 4. SAFA offers 52 indicators, which mostly offer semi-quantitative output. The sub-themes depict the major facets of impact of the dairy sector and can be easily employed to its context. In this respect, SMART can be used as an example. Schader et al. [56] have reported that, in SMART, a total of 654 indicators affects the environmental dimension in its entirety, as the same indicators are used several times throughout three dimensions due to synergy. When referring to dairy being linked to GHG emissions, it is important for these tools to be able to offer the appropriate indicators when identifying and measuring the main emission sources related to dairy, e.g., enteric methane. SMART does not contain this, while RISE and TIPICAL apply various parameters, including the estimation of methane emissions. In RISE, the environmental dimension can be considered as sufficiently covered and quantified. In fact, of all of the dimensions, this is the most comprehensively covered. This is due to RISE including a higher level of quantitative detailed indicators in the context of the dairy impact facets. This is also witnessed in MOTIFS, where 12 environmental indicators out of 21 cover the environmental impact.

Following the steps of Schader et al. [56] and the review of SMART indicators, RISE contains a total of 28 indicators that refer to the environmental dimension. SALCAsustain contains 42 indicators that address the overall dimension, while MOTIFS has 43 indicators. Other important sub-themes within the environmental dimension in SAFA address land, water, energy, material, and waste. In SAFA guidelines these themes refer to the resources

extracted from the environment and their use in the economic processes of the assessed entity [1]. A total of 132 indicators are assigned to the energy and material use sub-themes in SAFA. Due to the dairy chain being energy intensive, this sub-theme should be considered in a comprehensive sustainability assessment. Contrary to other tools, like RISE and SALCAsustain, which typically only included the non-renewable source-use measure, SAFA and MOTIFS also assess the target on renewable energy use as well as the established energy saving practices of the assessed entity. This is important due to renewable energy being essential in achieving sustainability goals in energy security, climate change and air pollution mitigation [67]. MOTIFS also highlights material use and efficiency of resource use. SMART employs about 62 indicators, which cover energy and material consumption, the latter referring to the flow of materials within and without the process being assessed [1]. The tool addresses all aspects relevant to this sub-theme, from the share of arable land devoted to different crops (each in separate indicators), to detailed information on organic or synthetic fertilizer use. Fertilizer use is part of the nutrient balance which falls into the materials and energy sub-theme in both SAFA and SMART. This indicator assesses the balance of nitrogen and phosphorous from the context of supply vs. demand and imports and exports at farm level.

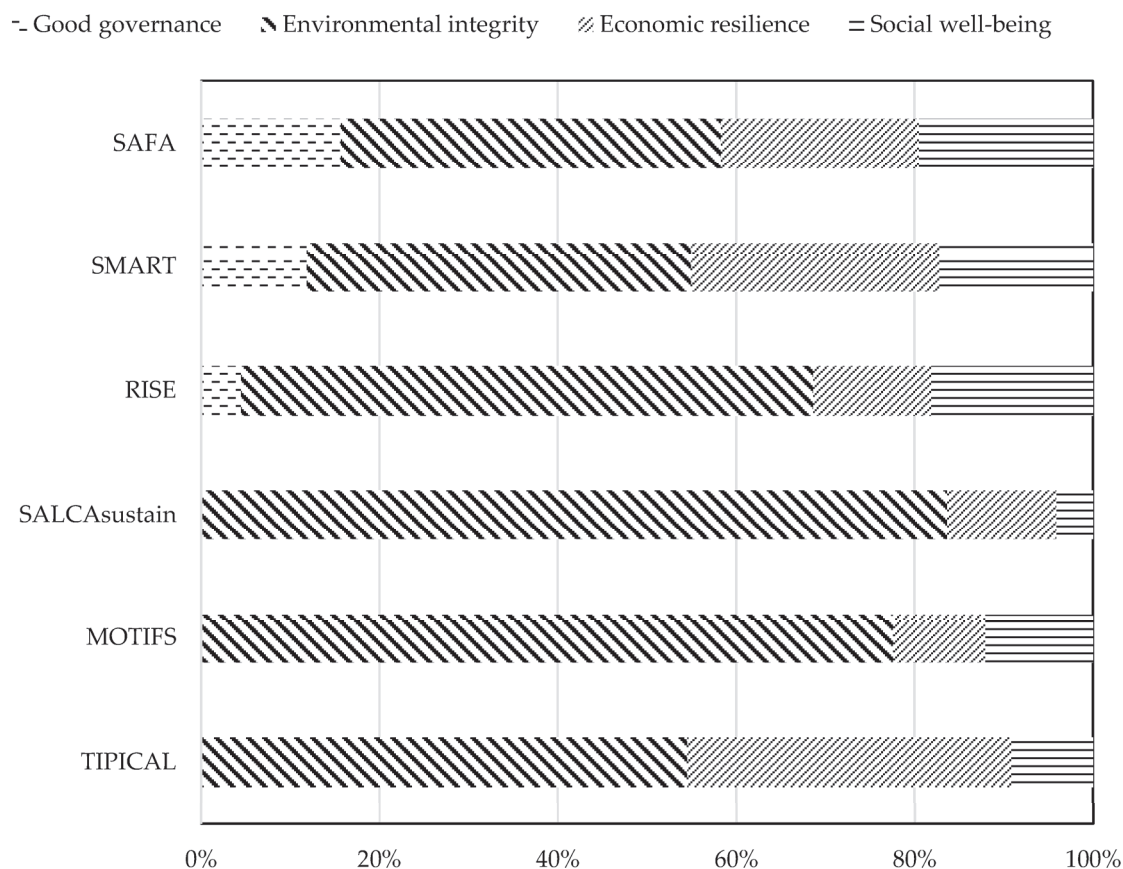


Figure 4. Distribution of sustainability dimensions in reviewed tools.

Biodiversity is also an important theme, encompassing the variety of species in the ecosystem and the diversity within these species [1]. RISE covers biodiversity with a small number of indicators on management and protection, intensity and diversity of production, and state and distribution of ecological infrastructures, which all fall within the sub-themes of the environmental dimension in the SAFA guidelines. However, genetic and species diversity, besides agricultural crop diversity, needs to also be taken into account, given that it is affected by a farm's activities, and the way in which multi-species farming has the potential to improve sustainability should be emphasized [68]. Ecosystem biodiversity

is also important, not just to the environmental dimension but also the social, due to the indicator impacting landscape. Agricultural landscapes not only represent societal values, but they also represent the visible result of the interaction between farming, environment, and natural resources [69]. SALCAsustain calculates landscape quality, RISE assesses the development of ecological landscape, and MOTIFS assesses landscape management through various indicators like nature conservation, architectural quality, visual nuisance and more. Given the landscape aspect and landscape scale effects of intensive dairy farms, the impact on biodiversity is significant. Grazing should also be covered in this aspect, as it presents one of the most common human activities which has an impact on the vegetation community both directly and indirectly [70]. This impact is not necessarily negative, and, considering local factors and different ecosystems, it can also be highly beneficial if properly managed and targeted [71]. Due to this, indicators developed for assessing grazing management plans need to be integrated in dairy sustainability tools. However, due to local factors not being properly integrated into the assessment [71], it is a challenge to analyze or portray the impact objectively. Biodiversity is not covered in TIPICAL.

One other important environmental issue which is not included in the SAFA guidelines or SAFA tool but should be integrated within a sustainability assessment is ecotoxicity. SALCAsustain accounts for terrestrial ecotoxicity, by taking into account pesticides and emissions released from their production [54]. The intensity of pesticide use is of high importance, especially due to the risk of soil, water, animals, and other vegetation damage. MOTIFS also accounts for pesticide use and pesticide management. SMART, on the other hand, employs a set of indicators with regard to pesticides' persistence in water and in soil and their management by the farmers. A pesticide-related indicator in SMART is instead part of the economic dimension, which falls within the aspect of food quality, and requires knowing how pesticide residues that affect food quality are handled. SMART includes indicators specifically related to the environmental impact of homegrown and purchased feed.

Looking at life cycle stages like transportation, dairy products are highly dependent on refrigeration, which has a high impact on GHG emissions globally [72]. This requires the engagement of different actors of the dairy supply chain to ensure that environmentally friendly ways are adopted and enabled, further establishing the connection to other dimensions. A dairy sustainability assessment tool should also focus on the processing and transportation part, due to their high impact. Considered to be one of the most GHG intensive stages, integration of this aspect related to the downstream impact was only witnessed in SAFA.

Animal welfare, defined as “the physical and mental state of an animal in relation to the conditions in which it lives and dies” by The World Organization for Animal Health (WOAH), Terrestrial Animal Health Code (TAHC), is considered to be a major challenge for agriculture in the 21st century [73]. SAFA and SMART consider animal welfare as part of the environmental integrity dimension. The inter-connectivity or synergy to the social-wellbeing dimension is given in both tools; however, the ethical and social nature of the aspect of animal welfare and wellbeing needs to be emphasized as such in a comprehensive tool. However, the quality of housing in SMART is accounted for. Injuries, animal losses, and risk of feed contamination are among the aspects considered. RISE also accounts for animal health, quality of housing and for the possibility to perform species-specific behavior [74]. These are identified as welfare consequences that impair the health of an animal [75]. Another aspect that is closely linked to animal welfare is livestock productivity—also accounted for in RISE. MOTIFS accounts for dirtiness, skin lesions and locomotion [74], among other previously mentioned concerns, which give a clear advantage to the tool regarding these particular aspects. It also accounts for udder health, using separate indicators, which is crucial to dairy sustainability. While these indicators are related to animal welfare, none of the reviewed tools can provide a reliable measurement on the overall animal welfare condition. The Welfare Quality® framework can be used as a reference by which to measure animal welfare accurately [74,76].

3.2.3. Economic Resilience

Economic turbulences and demand uncertainty drive farmers into recognizing and adapting to this ever-changing environment [77]. For an enterprise to be economically sustainable, or, essentially, economically resilient, it must have the resources to handle economic turbulence and downturns [1]. The dimension of sustainability assessment tools covers financial aspects such as profitability and vulnerability (all six tools), and aspects such as traceability, transparency, and information (SAFA, SMART, RISE). It includes indicators related to product quality and safety, supply chain management, and the economic viability of the farmers and their families (SMART). TIPICAL also offers an indicator similar to assessing the economic viability of the farmers, in the context of the decent livelihood sub theme. Investment and vulnerability are sub-themes in the SAFA tool which comprise a total 15 indicators and four sub-themes.

There is an evident synergy to the sub-themes of good governance with economic resilience both in SAFA and SMART, especially to aspects like traceability, transparency and information, which are considered effective development promoters within the economic resilience scope. Furthermore, the daily intake of dairy products by consumers depends on the assumption that the products are produced, processed, transported, and kept in compliance with safety and quality standards [78]. To ensure that, sustainability assessment tools should employ indicators to this aspect, and the respective results should be as transparent as possible. This theme also includes product labeling, certified production, and plans and set practices on ensuring product quality from farm to consumer. For the alignment of the dairy sector and sustainable development, stakeholders need to ensure quality of production and transparency regarding product safety through the entire production chain [13]. While these aspects pertain to the good governance dimension, in SAFA and SMART these are considered in the economic dimension as well. This ultimately depicts the interacting effect of the dimensions. Furthermore, a study has shown that the sustainability initiatives within the dairy supply chain enabled retailers to further divide and impose control over farmers/suppliers [72]. This could be seen as a synergy between the economic, social, and good governance dimensions.

In the SAFA tool, the 26 economic resilience indicators can be adjusted to all parts of the dairy supply chain. Stability is an important subject to the farmer, and for that, indicators that would require direct quantitative data from the farm are needed, such as capitalization ratio and equity-to-fixed-assets ratio [54]. RISE covers this sub-theme with the parameter of economic vulnerability in the context of indebtedness within the economic viability theme. In TIPICAL, vulnerability is covered through the indicators of risk management and liquidity. SALCAsustain covers aspects such as equity-to-fixed-assets ratios in the form of accounting data and presents an important indicator that could be considered to affect both the economic resilience and the wellbeing of the farmer.

Within the economic resilience dimension in SAFA, vulnerability also entails the stability of supplier relationships, which merely portrays whether a business contract is stable between the entity and the suppliers. In terms of the dairy supply chain, this is particularly important to the relationship between farmers and dairies as well as dairies and retailers. In SMART, the quality of cooperation between the farmer and contracted suppliers is an indicator of its own. This simultaneously contributes positively to the stability of production, due to also having a secure supply of farm inputs. In SALCAsustain, stability is a subject that is measured through equity-to-fixed assets ratios and fixed assets to total assets. While this is part of economic resilience, it does not contribute to the context of stability of production. This sub-theme could be particularly also applied in the context of the processing section of the dairy supply chain. This is somehow covered in SMART as the right of suppliers in collective bargaining and agreements, but still considered from the farmer's perspective. In addition, other indicators in SMART could be considered that also account for the processing part, regarding quality of products delivered. Some indicators also require information on whether the farmer cooperates with the processors in terms of common product development and planning. RISE also highlights stability of

production through farm management indicators, including parameters on supply and yield security and farm planning. Because everything starts from the farm, the dimension of economic resilience must garner a major focus, similar to the extensive coverage witnessed in SMART. SALCAsustain also covers the economic dimension in the farm context, in terms of general farm economic indicators. However, economic vulnerability and what it entails are also crucial, especially when looking at the dairy sector and its dynamic state. This is not covered by SALCAsustain in such a comprehensive manner as it is in RISE, SAFA, and SMART. SMART underlines stability of production and supply through a range of indicators. They account for production equipment, farm input restraints and many other related concerns.

3.2.4. Social Wellbeing

Most social indicators address themes such as working conditions, quality of life, and economic viability which characterize livelihood security of the farmers (witnessed in all six tools). Such indicators are considered very important for measuring social sustainability and the impact of agriculture production [24].

The social wellbeing dimension is addressed through a total of 19 indicators in SAFA. The social issues considered therein can be adjusted to the context of actors of the dairy supply chain. SMART applies a vast number, 358, of indicators in total, in terms of the themes of the social dimensions. This emphasizes the perspective of the farmers and their families' social and ethical concerns. The latter is not a focal point of SAFA [21], which puts little to no attention into the farmer's family situation and the related subjective wellbeing. Workload, work/life balance, education and social connections are among the aspects not considered in any of the tools in terms of the farmer's perspective. As small-scale family farms are highly reliant on their business, the family perspective is important when assessing social sustainability. Additionally, an indicator that measures whether the farmer's work is valued should also be incorporated, but is not accounted for by SAFA [21]. In the decent livelihood theme, SAFA accounts for quality of life and wage level. The quality-of-life indicator might leave room for different ways of interpreting and does not fully depict the reality of the life quality of the farmer. Giving a person-centric view by defining the pay level indicator (minimum salary to cover the family's needs) and the subjective wellbeing of farmers and their families is important [79]. RISE applies a set of parameters that account for the quality of life of the farmer, like education, occupation, personal freedom, and social relations etc., which also indicate the farmer's subjective wellbeing and satisfaction. The relevant farmer's satisfaction about leisure time, workload, time management, health, cultural activities etc., is explored in interviews. From a different perspective, MOTIFS also includes indicators on social services and a farmer's professional pride, which reflects how a farmer's identity connects with the ever-changing farming environment [49], which is an important concept regarding the critical issue of farm succession. Similar approaches were not witnessed in other tools. TIPICAL covers decent livelihood through farmer's income. Similarly, SALCAsustain measures quality of life through workload and family income at farm level. A well-developed set of indicators that portrays this aspect as to how dairy sector impacts the overall public health is necessary for a holistic dairy sustainability assessment tool. SAFA, SMART and RISE heavily account for this sub-theme, along with workplace safety. RISE takes it to another level by also considering satisfaction at work. Overall, the social wellbeing theme remains insufficiently addressed, as seen in Figure 4.

3.3. Input Data, Accessibility, and Practicability

Another important feature of a sustainability assessment tool is the input data type that it requires. For the end-user, this translates into time spent in assessment and the extent of facilitated contextualization the tool offers. First, it is important to establish the goal or the outcome intended from the sustainability assessment (sustainability performance measurement, to support decision making, quantifying impacts, identifying areas

of improvement, etc.), identify the most affected stakeholders, and thus design indicators accordingly [27].

In terms of input data type, RISE has proven quite flexible [52]. SAFA and RISE both allow for the use of primary and secondary data [1,51,52]. The main method for data collection for both of the tools is based on on-farm interviews for data collection. Similarly, for MOTIFS, the qualitative indicators require qualitative data based on questionnaires. SALCAsustain, RISE, MOTIFS, and TIPICAL provide mainly quantitative indicators. Indicators that were found to be not at all related or not of concern to the dairy sector in SMART were removed from its analysis. SMART provides for a total of 327 indicators, but 20 (qualitative) of these are not related to dairy systems or the overall dairy sector.

In terms of accessibility, SAFA is the only tool provided entirely free. For this research, tools were accessed either through trial versions of the tool (RISE and TIPICAL), or through scientific papers or reviews published regarding tools, throughout the years (SMART, MOTIFS, and SALCAsustain).

Data collection times can vary significantly. RISE has been deemed to take a fair amount of time and SALCAsustain was seen to be very time consuming [2]. Time for collecting all input data in SALCAsustain varied between 3 to 30 h, depending on the focus of the tool and the system boundaries as reported by Roesch et al. [54]. For SAFA, time needed to conduct an assessment depends on the type of input data to be used and their availability. This is usually estimated to last for several days or even weeks [1]. Comprehensive sustainability assessment tools are not solely using qualitative data.

In terms of the outputs depicted in Table 2 and, visually, in Figure 5. TIPICAL offers all quantitative indicators. SALCAsustain and MOTIFS offer more quantitative indicators, mainly for the environmental and economic dimension. RISE contains mostly quantitative and semi-quantitative indicators. SAFA provides mainly qualitative and semi-quantitative indicators, which is also the case for SMART.

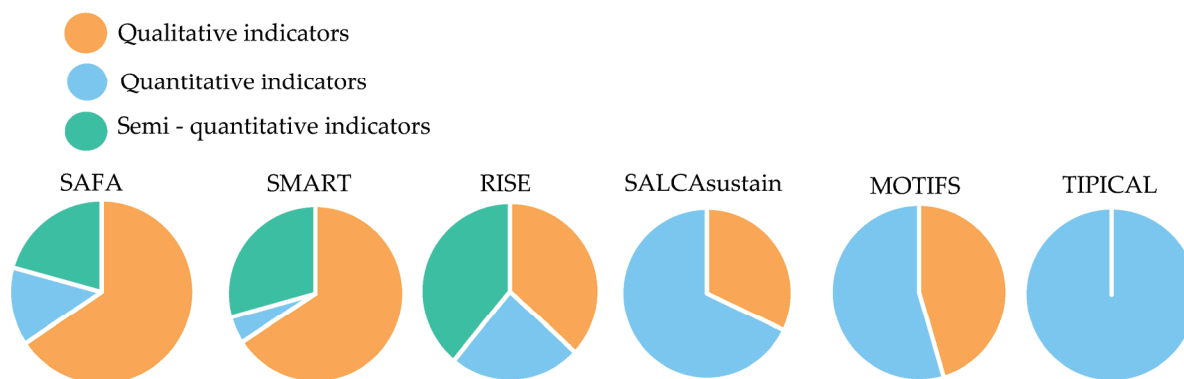


Figure 5. Distribution of indicator types in reviewed tools.

In terms of scale, SAFA has proven to be adequate when assessing the sustainability of small producers [80]. It provides a broad picture of sustainability, but it is entirely dependent on company information overlooking the influence of market dynamics [81]. The emerging instability of the dairy market [82] should definitely be taken into consideration for a future dairy sustainability assessment tool, as it should be within the scope of the economic resilience dimension. SALCAsustain has also proven to be adequate when applied to the assessment of a small-scale farm, yet its complexity is more suited for addressing research inquiries and analyzing farm management strategies. TIPICAL is based on the typical farming approach, so it integrates different farm scales as representative farms. Similarly, TIPICAL is more adequate for evaluating farm management strategies [53,54]. With these gained insights, stakeholders or experts engaged in assessing sustainability in the dairy supply chain can weigh the strengths and limitations of each reviewed tool. By considering differences in methodologies, indicators, and applicability to the dairy supply chain context, users can determine which tool provides more reliable and robust

sustainability assessment. Moreover, evaluating the reviewed tools' capacities to address key sustainability issues in the dairy supply chain will promote informed decision making.

4. Conclusions

There are various tools available for sustainability assessment in the dairy sector, each with its strengths and limitations, as were shown in this review. The main strength considered is the integration of multiple aspects of sustainability. A considerable limitation of all six tools would be the lack of comprehensive integration of various other sustainability aspects (especially pertaining to the social dimension). SAFA and SMART offer a holistic assessment by integrating many aspects of sustainability dimensions through many indicators but do lack the accuracy gained when quantifying some of those aspects, especially towards dairy farms impact issues. SAFA stands out for being accessible at no charge for the user, an option important to consider in terms of financial budgeting. SALCAsustain, RISE, MOTIFS and TIPICAL's main strength is the quantification which allows for a detailed assessment over the whole dairy supply chain. The advantage of MOTIFS and TIPICAL is that both specifically cater to the dairy sector, although TIPICAL lacks in terms of assessing sustainability in a holistic perspective. RISE, although designed as a farm advisory tool for different agricultural production systems, contains indicators that are oriented towards categories which are important for dairy farm impacts. These considerations are crucial for users in the dairy sector.

The advantage of RISE is its flexibility in terms of the user-friendly interface and data requirement, which makes it adaptable to different data availability scenarios. MOTIFS was also deemed user friendly, with an obvious equality of dimensions covered and an adequate share of quantitative indicators. Similarly, tools like TIPICAL are suitable for users in search of precise quantitative measures, while tools like SAFA and SMART offer broader insights with more qualitative and semi-quantitative indicators. Users must also consider their time capacity in data collection, which can vary significantly among all tools, with SALCAsustain, RISE, and SAFA reported as being particularly time consuming.

A combination of existing tools into one framework can help identify trade-offs and synergies between various sustainability dimensions, such as social, environmental, and economic impacts, and provide a more comprehensive and holistic view of dairy sustainability. While this review draws to such a conclusion, this might be challenging. In identifying an appropriate tool for sustainability assessment in the dairy sector, the specific goals and needs of the user, as well as the context in which the assessment is being conducted should be thoroughly considered. Future research should delve further into the practicalities in order to enhance tool usability and into the development of tools that integrate all sustainability aspects in a comprehensive manner while providing accurate quantification of those aspects. Applying methods for stakeholder engagement and collaboration could also present a future combination and consensus for a future tool.

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Abbreviations

SAFA: Sustainability Assessment of Food and Agriculture; SMART: Sustainability Monitoring and Assessment Routine; RISE: Response-Inducing Sustainability Evaluation version 3.0; SALCA-sustain: Swiss Agricultural Life Cycle Assessment; MOTIFS: MONitoring Tool for Integrated Farm Sustainability; TIPICAL: Technology Impact and Policy Impact CALCulations; DSF: dairy sustainability framework; GG: good governance; EI: environmental integrity; ER: economic resilience; SW: social wellbeing.

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Review

The “Noble Method[®]”: A One Health Approach for a Sustainable Improvement in Dairy Farming

Federico Infascelli, Nadia Musco, Daria Lotito, Eleonora Pacifico, Sara Matuozzo, Fabio Zicarelli, Piera Iommelli *, Raffaella Tudisco and Pietro Lombardi

Department of Veterinary Medicine and Animal Production, University of Napoli Federico II, 80100 Napoli, Italy; infascel@unina.it (F.I.); nadia.musco@unina.it (N.M.); daria.lotito@unina.it (D.L.); pacifico@eleonora7465@gmail.com (E.P.); saramatuozzo98@gmail.com (S.M.); fabiozicarelli@gmail.com (F.Z.); tudisco@unina.it (R.T.); pietro.lombardi@unina.it (P.L.)

* Correspondence: piera.iommelli@unina.it

Abstract: The Noble Method[®] has been successfully introduced in the last few years in Italy and in some foreign countries. This novel livestock management provides, among other rules, a high forage/concentrate ratio, no use of silage and supplements, no GMOs and the availability of outdoor paddocks. One of the goals is to achieve high-quality milk in terms of nutritional properties. Other benefits have been reported; amongst them, the forage/concentrate ratio of the diet was shown to reduce the amount of methane produced by animals, also, the system provides economic benefits, mainly for small breeders, in terms of the sustainability and market placement of milk. Thus, the method represents a sustainable approach to improve the production and the supply chain, from the land to the final product. In this review, the most recent studies on Noble Method[®] are depicted, showing that, besides the nutritional proprieties of dairy products, the method is able to improve animal welfare, human health and environmental sustainability, thus falling within a “One Health” approach.

Keywords: Noble Method[®]; Noble Milk[®]; dairy cow; behavior; milk quality; environment

1. Introduction

A balanced diet containing all the necessary nutrients is crucial in livestock breeding; ruminants are herbivorous, herd and social animals, thus grass represents the ideal environment to express their natural behavior. In view of this, a nutritional approach, the Noble Milk Method (NMM), has been successfully introduced in Italy in recent years and is now being applied in other countries in the world as well. The original idea was to achieve more natural feeding by following some rules [1]:

The “Noble Milk[®]” Guidelines [2]

- Animals must have free access to outdoor paddocks;
- Diet forage/concentrate ratio 70:30;
- Silage and GMOs prohibited;
- Fresh and/or preserved forages (hay) with five different essences (with at least 10% of each);
- Mineral nitrogen fertilization of meadows may not exceed 50 kg of N/ha in order to not imbalance meadow vegetation. The total nitrogen input (organic + mineral) should not exceed 120 kg of N/ha to allow sufficient development of legumes. Manure input should be made with mature product (8–12 months of maturation in heap covered with breathable plastic sheeting); in the case of pastures, the maximum dose of mineral nitrogen cannot exceed 30 kg of N/ha.
- Preference should be given to autochthon breeds for the best adaptation to the area. However, the “Noble Method[®]” model aims to encourage the breeding of native breeds that are well adapted to their production area.

- The levels of animal welfare required by the Welfare Quality[®] standard must be ensured.
- The hay must achieve a score of at least 70 points out of 100. This score is obtained through a sensory evaluation system, used to identify hay quality. It is scored on a scale from 1 to 100 (Table 1). At the end of the evaluation, the partial value of each characteristic is summed to obtain the final score.

Table 1. Hay sensorial evaluation.

Parameters	Evaluation	Lowest Score (0)	Highest Score (100)
Color	It ranges from green to brown. Is indicative of the good quality of the forage. A brown color may suggest rotting during drying.	Dark brown	Dark green
Number of essences	More essences correspond to higher quality forage.	Few essences	More than 5 essences
Presence of dust	Indicative of correct forage harvesting and storage.	Presence of dust	Absence of dust
Tactile evaluation	Woody forage presents a high lignin content, it corresponds a lower nutritive value.	Woody	Soft
Odor evaluation	The animals eat more willingly a fragrant forage than a less aromatic forage.	Old, mold	Persistent, aromatic and floral
Leafiness	The leaves are the part of the plant representative of the protein content.	Absence of leaves	Presence of leaves

Farmers who decide to join the consortium gain an extra 50% if compared to common milk farms. The evolution of the “Noble Milk[®]” circuit was the creation of the ME.NO (Method Noble) consortium also involving producers of other foods, either of animal origin (i.e., meat), recognizing the fundamental role of animal feeding to improve product quality [3], or of plant origin. This system proposes the application of a more sustainable approach in relation to animal welfare, respect for the environment and human health.

The aim was to achieve an improvement in milk quality by reducing the $\omega 6:\omega 3$ ratio and by increasing conjugated linoleic acid (CLA) content [4] without negatively affecting cow metabolic homeostasis. In the frame of the increasing demand of consumers for foods with beneficial properties for human health, obtaining food with favorable nutritional characteristics should represent one of the main goals of a farm. One of the primary aspects to be considered is the fatty acid profile, as it is known to be, probably, the most important factor to assess the health properties of food. The first parameter concerns $\omega 6:\omega 3$ fatty acids, whose intake through the diet is essential for humans, with $\omega 6:\omega 3$ ratios within 2.1 to 4.1 [5]. According to nutritionists, in fact, this range represents the optimum intake of these organic acids as it considers the balanced effects between pro-inflammatory compounds ($\omega 6$) and anti-inflammatory ones ($\omega 3$). The second one, due to its immune-modulating, anticarcinogenic and antiatherosclerosis properties, is the milk CLA content [6], for which dosages varying from 0.7 g/day to 6.8 g/day have been reported to be beneficial [7]. The diet is the main factor determining the fatty acid profile of cow milk, and, when cows are fed a high percentage of forage, the $\omega 6:\omega 3$ ratio in milk has shown to be near the one recommended for human health [8]. For instance, this ratio is at least two times higher [5] in milk from other breeding strategies that generally use a low forage/ concentrate ratio in order to increase yield [9]. Similar results have also been reported for CLA levels [10] in the milk of other domesticated ruminants (i.e., small ruminants, sheep [11]), for which significantly higher milk CLAs were obtained from feeding fresh forage instead of TMR (total mixed ration).

Once the Noble Milk[®] gained success due to the economic advantages for breeders and the benefits for human health [12,13], some researchers explored the effects of the

Noble Milk[®] method on animal welfare [14] by assessing other parameters such as cows' blood metabolic profiles, the evaluation of oxidative stress and behavioral patterns [15]. Thus, the second step of research was focused on the possible effects of the breeding system on animal welfare. Assessing animal welfare using animal-based, resource-based and management-based assessment tools provided a holistic view of the welfare state of facilities [16,17].

Animal welfare is an objective that can be exploited to advance sustainable development goals and vice versa. Pasture is frequently thought to be more beneficial to animal health because it can provide a positive experience for the animals. However, the welfare of ruminants may be different; it depends on management practices and environmental conditions affecting the different habits of the animals, such as nutrition-, environment- and healthcare-related, which, when more "controlled", may be decisive [18].

Given all the above-mentioned field of interests involved in the application of Noble Method specifications, it seemed important to give a global and comprehensive view of this farming system, analyzing in detail all the aspects that it concerns, as it is becoming increasingly adopted by farmers and highly demanded by consumers.

This review is aimed at highlighting the positive effects of NMM application in dairy farms, focusing on animal, environmental and human health. In Table 2, the main "Noble Milk[®]" rules are presented.

Table 2. "Noble Milk[®]" guidelines [2].

ANIMAL NUTRITION	MANAGEMENT SYSTEM
Prohibited	
Chemical weeding	Breeding without grazing
GMOs	Mineral nitrogen fertilization ≥ 50 kg of N/ha
Silage and bandages	
Synthetic vitamin and mineral supplements	
Required	
$\geq$ five dominant forage species	Dairy livestock load of the farm ≤ 1.3 livestock units (LSAs) per hectare of forage area
Forage/concentrate ratio $\geq 70:30$	Ensuring free access to outdoor paddocks
Fresh and/or preserved forage (hay)	Ensuring the levels of animal welfare required by the Welfare Quality [®] standard
Hay score $\geq 70/100$	
Preferable	
	Raising native breeds

2. Animal Welfare

Protecting animal welfare can turn into profit, in terms of reducing veterinary costs, increasing animal performance, improving product quality and maintaining hygiene standards in food production. Wellbeing is closely linked to the health and production efficiency of farmed animals and supporting animal welfare can also increase the commercial value of animal products. Thus, the demand for high-quality food is increasing and an increasing number of consumers expect animal products to be obtained and processed with greater respect for animal welfare. Rumen micro-organisms play a significant role in fiber breakdown because the rumen is a natural bioreactor for very efficient fiber degradation [19]. A high proportion of concentrates in livestock farms has resulted in increases in dry matter and digestible carbohydrate intake with a consequent reduction in fiber digestibility, altering volatile fatty acid patterns [20]. Kljak et al. [21] showed that a forage/concentrate ratio of 65:35 presents the most optimal balance of available ammonia-N and readily fermentable carbohydrates.

This ratio is very similar to the NMM one (70:30). In addition, a decrease in chewing activity caused by the inclusion of concentrates reduces saliva production, lowering rumen pH [22] and VFA concentration [23], and leading to a risk of rumen acidosis [24]. Moreover, it has been shown that by lowering the $\omega 6:\omega 3$ ratio in the diet and by increasing conjugated linoleic acids (CLAs), produced through the dehydrogenation of linoleic acid in the rumen due to the presence of volatile fatty acids (VFAs), the main products of degradation that occur at the ruminal level as a result of the microbial population could improve milk nutritional value [4]. CLA levels in sheep [11], cow [10] and goat [13] milk is demonstrated to be significantly higher when animals are fed fresh forage than when using the TMR technique. The major isomer of CLA, *cis*-9, *trans*-11 (rumenic acid), accounts for up to 80% of total CLA and is localized in the rumen, mammary gland and muscle. Linoleic acid $\omega 6$ (C18:2) and α -linolenic acid $\omega 3$ (C18:3), if correctly balanced in the diet, have beneficial effects. Linoleic acid shows pro-inflammatory, pro-aggregant and immunosuppressive activities, while α -linolenic acid has anti-inflammatory, antiaggregant and non-immunosuppressive activities. Hay and silages are able to decrease PUFA content, compared to fresh forages, due to oxidative processes during storage [25]. Therefore, the improved forage/concentrate ratio influences rumen activities and metabolic state (i.e., increased pH in the rumen) [26] and, consequently, the nutrient supply used for the synthesis of milk components, improving the activity of the ruminal microbiome [27–29]. This kind of diet aims at preserving the metabolic homeostasis of the animals, avoiding abrupt changes in pH and the onset of dysmetabolism, such as acidosis, thus improving the nutritional quality of the milk [4]. Unbalanced diets could cause an alteration in mitochondria activity, leading to an accumulation of free radicals and therefore oxidative stress. Blood metabolites, indeed, are highly indicative of animal nutritional and physiological condition [30] as well as oxidative stress, which is a parameter gaining more and more importance in evaluating animal welfare status [14]. A high level of reactive oxygen species can lead to oxidative stress, an emerging health risk factor implicated in many diseases, including inflammatory, infectious and degenerative disorders in both humans and animals [31–35]. Several authors examined in depth the impact of nutrition on regulating oxidative stress. In the work of Bernabucci et al. [36], the authors examined the link between body condition scores and oxidative status and suggested that nutrition plays an important role in this modulation due to its involvement in the rate of free-radical-mediated lipid peroxidation, which is critical in high-producing dairy cows due to their greater susceptibility to oxidative stress conditions. Musco et al. [14] demonstrated that animals with a high forage/concentration ratio in their diet showed an improvement in oxidative status.

Feeding with higher forage content turns out to be efficient for several reasons (Table 3):

- The hay acts as a filter for the passage of grain, thus preventing the onset of acidosis. Propionic acid, which is formed from starch, thanks to the amilolytic bacteria that are activated by the concentrate, gives an energy boost by becoming glucose, which if present in excess can also become lactic acid and create acidosis [37].
- Fiber promotes the function of cellulolytic bacteria and is responsible for the formation of acetic acid in the rumen, important for the milk fat content [38].
- Increases salivation by lowering ruminal pH due to the presence of bicarbonate in saliva, which has a buffering effect [39].

However, the metabolic requirements of the ruminants in production are not satisfied with only the use of fresh forages. For this reason, “Noble Milk[®]” suggests a moderate use of concentrates without completely abolishing them. Otherwise, a reduction in production and animal welfare could be observed [40]. This must be avoided, because animal welfare is considered a critical pillar of sustainability in livestock systems.

The pasture, with incorrect management, could also affect animal health and longevity, milk quality and reproductive efficiency. As reported by [41], an association of animal density with stress in lactating ruminants has been observed in intensive farms. In particular, injuries or nutritional deficiencies can occur and contribute to reduced animal welfare [42]. A benefit of a high forage/concentrate ratio is also the possibility for ruminants to accu-

modulate carotenoids in milk, which will then be transferred to dairy products, contributing to their nutritional and sensory properties [43]. The modulation of feeding systems can enhance the quality of dairy products in terms of the presence of antioxidant compounds (i.e., tocopherols, carotenoids, phenolic compounds) [44–46].

Table 3. Physiological effects of two different feeding systems on animal welfare.

PHYSIOLOGICAL EFFECTS	
Forage/Concentrate Ratio $\geq$ 70:30 (Noble Milk [®] Method)	Forage/Concentrate Ratio < 70:30 (Intensive Farming Method)
Optimal balance of available ammonia-N and readily fermentable carbohydrates [21].	Reduction in fiber digestibility, altering volatile fatty acid patterns [20].
Higher CLA levels in sheep milk [11], cow [10], and goat [13] milk for animals fed with fresh forage than with total mixed ration (TMR) technique.	Decrease in saliva production, decrease in rumen pH [22] and VFA concentration [23].
Improvement in oxidative status [14].	Accumulation of free radicals caused by altered action of the mitochondria.

Mastellone et al. [15] also showed that the NMM is able to favor positive behaviors in dairy cows. These authors observed a modification in the behavioral repertoire of a group of dairy cows bred with the Rubino system [1] compared to traditional livestock breeding. Animals bred with the NMM were more dynamic, with an increase in walking and a decrease in all stationary behaviors such as lying down, standing and sleeping. Such a result was attributed to access to outdoor paddocks which, by allowing cows to move freely, is able to increase leg health, improving cows' locomotory ability [47,48]. This is in accordance with Crump et al. [49], who noted a positive effect of exercise on dairy cattle welfare.

The NMM also affected feeding behaviors. Cows showed longer rumination and a decreased drinking time. Obviously, a diet with high forage content requires more time to eat [50], while the concentrate content has been shown to be positively correlated with water intake [51]. Also, improving rumination increases salivary secretion [52,53], which is associated with higher intake of forages [39]. As a consequence, the NMM, by promoting rumination, may reduce the risk of subacute ruminal acidosis [39]. Interestingly, the NMM also affects some social behaviors, increasing allogrooming and social rubbing times. A similar study has been performed in dairy heifers allowed to access pastures showing different social interactions in pastures [54]. In particular, a larger space availability was considered responsible for both an increase in allogrooming and a decrease in agonistic interactions.

Mastellone et al. [15] reported that the larger space availability provided for the NMM should give less opportunity for social contact but positive social interactions are longer lasting. The authors underlined that allogrooming is an important behavioral pattern that, reflecting positive interactions between ruminants, is involved in the formation and maintenance of social bonds [55]. In general, social grooming is also believed to reduce social tension and to balance positive and negative social interactions [56]. Therefore, it seems that the NMM improves social interaction in dairy cows and that this effect is more likely related to the diet.

Importantly, breeding systems are always designed to improve production, ignoring the behavioral patterns that may be signs of animal welfare. Mastellone et al. [15] showed that the NMM significantly influenced the behavior of dairy cows, including locomotor activity and affiliative social behaviors (Table 4).

Table 4. Effects of Noble Milk® feeding systems on animal behavior and eating behavior.

“Noble Milk®”	
EFFECTS ON ANIMAL BEHAVIOR	EFFECTS ON EATING BEHAVIOR
Increase in ambulation and decrease in all stationary behaviors.	Risk of subacute ruminal acidosis reduction by promoting rumination [39].
Increase in leg health, which improves locomotor capacity of cows [47,48], resulting in a positive effect on the welfare of dairy cattle.	Increase in allogrooming and social rubbing times, which are involved in the formation and maintenance of social bonds [55].
Increase in duration of positive social interactions [15].	Decrease in social tension among dairy cows [56].

Using proper animal welfare practices, it is possible to achieve a balance between sustainable agricultural practices, which reduce biodiversity decline, and overdependence on human edible food items, which will in turn enhance food security.

3. Environmental Mitigation Strategies

3.1. Animal Nutrition

The efficiency of nutrients fed to animals would also lead to significant benefits in terms of sustainability; in fact, it could decrease pollution due to the waste nutrients excreted and could improve the relationship between unit production and unit pollution [57]. Furthermore, the benefits may also come in economic terms because there would be a reduction in direct (both financial and environmental) and indirect costs (transport of feed to the animal). Milk production, like all human activities, is known to have a certain effect on the environment. Dietary manipulation represents a simplistic and pragmatic approach to mitigate CH₄ production, while improving farm productivity. This approach is based on the alteration in rumen fermentation, which can lead to up to 40% reductions in CH₄ emissions [58,59]. There are many dietary strategies, but they can be divided into two main categories: (i) alteration in the forage content in the diet and the quality of the forage itself and (ii) use of additives in the diet that inhibit the action of methanogenic bacteria [58]. As reported above, the Noble Milk® guidelines require that forage makes up at least 70% of the ratio.

The assessment of the impact of ruminant production on the environment is fundamental for the development and adoption of adequate mitigation strategies. Through the use of the LCA (Life Cycle Assessment) index, it is possible to estimate the environmental impact deriving from animal production [60]. Such estimation is based on the environmental impact of a given product considering the outputs and inputs of its production system. Animal carbon and water footprint are the main impacts deriving from ruminant production. The environmental impact that the “Noble Milk®” type of breeding has should be certainly considered as multifactorial and depends on many characteristics and management strategies [59], especially starting with feeding: nutrition is an important factor influencing the excretion of nitrogen (N) by animals [61]. Animal nutrition is a critical issue for the livestock sector, both in terms of production efficiency and its impact on the environment; in the dairy sector in particular, the production of feed for livestock is a major contributor to potential global warming, acidification and eutrophication. Interestingly, the interest in alternative feeds to improve soil fertility and reduce the need for chemical fertilization is progressively increasing [62]. The synergy of several production factors must be considered. Emissions, particularly those of methane, are linked to enteric fermentation, as ruminants produce methane themselves during digestive processes (which is then eliminated by belching). In the rumen, microbial fermentations transform carbohydrates into simpler molecules that can be utilized by the animals. Methane (CH₄) is a byproduct of this process [63] and is considered the main greenhouse gas produced through enteric fermentation during the normal digestive process of ruminants [64].

Forage quality is a key factor in modulating ruminal CH₄ production [65]. Young plants lead to a reduction in CH₄, thanks to the lower NDF content and more fermentable carbohydrates, leading to a greater digestibility and passage speed [66,67].

In contrast, old forages are less digestible and increase CH₄ production, mainly due to an increase in the C:N ratio [68]. The chemical composition of forages can also be responsible for a greater or lesser production of CH₄ [69].

The presence of antinutritional factors (mainly represented by condensed tannins), low fiber content and high dry matter intake in legume forages are responsible for lower CH₄ yield [70]. Processing techniques and forage conservation also influence CH₄ emissions [71]. As reported by Boadi et al. [72], chopped or pelleted forage leads to a reduction in CH₄ production because the smaller particle size of the particles requires less degradation in the rumen.

Serra et al. [73] conducted an analysis on dairy cattle farms in Italy based on the calculation of average emissions, and found a value of 1.3 kg CO₂eq/L of milk produced, with a strong tendency towards reducing the impact, when going from less productive to more productive farms. As proof of this, in a comparative study on the carbon footprint of dairy herds in Northeast Italy and Slovenia [74], the kg CO₂eq/L of milk corrected for fat and protein estimates was significantly higher for Brown Swiss cows (1.61 kg CO₂eq) compared to Friesian Simmental and Holstein cows (1.15 and 1.04 kg CO₂eq, respectively), thus providing an important insight concerning milk quality. This study was based on an LCA approach to estimate potential emissions as well as consumption of renewable sources. The differences between the breeds were attributable to the quantity of milk produced, which was lower for the Brown cows, and the animals were fed a diet richer in forages when compared to the Friesian Simmental and Holstein breed herds. According to Serra et al. [73] and Bava et al. [75], intensive livestock and increased milk yield/cow, dairy efficiency and stocking density were negatively related to emissions/kg of product. This last suggests a positive effect of these factors on mitigating greenhouse gases. In conclusion, the use of a ratio of young forage, characterized by low fiber content and a higher soluble carbohydrate content, could be useful to contain methane emissions. Supplementing the diet with a small amount of concentrates, preferably cereals, is also a promising mitigation approach. Increasing the dietary level of concentrate reduces CH₄ production since the energy share is mainly used for animal products, such as milk and meat [71]. In contrast, the concentrates are associated with increased DMI, ruminal fermentation rate and feed turnover rate and can change the rumen environment and microbial composition [71]. Indeed, it is not necessary to exceed the amount of concentrate because diets with a high-concentration content are poor in structural fibers and, in the long term, can negatively affect ruminal function, leading to acidosis; therefore, these ratios are not sustainable for ruminant production.

The use of smaller quantities of concentrates drastically reduces the pollution attributed to ruminant farming. In particular, concentrates represent the foods with the greatest impact on the livestock sector, firstly because many are produced in overseas countries, using cultivation techniques that are sometimes not respectful of the wellbeing of the soil and are the result of significant deforestation. Furthermore, the transport of these concentrates leads to further emissions of harmful gases into the atmosphere. By using better quality forages, it is possible to significantly reduce the inclusion of concentrates in ruminants' diet, thus improving the sustainability and welfare status of the animals.

3.2. Forage/Concentrate Ratio

The forage/concentrate ratio in the diet can affect the amount of methane produced by animals [27]. In the rumen, microbial fermentations convert carbohydrates into simpler molecules that can be used by animals. Methane is a byproduct of this process: reactions with high fiber content cause higher methane emissions per unit of energy ingested [76].

Ruminal micro-organisms produce acetic acid (acetate) and propionic acid (propionate) from fodder and concentrate intake, respectively.

The production of a low acetate/propionate ratio by the rumen results in a reduction in ruminal pH and in the number of protozoa [77], which have been found to reduce methanogens in terms of growth and/or activity [27,78] and cellulolytic bacteria [79].

Therefore, the forage/concentrate ratio adopted by the “Noble Milk[®]” specification does not cause higher animal emissions. Shiddieqy et al. [80] evaluated the environmental impact of different Indonesian cattle breeds fed with different forage/concentrate ratios, concluding that the highest amount of CH₄ emissions occurred in the feces of Bali cattle with a forage-to-concentrate ratio of 30:70 on the first day of observation. According to Fadaee et al. [81], methane emissions may vary when the buffering capacity of the diet is modified using inorganic buffers. However, various strategies have been studied to reduce methane emissions from ruminants, for instance by adding *Lotus pedunculatus* to animals’ diet [82] or through genetic selection [83] of the breeds chosen for milk production. Aemiro et al. [84] conducted a study to investigate the effect of different concentrations of *Euglena* (*Euglena gracilis*) on CH₄ production and it turned out that the addition of *Euglena* to the diet has the potential to mitigate methane emissions.

3.3. The Use of Pasture

Grazing is one of the most competitive and sustainable feeding systems for dairy cows due to its low environmental impact, benefit for animal welfare and relatively low cost in the production and use of concentrate [85]. Indeed, grazing is not always possible due to seasonal variations in grass production and adverse weather conditions [86]. In addition, grazing livestock is the focus of many rural communities, using land that is difficult to use for other activities, providing jobs and enriching the landscape. Furthermore, highly productive dairy cows, resulting from genetic improvements, can no longer rely exclusively on grazing to provide the nutrient supply needed to satisfy milk production [87]. If the pasture is of high quality, the proportion of additional feed decreases, while productivity remains unchanged [88], with the additional benefit of obtaining an improvement in the chemical and nutritional composition of milk [89]. Grazing protects the soil from erosion thanks to the strong root system, so there is a benefit of preserving the eco-systems of permanent meadows and pastures [90]. The presence of ruminants can positively modify nutrient pathways and soil aggregation, increasing soil quality [91]. With grazing, there is a return of organic matter and nutrients to the soil through manure [92].

Therefore, nutrients ingested by animals are excreted and return to the system, bringing an advantage to the crop and increasing its yield. This technique limits the use of synthetic fertilizers for the cultivation of plant species that also enter into the human food chain [93]. With this type of feeding, animals do not compete with humans for food [94]. In addition, eutrophication, which is the uncontrolled increase in nutrients in water, is lower in grazing farms than in non-grazing ones due to the lower use of nitrogen fertilizers for feed production [95]. In some pastures, legume forages (i.e., clover, common vetch, purple clover, sainfoin and sulla) are largely present. According to Aboagye et al. [96], legume fodder could reduce enteric methane emissions by ruminants, as well as tannins, the secondary metabolites particularly abundant in legume plants, which help control enteric methane emissions [97,98]. Grazing allows for offsetting, at least partially, the greenhouse gas emissions produced by cattle breeding, because it captures organic carbon in the soil for a few years [99–101].

Furthermore, in terms of grazing, it must also be taken into account that the supply of feed is one of the main input costs in dairy cattle breeding. The environmental impact, considered as the carbon footprint (CF) used as an indicator of the sustainability of livestock farming, is lower in grazing farms than in semi-intensive or intensive farms [102]. A sustainable form of agriculture is supposed to respect the environment in order to allow long-term practice. In general, the goal is to maximize the use of grazed grass. This is achieved by ensuring that the duration of the grazing season is as long as possible. Previous research has shown that increasing the length of the grazing season is associated with a reduction in greenhouse gas emissions per unit of produce [103].

Overgrazing on a given area causes erosive problems in the soil, leading to economic disadvantages [104]. Soil damage is linked to two factors: animal load and soil characteristics [105].

3.4. Livestock Units

According to “Noble Milk[®]” procedural guidelines, the dairy livestock load of the farm may not exceed 1.3 livestock units (LSAs) per hectare of forage area. LSA is the unit of measurement of the size of a herd. The Ministry of Agriculture and Food Sovereignty does not provide a maximum density for livestock loading, but the ministerial decree will be increased to provide for a maximum livestock loading of 2 LSAs per hectare in vulnerable areas (NVs) and 4 LSAs per hectare for the other non-vulnerable areas (NVZs) [106]. Animal load is one of the main factors that can change the amount of N excreted by a herd. Increasing the number of animals per ha risks compromising the sustainability and productivity of resources [107].

The environmental sustainability of livestock farming has become a major issue. In recent years, consumers have recognized and required a high quality in animal products. In addition, consumers are increasingly interested in ethical aspects such as the production process, environmental sustainability and animal welfare.

4. Human Health

Milk and dairy products are considered essential sources of micronutrients like minerals (Ca, Mg, Na, K) and vitamins, which support a variety of essential body functions [108]. Vitamins have an important role in physiological processes such as the visual process (vitamin A), as antioxidants (carotenoids, vitamins E, C, and riboflavin), in modulating calcium metabolism (vitamin D) and in hematopoiesis (vitamin B12, folates and vitamin B6) [109]. The epidemiological data currently available also indicate that milk consumption helps to protect from allergies, asthma and respiratory tract infections, with bovine IgG being able to destroy pathogenic micro-organisms [110]. Vitamins and minerals found in cows’ milk can also have positive and significant effects on strengthening the immune system [111].

In addition, regarding the thermal processes to which milk is subjected before sale, pasteurization does not cause a loss of vitamins while UHT sterilization causes a limited loss of vitamins [112]. Cows’ milk is also recognized as an excellent source of proteins, characterized by high biological value and high digestibility [113]. It was shown by McGregor et al. [114] that the consumption of milk protein reduces the incidence of metabolic risk factors, such as hypertension, dyslipidemia and hyperglycemia. Gastric, pancreatic and microbial proteases can hydrolyze whey proteins to produce peptides that have physiological functions [115]. These bioactive peptides are efficient in preventing parasitic, bacterial and viral infections as well as autoimmune inflammatory processes in the body [111].

With regard to the function of calcium, this mineral is essential for the contraction of muscles, including the heart muscle, the release of neurotransmitters, digestion and blood clotting [116]. Heaney et al. [117] showed that calcium intake from dairy products promotes bone health in humans. Indeed, calcium deficiency is related to the development of osteoporosis or other disorders, and for that reason it is crucial to integrate this mineral into the diet through milk and other dairy products [118]. In this regard, Black et al. [119] showed that kids who had avoided cow milk for a long time had low calcium level and had poor bone strength and density when compared to kids who consumed milk, [120].

Balivo et al. [89] reported the health implications of Noble Milk[®] consumption for humans. In particular, in this review the importance of the conjugated linoleic acids (CLAs) that are principally present in milk and meat of ruminant is analyzed. The primary geometric isomer of CLAs found in nature is *cis*9 *trans*11-CLA (*c9t11*), which is created as a byproduct of ruminant microbes’ biohydrogenation of dietary linoleic acid to stearic acid (C18:0) [120]. Milk CLA results from the activity of stearoyl-CoA desaturase (SCD) in the

mammary gland on trans-11C18:1 (TVA, trans vaccenic acid), an intermediate product of several polyunsaturated fatty acids biohydrogenation [121].

CLAs have been demonstrated to have physiologically beneficial effects, including anticarcinogenic, antiobesity, antidiabetic and antihypertensive characteristics [122] (Table 5). Ip et al. [123] showed that CLAs are more effective than any other fatty acid in controlling the growth of tumors. The effects of physiological concentrations of CLAs on humans were tested. According to the evidence reported by Shultz et al. [124], the results from in vitro experiments showed that CLAs might be cytotoxic to human cancer cells. In particular, physiologic levels of CLAs can inhibit the proliferation of human melanoma, colorectal and breast cancer cells in vitro [124]. More recent research has shown that using CLA supplements helps patients to lose weight, have lower leptin levels and have less body fat. CLAs were demonstrated to decrease body fat mass (BFM) in healthy human volunteers who were overweight or moderately obese [125]. Cavaliere et al. [12] studied the effects of milk obtained from cows fed a high forage diet on lipid metabolism, inflammation, mitochondrial function and oxidative stress using a rat model. The experiment lasted 4 weeks; the rats were fed with an isoenergetic diet supplemented with milk obtained from cows fed with a high forage/concentrate diet or a high concentrate/forage diet. The results showed a positive effect on lipid metabolism, mitochondrial function and oxidative stress in the experimental group, providing first evidence of the beneficial effects of milk obtained from cows fed a high-forage diet. Furthermore, Trinchese et al. [13] showed reduced lipid content and inflammation levels and improved mitochondrial lipid oxidation and redox status when supplementing rats' diet with milk obtained from cows fed a high-forage diet.

Thanks to the presence of bioactive fatty acids, dairy products can promote human health. Gomez et al. [126] illustrated the essential role of vaccenic and rumenic acids in the preservation of gut microbiota, weight control and the prevention of chronic inflammatory diseases. Rubino et al. [1] examined the metabolic effects of different isomers of CLAs, specifically highlighting the beneficial action of the c9t11 isomer on the improvement in insulin sensitivity in young, sedentary humans. In general, studies concerning the effects of CLAs on humans are fewer than those on animals. In developed nations, cardiovascular disease (CVD) is a leading cause of death, and atherosclerosis is the secondary cause of the majority of cardiovascular events [127]. For example, Toomey et al. [128] tested the effect of c9t11 on the reduction in atherosclerosis in mice. It was shown that CLA supplementation reduced atherosclerosis by suppressing the expression of pro-inflammatory genes and inducing apoptosis in the atherosclerotic lesion [128]. Moreover, Lee et al. [129] investigated the effects of diets supplemented with CLAs in rabbits on atherosclerosis and found significantly lower LDL cholesterol and triglycerides in the CLA-fed group compared to the control one. Additionally, CLA-fed rabbits had less atherosclerosis as seen via an aorta examination. It is clear that additional research, particularly on human subjects, will be required to further investigate the potential health advantages of consuming CLAs.

Dairy products can be identified as functional foods as they naturally contain high levels of vitamins, minerals and CLAs [129], thus constituting an essential element of a healthy diet.

Table 5. Health effects from dietary ingestion of CLA isomer cis9 trans 11.

BENEFICIAL EFFECTS	MECHANISM OF ACTION
anticarcinogenic	Cytotoxic activity against human cancer cells, in particular toward malignant melanoma and breast cancer [123]
antiobesity	Reduction in body fat mass [124]
antidiabetic	Normalization of glucose metabolism and improved insulin sensitivity [120]

Table 5. Cont.

BENEFICIAL EFFECTS	MECHANISM OF ACTION
prevention of chronic inflammatory diseases	Reduction in inflammatory markers in human cells, and prevention of subsequent related disease [125]
prevention of cardiovascular disease	Resolution of atherosclerosis by inhibiting the expression of genes that promote inflammation and cause apoptosis in the atherosclerotic lesion [127]

Public awareness of quality food production related to organoleptic and nutritional properties, cultural enhancement, environmental protection and animal welfare protection is constantly growing and is leading to individuals searching for healthy food. The implementation of NMM could increase the market of sustainable and better quality products with benefits for human health.

5. Conclusions

The “Noble Method[®]”, applied to the dairy sector (Noble Milk[®]), represents a novel livestock management system for a sustainable approach in terms of improvements in animal welfare, milk nutritional quality, human health and environmental factors. The increasing diffusion of the concept of One Health is an acknowledgement that the health and welfare of humans, animals and ecosystems are interconnected. In terms of human health, improved milk quality with an increase in CLA content improves immune functions and could have protective effects against cancer, obesity, diabetes and atherosclerosis. In terms of animal health, some studies have shown an improvement in oxidative status. The latter result could also be interesting in terms of a prolongation of productive life. Moreover, with the “Noble Method[®]”, the environmental impact of livestock farming could decrease. However, further studies are required to investigate the potential benefits of these productions in different fields.

The “Noble Method[®]” farming system reminds the consumer of a farm concept back to the origin. In fact, it includes all the expectations of the modern consumer: wholeness and respect for biodiversity and the ecosystem in general. At a time when multinational corporations are imposing the same foods and drinks on the world, the diversity of taste and local identities are felt to be values that need to be defended and encouraged.

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Review

Sustainable Management and Valorization of Agri-Food Industrial Wastes and By-Products as Animal Feed: For Ruminants, Non-Ruminants and as Poultry Feed

Dunja Malenica ¹, Marko Kass ² and Rajeev Bhat ^{1,*}

¹ ERA-Chair for Food (By-) Products Valorisation Technologies (VALORTECH), Estonian University of Life Sciences, Fr. R. Kreutzwaldi 1, 51006 Tartu, Estonia

² Chair of Animal Nutrition, Institute of Veterinary Medicine and Animal Husbandry, Estonian University of Life Sciences, Fr. R. Kreutzwaldi 1, 51006 Tartu, Estonia

* Correspondence: rajeev.bhat@emu.ee

Abstract: Substantial increase in the production of agri-food commodities over the past years has resulted in the generation of enormous volumes of wastes and by-products, thus contributing to increased environmental pollution. Being an under-exploited raw material which are rich in bioactive compounds (e.g., polyphenols, dietary fibre, oils, essential vitamins, minerals, etc), novel strategies and initiatives have been proposed and implemented for the effective management and valorization of these wastes and by-products. The proposed initiatives and strategies support the concepts of EU circular economy and green biorefinery, thus promoting sustainability. One of the strategies of management of waste and by-products includes the effectual development of nutritious low-cost sustainable animal feed. Currently, in the world market, there are a range of fruit and vegetable wastes and by-products that have been effectively introduced in animal diets. Within this context, this systematic review focuses on a diversified group of agri-food wastes (and the industrial by-products), their bioactive components, the opportunities for the development of animal feed or feed supplements (for Ruminants, Non-Ruminants and as Poultry feed) and conclusively the health benefits imparted. In addition, the safety issues and regulations aspects are also covered.

Keywords: animal feeds; bioactive compounds; circular economy; green biorefinery; waste and by-products; valorization; safety regulations

1. Introduction

Recent years have seen significant growth in the production of horticulture-based agri-food commodities. One of the reasons for the increased production is to fulfil the needs of the ever-growing population as well as to meet the changed dietary habits of consumers who have shifted to vegetarian-based diets [1]. Today, fruit and vegetable-based food industries are making upright progress wherein a wide range of products are produced and marketed such as jellies, syrups, juice, and chips. However, the production has also resulted in large quantities of waste and by-products (fruit and vegetable wastes; FVWs) being generated that go either as a landfill or are discarded in an unsustainable way. Owing to unsustainable disposal methods and practices, a significantly higher increase in environmental pollution is being witnessed [2,3]. As per the latest reports of the Eurostat, annually in the EU, approximately 57 million tons of food waste is generated [2]. Nearly 18 % of the total share of waste came from the processing and manufacturing sectors and the amount was nearly 10 million tons of fresh mass [2]. In the EU alone, an estimated €143 billion loss due to food waste is known, leading to approximately 6% of the total greenhouse gas emissions. According to the FAO (2014), 1.3 billion tons of food waste is generated annually, and 60% of this comes from fruit and vegetables. The amount of fruit and vegetable loss exceeds all other types of food wastes [4]. This can be the result of

poor processing, poor infrastructure and/or handling, as well as the behaviour of retailers and consumers [1]. Processing of agri-food materials tends to transform the raw material into stable products [5] and involves the application of selective processing techniques like drying, freezing, canning, peeling, pressing, etc. [6,7]. Recently, the main focus has been laid towards the management of food industrial wastes and by-products, their management and valorization [8–10]. Pomace represents the solid remains of processed raw material (fruit or vegetable) and it usually consists of the pulp, skin, stem and seeds. It is referred to as a by-products of the fruit and vegetables [11–13]. In Figure 1, fruit and vegetable processing leading to pomace generation is depicted.

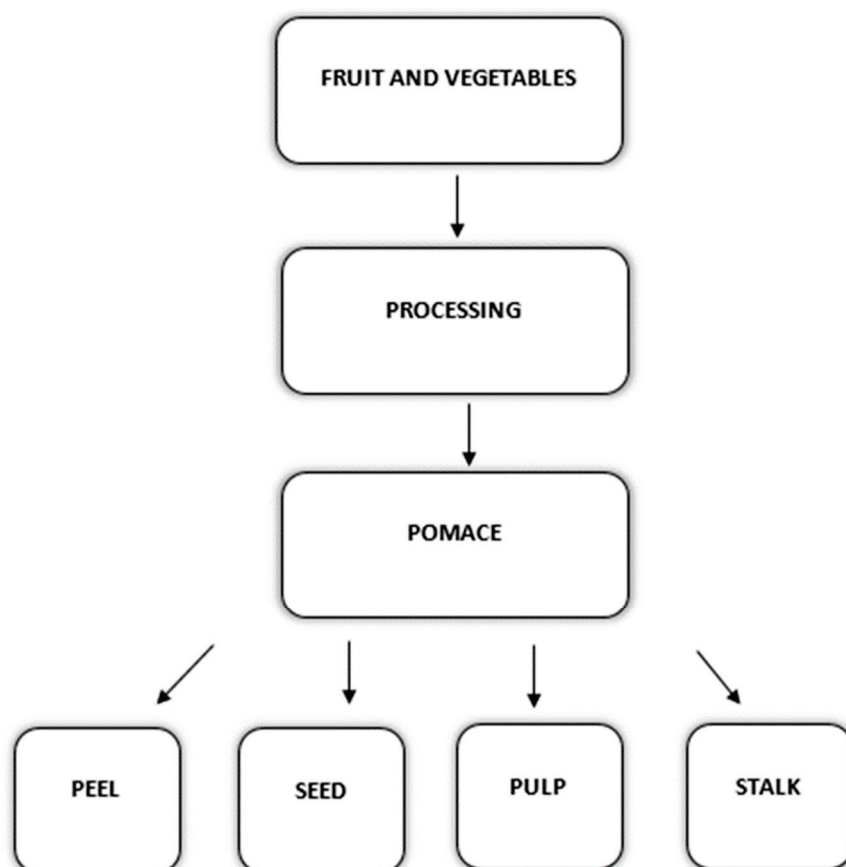


Figure 1. Fruit and vegetable processing leading to pomace generation.

Novel waste management strategies and initiatives have been implemented for the valorization of FVWs. One of these approaches includes green extraction techniques for extracting bioactive compounds and the development of animal feed. FVWs represent a highly under-exploited cheap raw material source, rich in bioactive compounds [3,14–16] and it holds high potential in animal feeds production. Exploiting these FVWs has been proven highly beneficial in animal nutrition and health, specifically in the livestock industry [17]. In addition, bioactive compounds obtained from FVWs have been proven useful in applications in food, cosmetics, paper, pharmaceutical industries, and others [18,19].

Today, the manufacturing of animal feed is already facing several issues and challenges due to a shortage of available fertile land, fresh water, ongoing climate problems, coupled with food-fuel-feed competition and a shortage of livestock feedstuff [17,20–23]. These challenges are especially prominent in middle- and low-income generating countries [24]. In addition to this, the cost of currently utilized ingredients for the development of animal feeds such as maize, wheat, soya and other commodities has recently increased [25]. Therefore, it has become a necessity to explore low-cost nutritious raw materials as well as develop novel low-cost feed in order to maintain the sustainability of livestock produc-

tion [26]. In this regard, FVWs have been evaluated as one of the potential and profitable substitutes/ingredients to produce animal feed due to their relatively low cost, easy availability and rich content of bioactive compounds, which could have a positive impact on animal welfare, growth and health [8,27,28]. Utilization of FVWs as animal feed may seem practical and economically useful, however, it meets certain limitations.

The digestibility of the feed is an important factor to be considered when it comes to including wastes as feed material for livestock. Feed digestibility is related to the nutritive value of feed and it predicts potential animal performance [29]. Adding high levels of FVWs in animal diets can lead to potential low digestibility of feed. In addition, increased amount of FVWs can result in decreased nutrient intake and growth performance of animals [30,31]. Low digestibility is attributed to a high content of neutral detergent fibre, especially lignin and also high concentrations of dietary phenolic compounds in FVWs. The high content of lignin in waste negatively affects the digestion of fibers as it compromises the access of fibrolytic enzymes to cellulose and hemicellulose which results in slower digesta passage rate thus causing a decline of dry matter intake (DMI). Dietary polyphenolic compounds are believed to inhibit the growth and activity of ruminal microbes such as *Bacteroides fibrisolvens* and *Ruminococcus albus* and several microbial enzymes too. Dietary phenolic compounds also have the ability to irreversibly bind certain nutrients such as fibre and crude protein [30–32].

Supplementing animal feed with FVWs at certain proportions could lead to adverse effects on animal performance, expressed as a decrease in milk yield or inhibited weight gain both in ruminant and monogastric animals [33–35]. Therefore, it is essential to evaluate the nutritional value, the content of active compounds and bioavailability of FVWs. It is important to evaluate their effect on animal performance and health too. Another limitation on FVW's use as feed ingredients can be attributed to insufficient research activities undertaken on the influences of FVWs on animal welfare.

Further, a consequential limiting factor of FVWs valorization in production of animal feed is the potential presence of heavy metals, chemical residuals, pesticides, toxins and anti-nutritional factors in high levels, which could have an adversarial effect on animal health or can even be fatal [28]. In order to avoid toxic agents, the manufacturing of animal feed must follow safety guidelines and good practices for use of agricultural wastes as animal feed [36]. Using FVWs as feed resources requires compliance with legislation and requirements of feed safety. The final product must meet chemical and microbiological safety standards [14,37,38]. However, complicated safety regulations and legislation of the utilization of FVW can sometimes intimidate farmers and feed technologists from using them as feed material [14]. Another aspect that needs to be considered is the hygienic quality during storage. Not enough information is available on handling, storage, processing conditions and production costs which can discourage animal nutritionists from including FVWs in feed development [14].

Even though, FVWs are of low-cost, their transport, treatment and processing can sometimes be very expensive and economically inefficient [14]. For example, the high moisture content of FVW is a problem, as it can lead to microbial deterioration and spoilage. In order to prevent the decay of FVW, it has to be transported urgently to the facilities, where water reduction strategies are performed on the waste. This results in high transportation costs especially if the facility is far away or transported waste material is heavy [39]. In addition, water reduction strategies can be pricey as well [40]. One of the solutions could be drying the waste and producing the feed at the same spot as where the waste originates in order to reduce transportation costs [39]. In addition, treatment and processing of FVWs can result in unknown effects on the nutrient content of the FVWs [14]. For example, drying methods can have a negative impact and decrease the level of bioactive compounds of FVWs. Among drying methods, freeze-drying has proven to be a suitable method for retaining the maximum amounts of bioactive compounds [40–42].

Other limiting factors for effective utilization of FVWs would be their seasonality and full-time availability. For manufacturing animal feeds, fruit and vegetables which

are produced throughout the year and are available in large quantities are always a better option. Low availability of certain fruit and vegetables also means inadequate product quantity, which further-on fails to support the supply chain. Therefore, a detailed evaluation of the selection of FVWs needs to be performed before their use as feed material [14]. In addition to this, the nutrient composition of FVWs varies depending on the season and this is important to consider while evaluating their use for feed development. [39]. Animals' response to FVWs is a very important factor as well. Animals responding poorly to feed with selectively supplemented or fortified FVWs could limit their further use as feed ingredient [14].

There are number of factors which need to be considered when it comes to the utilization of FVWs, but these should not outshine their positive impact on animal welfare, health and animal products. Bioactive compounds present in FVWs have been shown to have a high potential for enhancing animal well-being. In addition, the utilization of FVWs for the development of animal feed corresponds to the EU circular economy concepts created with the goal of reducing the production of waste and supporting the continued use of waste and by-products as resource material. The circular economy concept is an excellent alternative to the current inefficient linear economic model. Its principles offer tools and help to create sustainable feed and food systems [43]. With this background information, this systematic review focuses on a diversified group of agri-food wastes (and the industrial by-products), their bioactive components, the opportunities for the development of animal feed/feed supplements (for ruminants, non-ruminants and as poultry feed) and conclusively the health benefits imparted. In addition, the safety issues and regulations aspects are also covered in this review.

2. Methodology

For the current review, relevant research articles in international databases (Pubmed, Scopus, Science Direct, Google scholar) were explored, evaluated and compared. The literature survey was conducted in 2021 and 2022 and it focused on articles with keywords as fruit and vegetable waste, pomace, animal feeds, circular economy, safety and valorization technologies. The aim of writing this review is mainly focused to discuss the bioactive contents of selected pomace (waste and by-products) as well as to explore for opportunities on their role in animal nutrition and performance after processing it as animal or livestock feed. In addition, some of the current studies/reports wherein pomace has been studied as animal feed have been critically evaluated (Figure 2).

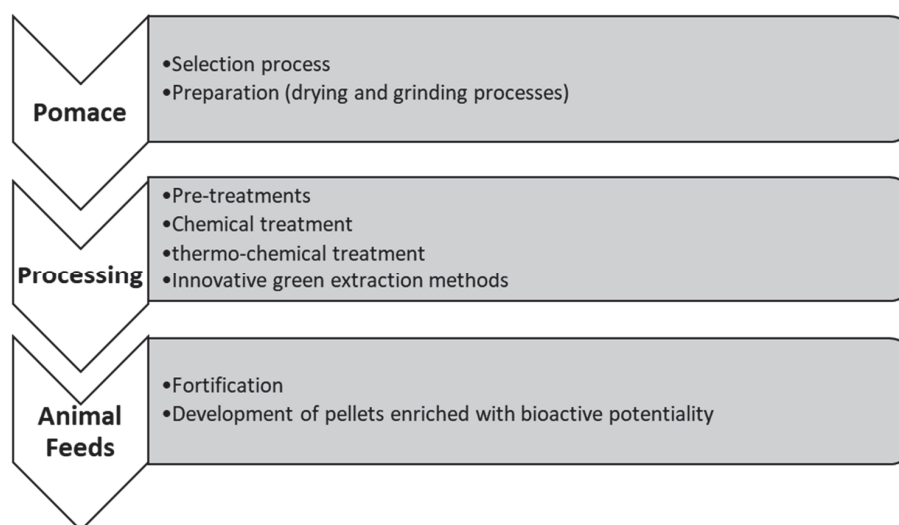


Figure 2. General processes involved for conversion of pomace to animal feed.

3. Composition of Fruit and Vegetable Wastes

Fruit and vegetable wastes (FVWs) encompass high amounts of various bioactive compounds with established bioactivities [1,3,18,22,44]. Nowadays, these compounds are frequently used in a range of industries, including paper, textile, pharmaceuticals, and food industries [1,19,45–48]. Therefore, the extraction of these bioactive compounds has recently gained a lot of attention and has been studied extensively. Green extraction methods are constantly being improved and modified so optimum yield and quality of bioactive compounds can be achieved. Environment-friendly procedures and green biorefinery techniques are being chosen over traditional methods.

3.1. Proteins and Enzymes

Proteins are an essential component in both human and animal diets influencing their growth. Proteins play an essential role in forming the muscles and are components of other molecules too. A deficiency in essential proteins often leads to various types of diseases in livestock, and therefore an adequate and high-quality source of protein is necessary. Soybean, rapeseed and crop legumes are the main sources of protein both for ruminant and monogastric animals. FVWs are an excellent source of protein too. For this reason, protein in FVWs is often used as valuable ingredients for the manufacture of feed components for livestock. Some examples include apple pomace, cabbage leaves, cauliflower stalk, radish leaves, pea pods, snow peas, potato, beetroot and carrot pomace [28,49]. In Table 1, the protein content of certain FVWs has been compared to protein content of conventional animal feed.

Enzymes are proteins which regulate chemical reactions in living organisms [50]. Enzymes such as pectinase, invertase, cellulase and amylases are extracted from FVWs with the help of certain bacteria or fungi [51–54]. Enzymes are used in a large number of industries, especially in the pharmaceutical sector and food industry [55,56]. Exogenous enzymes are often added to animal feed to improve digestion, animal performance and growth [57]. This is often seen in post-weaning pigs whose gastrointestinal tract, immune system and enzyme secretory capacity are not fully developed [58–60]. In the first few days after weaning, piglets often suffer from growth checks. In order to prevent growth check in weaned piglets, piglets' diets were supplemented with antibiotics, zinc oxide and copper, however, with the growth of antimicrobial resistance, new solutions had to be implemented, and exogenous enzymes have been successfully given instead [57]. In the research articles that have discussed the addition of exogenous enzymes to animal feed, there is limited information on whether enzymes were derived from FVWs. However, it is well-known that many enzymes, such as cellulase, hemicellulase, xylanase and invertase can be efficiently produced using FVWs. Commonly used FVWs for recovery of mentioned enzymes are peels of banana, orange, pineapple, pomegranate and citrus waste and by-products [53,55,61–63].

Based on the above-mentioned features, it is evident that protein plays a significant role in animal diets, however, protein content in feed does not describe the protein quality. Hence, it is necessary for the measurement of digestibility and degradability of protein in FVW to be evaluated prior to including them in the animal diet as this is more important compared to protein content. In addition, crude protein content is no longer considered a valuable parameter in the evaluation of feed quality. Crude protein content represents the amount of nitrogen present in feed which is then used to determine the amount of protein in feed [64]. However, protein is not the only component which contains nitrogen as nitrogen is also present in components such as nucleic acids and nucleotides, vitamins, amines, urea and amides. Nitrogen which is provided by these components is referred to as non-protein nitrogen (NPN). NPN fraction usually makes up a considerable percentage of crude protein content [64]. And even though ruminants can use non-protein nitrogen in their bodies [65] there are still problems with using crude protein as a measure of feed's protein quality. In addition, crude protein does not provide information on the actual nutritional value of protein, but the composition and the ratio of essential amino acids

(EAA) does give more information [66]. This emphasizes the importance of analyzing amino acids content in raw materials used for animal feed production. In addition, a deficit in any one of the essential amino acids can result in the interruption of protein synthesis which further negatively affects the performance of the animal [67,68]. A shortage of one amino acid (AA) can be limiting the absorption of others. The amount of AA in feeds is crucial as it could limit the growth and production in young stock [69].

Table 1. The protein content of selected FVW in comparison with typical protein feeds.

Feed	Crude Protein (% of DM)	Metabolizable Protein (g/kg DM)	Protein Degradability (% DM)	Reference
Soybean meal	53.60	95	58.50	[70]
Heat treated Rapeseed cake	36.30	166	53.40	[71]
Cold pressed Rapeseed cake	33.20	102	89.20	[71]
Maize grain	10.28	95.26	6.73	[72]
Wheat bran	15.68	107.11	9.23	[72]
Maize fodder	9.77	72.01	5.37	[72]
Canola meal	40.10	92	4.75	[70,73]
Tomato pomace	22.21	6.30	9.74%	[74]
Beetroot pulp	93.40	4.8	3.46%	[74]

3.2. Dietary Fibre

Dietary fibre plays a vital role in livestock nutrition as their source and fractions affect physiological functions of the gastrointestinal tract, gut health, gut microflora, and performance in ruminants [75], monogastric animals [76] and poultry [77]. Dietary fibre represents non-starch carbohydrate polymers, which cannot be digested in the small intestine of non-ruminant species [49,78]. Dietary fibres are commonly divided into insoluble and soluble dietary fibre based on their water solubility [49]. However, recent research on the contribution of dietary fibre to a monogastric diet, argues against this classification because the solubility of polymers depends on more factors than just solubility in water [79]. These factors include molecular properties and conformational entropy. Therefore, certain polymers which are considered soluble can sometimes be in fact poorly soluble in water. The study has debated that the current classification of dietary fibre into soluble and insoluble is not enough to clarify how dietary fibre positively affects the health of monogastric animals [79]. More information on the classification of dietary fibre based on their chemical properties is discussed by Arranz et al. [80].

Dietary fibre includes cellulose (as the main macromolecule in vegetable waste), hemicelluloses, lignin, pectin, inulin, β -glucans, gums and non-digestible oligosaccharides [49,81]. Today, many sources of dietary fibre such as hay and silage are being partially replaced by FVWs in the production of animal or livestock feed. This is because many FVWs are rich in dietary fibre, and they represent an affordable and easily available source of needed nutrients.

Regarding the role of dietary fibre in monogastric animals' diets, Montagne and co-workers undertook a study to evaluate the effects of dietary fibre on health and gut development in young non-ruminants such as piglets and chicken [82]. The study concluded that some components of dietary fibre improve gut health and play a role in prevention of reducing duration of diarrhea in young non-ruminant animals.

A difference between the effects of soluble and insoluble dietary fibre has also been established. For example, when it comes to general effects on intestinal pathology of non-ruminant animals, soluble fibre increases intestinal transit time, delays glucose absorption, delays gastric emptying, increases pancreatic secretion and slows absorption while insoluble fibre decreases intestinal transit time, improves water holding capacity and it helps in faecal bulking. Dietary fibre can positively affect the reproductive performance in pigs [82]. In weaned piglets, DF (dietary fibre) helps the GIT (gastrointestinal) function and development mostly by changing the microbial composition, and the activity of microbials and by stimulating the production of volatile fatty acids (VFA). VFAs, and especially butyrate, help the proliferation and differentiation of epithelial cells [83]. In growing pigs, even though only partly digested, dietary fibre is an inevitable part of the feed. Dietary fibres' contribution to energy supply is almost negligible in growing pigs; however, its contribution to energy supply increases in mature pigs and especially sows. The digestibility of dietary fibre depends highly on the source as it has been shown that dietary fibre extracted from beet pulp and soybean hulls is more digestible by pigs than the one coming from wheat straw [84].

Further, dietary fibre is established to play an important role in ruminants' diets. Dietary fibre influences the intake and digestion of nutrients which affects the animal's performance. A high dietary fibre diet increases mastication and rumen fermentation time and therefore salivation as well. Reducing the particle size through mastication and rumination is an important part of digesting forage. Mastication and rumination reduce the size of particles and increase the surface available for rumen enzymes and microbes. Increased salivation time plays a significant role in maintaining the normal rumen function as it affects the buffering capacity of rumen fluid and provides optimal ruminal pH for the growth of cellulolytic microbes. The growth of cellulolytic microbes tends to stimulate the production of acetic acid, a precursor for milk fat, and hence high-fibre diets can prevent milk fat depression in lactating ruminants [85]. Animals' performance depends on the intake of digestible nutrients so the digestibility of fibre is an important aspect which needs to be considered [86]. For example, 20–70 % of cellulose might not be digested by an animal which further influences net energy being significantly decreased compared to energy intake [87]. There are a number of factors affecting the digestion of dietary fibre and those include plant structure, plant species and maturity, nature of the predominant microbial fibre-digesting microorganisms, factors that control the adhesion of hydrolytic enzymes of microbial population, and animal factors which influence mastication and salivation [86]. The composition and amount of animal feed also play a role in the digestion of dietary fibre, especially the concentration of non-structural carbohydrates, N supply of feed and supplementation of diet with fat and fatty acids [87]. For example, an increased supply of non-structural carbohydrates decreases fibre digestion as this leads to lower ruminal pH, which might not be suitable for cellulolytic bacteria. In addition, the increased availability of amino acids showed an increased rate of fibre digestion while an increased supply of fats and fatty acids negatively influence fibre digestion due to their toxic effect on rumen bacteria [86]. Increased feed intake decreases rumen residence time which leads to incomplete digestion of digestible neutral detergent fibre [86].

Several FVWs such as apple pomace, grape pomace, pumpkin pomace and potato peels, contain significant amounts of dietary fibre (see Table 2) [1,49,88,89]. For example, apple pomace is a superior source of soluble (pectin) and insoluble fractions of dietary fibre with the proportions of these two fractions being well-balanced. Grape pomace are also a rich source of dietary fibre, mostly hemicelluloses, cellulose and in small amounts, pectin [1].

Table 2. Dietary fibre in some of the fruit and vegetable pomace.

Trait	TDF (%)	IDF (%)	SDF (%)	References
Apple pomace	53.1	47.0	6.10	[90]
Banana peel	65.55	54.06	11.49	[91]
Black currant pomace	76.87	68.73	8.14	[91]
Blueberry pomace	59.1	56.7	2.4	[90]
Cranberry pomace	59.3	56.2	3.0	[90]
Carrot pomace	69.85	45.12	24.73	[92]
Grape pomace	65.56	61.20	4.06	[93]
Potato peels	73.25	53.39	19.86	[92]
Pumpkin pomace	76.94	57.69	19.25	[94]
Peach pomace	54.5	35.5	19.1	[1]
Pear pomace	43.9	36.3	7.6	[1]
Tomato pomace	58.8	47.3	11.5	[95]

TDF = total dietary fibre; IDF = insoluble dietary fibre; SDF = soluble dietary fibre.

The aforementioned studies have shown the positive effect of dietary fibre in animal nutrition. A well-balanced diet involving high content of both protein and dietary fibre contributes to animal health with an emphasis on the positive impact on GIT. Fruit and vegetable-derived pomace remain a highly under-exploited source of many important bioactive compounds including dietary fibre. Their disposal means meagre wasting of numerous important bioactive compounds, which could be utilized and could contribute to animal and human nutrition. Therefore, dietary fibre from agri-food waste needs to become efficiently utilized in order for the sustainability of food and feed systems to be achieved.

3.3. Polyphenolic Compounds

Polyphenolic compounds are bioactive compounds that can be easily obtained from a large number of plant products, including those of FVWs and by-products. It is opined that the amount of these secondary metabolites are higher in the waste portion of many fruits and vegetables compared to their edible fractions [1,18]. Owing to the positive health properties that phenolic compounds extracted from FVW exhibit, they are often added to animal diets. In Table 3, research activities undertaken on the phenolic contents in selected fruit and vegetable pomace are depicted.

Table 3. Phenolic compounds in some of the selected fruit and vegetable pomace.

Fruit & Vegetable Wastes/By-Products	Phenolic Compounds	References
Grape pomace	Gallic acid, galloyl glucose, quinic acid, protocatechuic acid vanillic acid glycoside, feruloyltartaric acid, p-coumaric acid O-Glycoside, caffeic acid, eriodictyol hexoside, myricetin-O-glycoside, quercetin, quercetin 3-O-galactoside, quercetin 3-O-glucoside, quercetin 3-O-glucuronide, quercetin 3-O-rhamnoside, quercetin-glucuronide, Laricitrin 3-O-galactoside, laricitrin-3-O-rhamnose-7-O-trihydroxycinnamic acid, syringetin -3-O-galactoside, Isorhamnetin 3-O-glucoside, robinin, catechin, epicatechin, Procyanidin B3, Procyanidin B1, Procyanidin B4, procyanidin B2; cyanidin glucoside or galactoside; peonidin 3-glucoside or galactoside; malic acid, critic acid, tryptophan; malvidin-hexoside malvidin-acetylhexoside, delphinidin-rutinoside, malvidin-dihexoside, petunidin-rutinoside, peonidin-rutinoside, malvidin-rutinoside	[16,96]

Table 3. Cont.

Fruit & Vegetable Wastes/By-Products	Phenolic Compounds	References
Apple pomace	proanthocyanidins, flavonoids: quercetin 3-O- rutinoside, quercetin 3-O-galactoside, quercetin 3-O-glucoside, quercetin 3-O- xyloside, Quercetin 3-O-arabinoside and quercetin 3-O-rhamnosidehydroxycinnamates, and dihydrochalcones, phloridzin, chlorogenic acid, coumaric acid, chlorogenic acid, gallic acid,	[49,97]
Pumpkin waste	Gallic acid, protocatechuic acid, 4-hydrxybenzoic acid, caffeic acid, chlorogenic acid, p-coumaric acid, feluric acid, sinapic acid, and vanilic acid Flavonols: Astragalin, Rutin, kaempferol, isoquercetin, myricetin, and quercetin	[21]
Sea buckthorn pomace	Flavanoid glycosides, ellagitannins, flavonoids, isorhametim, quercetin derivatives, anthocyanins, tocopherols and carotenoids	[98]
Apricots pomace	Neochlorogenic and chlorogenic acids, proantocynidin, kaempferol glycosides, cyanidin 3-glucoside and certain quercetin derivatives	[15]

Phenolic Compounds in Wastes and By-Products

The content of polyphenolic compounds in FVWs are associated with the nutritional quality of plant material. For example, grape waste (pomace), generated in wine or juice industries consists of large quantities of grape pomace, which includes grape seeds, pulp, skins and stalks and is rich in phenolic compounds. It is commonly disposed-off creating environmental issues, so its utilization in developing animal feed is one of the better alternatives. Grape pomace is easily available, and of low cost which makes it a good and cheap source of important nutrients [16]. Grape seeds contain high amounts of polyphenolic compounds, in particular pro-anthocyanidins, the class of phenols which exhibit antioxidant activity and free radicals scavenging capacity [17]. The amount of phenolic compounds in grape seeds is higher than in grape skins and stems [96,99]. Grape seeds also manifest the highest anti-oxidant, cytotoxic and antibacterial (against Gram-positive bacteria) activities [15]. In addition to pro-anthocyanidins, grape wastes contain flavonoids. Grape seeds and grape marc have been shown to prevent fatty liver disease and ketosis when added to the diet of dairy cows by reducing inflammation and stress in the endoplasmic reticulum in the liver. This has been attributed to high content of flavonoids. In addition, the high content of tannins in grape seeds and grape marc influences ruminal metabolism. Tannins have also shown to improve milk yield [100]. In addition, phenolic compounds extracted from grape pomace play a role in inhibiting the growth of certain bacteria such as Gram-positive *Staphylococcus aureus*, *Listeria monocytogenes* and Gram negative *Pseudomonas aeruginosa* [101]. Due to their health-beneficial properties, the recovery of phenolic compounds has received a lot of attention.

Sea buckthorn (SBT) berries (fresh and processed) are a common food ingredient rich in nutrients and health-promoting compounds [102–104]. SBT pomace and leaves are rich source of polyphenolic compounds. Moreover, berries, leaves and twigs have equal cytotoxic activity which makes the whole plant of sea buckthorn attractive to be used at the industrial level [105]. In addition to phenolic compounds, they contain numerous minerals, vitamins, carotenoids and fatty acids [98,104,106]. However, the content of phenolic components is highly related to a variety [107], cultivation techniques [108], and processing methods adopted [109]. Recent years have witnessed extensive research with regard to the recovery of bioactive compounds from SBT pomace. SBT leaves have a higher content of phenolic compounds compared to berries. Leaves are rich in flavonoid glycosides, especially isorhamnetin and quercetin derivatives, and ellagitannins [98]. In addition, the young shoots of SBT are considered to have similar levels of bioactive com-

pounds as leaves [110]. Several studies on livestock have shown that SBT leaves or leaf extract have a beneficial effect on the growth performance in calves [111], piglets [112] and in poultry [113]. Moreover, the leaves could have specific or general health-promoting effects on farm animals [114–117].

Significant amounts of olive pomace are obtained from olive oil industries and their disposal in landfills and rivers negatively affects the environment. There are several alternatives recommended for olive pomace utilization and one of them is the extraction of polyphenolic compounds that have wide applications in the food and pharma sectors. Efficient valorization of olive pomace can also provide financial support to farmers and animal feed producers. Oleuropein represents the most profuse phenolic compound in olive pomace [118,119]. In addition to oleuropein, hydroxytyrosol is the most important phenolic compound derived from olive pomace and especially olive leaves. Recent years have seen a great interest in recovering phenolic compounds from olive leaves. Olive leaves are rich in polyphenolic compounds such as gallic acid, egallic acid, caffeic acid, salicylic acid, pyrogallol, catechin, catechol, syringic acid, chlorogenic acid, coumarin, ferulic acid, vanillic acid. Olive leaves are also rich in flavonoids like hesperidin, naringin, hesperidin, rutin, quercetin, luteolin, apigenin 7-O-glucoside, kaempferol, rosmarinic acid, rhamnetin and apigenin [118,120,121]. They are often utilized for the production of ruminant feed and as feed supplements. In the diet of ewes, polyphenols from olive pomace influence the rumen metabolism at various levels as they affect the microorganisms related to bio-hydrogenesis. Food and feed supplemented with phenolic compounds extracted from olive waste showed increased nutritional content [119].

Pumpkin wastes are also a rich source of bioactive polyphenolic compounds. It contains protocatechuic acid, caffeic acid, chromogenic acid, p-coumaric acid, gallic acid, vanillic acid, 4-hydroxybenzoic acid, sinapic acid, kaempferol, isoquercetin, myricetin, rutin, astragalin, and quercetin [21]. The application and uses of pumpkin waste as a feed supplement is discussed later on in the text.

Apricots pomace also has high contents of phenolic compounds, specifically - neochlorogenic and chlorogenic acids, proanthocyanidins, kaempferol glycosides, cyanidin 3-glucoside and certain quercetin derivatives. The phenolic content in apricot pomace depends on the cultivar of the apricot. The content also differs between apricot skin and flesh [15]. Citrus fruits pomace contains phenolic compounds, especially flavonoids like narirutin, hesperidin, naringin, and eriocitrin, and the quantity is comparable to edible portions [122]. These fruits exhibit strong bioactivity and are often used in livestock diets. Phenolic compounds in banana peels include benzoquinones, hydroxyl-benzoic acids, and acetophenones, phenylacetic acids, anthraquinones, naphthoquinones, isoflavanoids and flavonoids, lignins, lignans, and tannins. In addition, banana peels contain galocatechin and dopamine, which are natural antioxidants as well and are used in pharmaceutical industries or in food industries as a natural food preservative [17]. Apple pomace, frequently obtained during post-processing of apples for the production of fruit juice, has been proven as a good source of polyphenolic compounds. Pomace contains apple seeds, a little amount of stem, residual flesh and apple peel. Apple pomace is especially rich in pro-anthocyanidins and flavonoids [123]. In addition, non-specific poly-phenolics such as chlorogenic acid were also detected in apple pomace. Apple seeds are a good source of polyphenols. In fact, polyphenols represent a predominant component of seeds. The most abundant polyphenol in apple seed is phloridzin but its content is very high in other portions of this fruit as well.

3.4. Essential Oils and Lipids

FVWs have also been explored for the recovery of bioactive essential oils, lipids and organic acids. Some of them are discussed in the below text.

Essential oils (EO) are extracted from a number of fruits and vegetables wastes, especially citrus fruits [122,124,125]. There are numerous studies reporting on the effect of addition of EO to animal feed. The study by de Souza and co-researchers reported the

effect of clove, eugenol, thymol, vanillin and rosemary EO on animal performance, in situ digestibility, behaviour activities, feed intake and carcass characteristics of heifers [126]. EO was added to a high-grain diet and the study reported improved daily weight gain, in situ dry matter, neutral detergent fibre (NDF) digestibility, behaviour activities and feed efficiency of animals. EOs had negligible or no effects on the muscle, fat or bone percentage of the carcass. In the study by Nanon [127], it was reported that lemongrass oil and a mixture of garlic and ginger oil to improve the dry matter digestibility of fibrous feed due to improved NDF digestibility. The reported work showed that the EO can be used as rumen modifiers to improve the digestion of feed, especially roughage feeds. Furthermore, adding EO to animals' diet had no effect on methane production. The addition of baccharis, tamarind, cashew nutshell liquid and clove oil to high grain diet of beef cattle did not alter feed intake, nutrient digestibility, animals' performance or feeding behaviour. In fact, supplementing EOs to the diet resulted in improved dry matter, organic matter and NDF digestibility. The addition of mentioned EO increased the concentration of propionate causing the reduction of the acetate /propionate ratio [128]. Furthermore, in the study by Mottin and co-workers, the inclusion of clove, cashew, castor oil and a blend of eugenol, thymol and vanillin did not alter carcass characteristics, but it did alter the body composition of fat and muscle. EO did not modify drip losses, pH or fat thickness [129]. In addition, supplementation of these oils affected thawing/ageing and cooking losses, it increased water loss and altered the colour, texture, antioxidant activity and lipid oxidation of the meat. It has been concluded that EO can be added to animals' diets in the right dose as the high doses can present oxidative effects.

In addition, FVW contain a high amount of lipids as well. Some of the waste that contains high amounts of lipids include mango kernels (stearic acid, oleic acid and palmitic acid), tomato seeds, apple seeds, pomegranates seeds and apricot seeds [1,17,49].

3.5. Organic Acids

Citric and lactic acids can be obtained from various types of FVWs. Owed to citric acid's multiple usage and demand, its production and utilization have been thoroughly studied. The strategy of obtaining acids from FVW is opined to reduce production costs, as FVW is readily available and of no cost, besides being environmental-friendly [130,131]. Organic acids can be obtained from apple pomace [132,133], white grape pomace [134], pomegranate peel [131], pineapple waste [135], banana peel [130], mango peel [136] and orange peel [136,137].

4. FVWs in Animal Feeds

4.1. Utilization of FVW in Ruminant Feed

Today, the livestock sector contributes significantly to global warming and the production of greenhouse gas emissions mainly through processes of growing livestock, and processing and transportation of animal feed and products of animal origin [21,138].

The quest for exploitation of novel feed resources could be one of the solutions for sustainable animal feed production. Their utilization could lead to a reduced negative impact on the environment and promote zero-waste horticulture [139,140]. It is believed that FVWs can up to a certain extent replace the current feed resources, that are already in shortage, and additionally enhance animal health [17,18,20,141]. Utilization of FVWs in animal feed development could also be a solution to the shortage of available land and water, current food-feed-fuel competition and continued increase of the price of currently used ruminant feed material. In addition, not only does the utilization of FVWs mitigate environmental pollution by not being disposed in landfills or via other unsustainable ways, but also feeding of selective FVWs has been noted to decrease nitrogen (N) and methane (CH₄) emissions. For example, condensed tannins from grape pomace have been shown to adjust the metabolism of nutrients in ruminants. They have the ability to shift the excretion of N from urine to faeces. The excretion of N through faeces contributes less to N emission compared to urine N [31]. In addition, condensed tannins have the ability to also

change microbiomes in rumen and fermentation process resulting in a decrease of CH₄ emissions [142,143].

As production-related waste in fruits and vegetables ranges between 30 to 70% of the proceeded material [14], there have been many studies evaluating the use of certain FVWs for the production of ruminant feed [28,123,144]. Moreover, the utilization of FVWs initiates the use of less food-competing materials in ruminant diets [141]. A number of factors influence the use of FVWs as alternative feeds for a ruminant. These include the nutritional value of FVWs and their effect on the production, performance and quality of milk and meat. In addition, the digestive physiology of ruminants and the high content of fibre in FVW needs to be considered when adding a large amount of FVWs to the animal diets [144]. It is important to consider various costs involved in the production too. In addition, it is necessary that these feed resources are not suitable for human consumption or production of energy so that food-feed-fuel competition can be avoided [17,20].

Pumpkin waste has been characterized as a potential feed resource for livestock feed. In the review by Valdez-Arjona & Ramírez-Mella [21] the researchers evaluated its addition to diet of ruminants and concluded that pumpkin wastes possess good nutritional value and bioactive compounds such as polyphenolic compounds (carotenoids especially), polyunsaturated fatty acids, proteins, vitamins, minerals, pigments and polysaccharides which positively affects the milk and meat composition of ruminants. In addition, study reported increased amounts of α - and β -carotene, violaxanthin and lutein in milk [21]. Further, Boldea and co-workers concluded that addition of pumpkin seed cake to the diet does not alter milk yield or milk composition in dairy goats [145]. Replacing 30% of corn stubble (stover) with pumpkin wastes in the diet increased the ruminal digestibility of dry matter, but decreased the digestibility of NDF. The addition of pumpkin waste also enhanced the overall health and welfare of ruminants as the waste manifests a number of health activities such as anti-parasitic, antioxidant, antimicrobial, antifungal, and anti-inflammatory activities [21].

In the study by Mannelli and co-workers, supplementing olive pomace to ewe's diet increased the content of oleic acid and α -linoleic acid (α -LNA) in milk. It also increased milk yield and improved its nutritional quality [146]. Adding olive pomace to the feed did not alter the rumen functionality of ewes and there was no negative influence on animals' welfare. In the study by García-Rodríguez and co-researchers it was shown that the inclusion of olive cake increased diet degradability but did not alter rumen fermentation, synthesis of a microbial protein nor microbial growth [147]. Replacing barley straw and maize silage with olive cake showed increased diet disappearance, decreased methane production and there were minimal changes in the microbial population in dairy sheep. Dried stones of olive pomace added to the diet of lactating buffalos showed no negative effect on the quantity or quality of milk as the chemical properties of milk remained unchanged. The nutrient quality of milk however has increased as it showed a higher content of tocopherols, retinol, the presence of hydroxytyrosol, and an improved fatty acid composition [148].

Apple pomace has been routinely added to ruminants' diets without any detrimental effects on animal's growth, productivity or health. For example, feeding dairy goats with tomato and apple pomace silage, which replaced berseem hay up to 50%, improved milk yield and milk composition, digestibility and feed efficiency. This study concluded that the addition of tomato and apple pomace to ruminant feed is economically beneficial. It showed no negative effects on the animal performance or health of dairy goats and their offspring [149]. In a study by Fang et al. it was reported that the addition of apple pomace improves silage fermentation. It also enhanced ruminant productivity [150]. In addition, ensiled apple pomace has been successfully supplemented up to 30% in the feed of dairy cows [27]. The incorporation of 15% of ensiled apple pomace in the diet of dairy cows along with wheat bran, milled rice bran and chopped alfalfa resulted in enhanced production of milk with less milk fat [17]. However, even though apple pomace showed high potential

and is widely used, its utilization can be limited due to the alcohol content that is produced during fermentation.

Incorporation of banana peels into ruminant diet shows immense potential as the banana peel is rich in bioactive compounds, it is highly nutritious and a good source of protein, fibre, minerals and phenolic compounds, including tannin, which is often used as a feed additive to improve performance of ruminants. In addition, banana peel is a good feeding material for ruminants since the rumen microbes are capable of digesting it and valuable bioactive components are therefore easily absorbed in the small intestine. Their presence in blood increases the production and quality of milk and meat. The addition of banana peel to the sheep diet increased degradability and VFA production [151]. Dairy cows fed with ripe banana peel showed increased milk productivity [123]. In many countries, banana foliage has been used in ruminant feed, and it has been reported that it contains high amounts of tannins, flavonoids and terpenoids which manifest various health benefits including anti-parasitic activities [17].

Sea buckthorn (SBT) pomace has been also considered as a supplement to the ruminant diet. It is rich in valuable components, mostly phenolic compounds—flavonoids, tocopherols, vitamins, proteins, highly digestible carbohydrates, etc. In a study reported by Hao and co-workers, SBT pomace was added to the sheep diet to evaluate its effect on digestion physiology and growth performance [152,153]. The study showed that the addition of SBT pomace to a certain percentage in sheep diet increased dry matter intake, average daily gain and *in situ* NDF degradation, without adverse effects on feed efficiency [152] or energy metabolism [153]. In addition, Qin et al. showed a positive effect of the administration of SBT pomace on meat quality characteristics and increased muscle mass in ram lambs [154]. Furthermore, in another study conducted on ram lambs [58], it was concluded that SBT pomace could act in various molecular targets regulating the browning of white adipose tissue. Similar results have been reported in studies with monogastric animals. Further, up to 12% of SBT pomace was administered in pigs without any negative effect on growth performance and overall meat quality [155]. In a study by Dannenberger and co-researchers, supplementation of 12% of dried SBT pomace was shown to have a moderate effect on immunity and the metabolism of fatty acids in growing pigs [156]. In addition, there are several other aspects which support SBT's potential in ruminant nutrition. Firstly, there was a finding that SBT meals could be a bio-sorbent to inhibit the negative effect of mycotoxins in feed [157]. Secondly, similar to apple pomace, sea buckthorn pomace at the level of 5% has the potential to improve the fermentation of alfalfa silage [158] and therefore could be considered as a silage additive.

Grape pomace can also be added to the ruminant diet and can be a partial replacement to forage in small ruminant diets [159]. It can improve BMI, animal growth, health, and overall welfare. A study conducted on addition of grape pomace in the sheep diet by Guerra-Rivas et al. [160], revealed increased quality of milk due to higher content of antioxidants and fatty acids. These acids also have a beneficial effect on sheep meat. However, many researchers have pointed out certain constraints and issues related to the utilization of grape pomace for the production of ruminant feed [161,162]. It has been established that high content of tannins and anthocyanins can negatively affect utilization of nutrients. On the other hand, tannins (along with other phenolic compounds) can enhance the metabolism in rumen by reducing methanogenesis (they can inhibit the growth and activity of certain methanogen bacteria) and by supplying small intestine with proteins due to decreased ruminal degradability [160]. Grape seeds are believed to possess immunomodulatory effect in sheep due to high amount of flavonoids and proanthocyanidins [22,159]. The supplementation of grape and citrus by-products to ruminant feed can also decrease the food production costs and prolong the shelf life of ruminant products. Their addition to the diet in the study showed no detrimental effect on animal growth, it improved DMI, the fatty acid profile and overall quality of ruminant meat. Grape and citrus fruits by-products also exhibit various bioactivities such as antioxidant, anti-inflammatory and anti-helminthic activities along with enhancing and modulating the

immune system of animals. Adding flavonoids extracted from grape pomace and citrus pulp below 200 g/kg DM can result in decrease of occurrence of parakeratosis and acidosis in ruminants. In addition, they can reduce oxidative stress due to high content of phenolic compounds [22].

4.2. Utilization of FVW in Poultry Feed

The predicted growth of the global population challenges the production of poultry feed resources as well. FVWs can be a representative of an excellent alternative to the current poultry feed resource in the market [163]. Presently, poultry are given xenobiotic drugs, which have proven to enhance animal productivity [163,164]. However, the long-term use of xenobiotic drugs frequently leads to excessive amounts of undesired chemical residues in the bodies of animals, which could be a threat to human health too. Xenobiotic drugs also have a negative impact on the reproductive performance of animals. It is believed that fruit and vegetable waste, apart from benefiting the health and performance of animals, can be a good alternative to synthetic growth hormones and antibiotics [163].

Apple pomace is rich source of dietary fibre, pectin, vitamin C and phenolic compounds. Previous studies have showed that the inclusion of apple pomace in a poultry diet improves the productivity and reproduction performances of chickens. However, there are several limitations to its inclusion. These include low digestibility due to the high rate of lignin/cellulose and small amounts of minerals and proteins [165]. On the other side, apple pulp has a high content of pectin, polyphenols and carbohydrates and it can be used to decrease the amount of uric acid and increase blood glucose levels in chicken [163]. According to Yitbarek and co-workers, apple pomace can replace 10% of maize bran without a negative impact on performance and production in broilers [25]. The addition of more than 10% can lead to reduced feed efficiency due to low fibre content. In a study where dried apple pomace was added to the broiler diet in different extent [165], the evaluation of gut development, antioxidant capacity, growth, immune response and blood biochemical parameters was performed. The study showed detrimental effects on the mentioned parameters when incremental levels of dried apple pomace were added to the diet. In a study conducted by Heidarifar and co-researchers, the inclusion of processed apple peel waste on broiler chickens under heat stress was evaluated [166]. Heat stress can often lead to oxidative stress and decreased productivity of animals. Antioxidants are often used to mitigate oxidative stress, however, the traditional poultry feed, which contains maize and soybean lacks antioxidants. Therefore, there is a vast scope on using feed resources rich in antioxidants such as apple pomace. The study concluded that the inclusion of apple pomace into the feed of broilers from 28 to 49 days of age, increased high-density lipoproteins (HDL) cholesterol, decreased low density lipoprotein (LDL) cholesterol and did not have any adverse effect on broilers' performance, productivity or carcass characteristics.

Banana waste has the ability to manage blood pressure and prevent the development of cancerous cells, diabetes and certain gastrointestinal diseases due to its high oligosaccharides content. It provides additional energy and has a positive effect on the growth, development, and reproductive performance of poultry due to its high starch levels [163]. In the study conducted on banana peel, Yitbarek and co-workers concluded that the addition of 10% banana peel enhanced poultry feed efficiency and feed conversion and the quality of poultry eggs and meat. However, its incorporation of more than 10% could result in a decreased growth rate of poultry [25].

Grape pomace has also been incorporated into poultry feed. Its high content of polyphenolic compounds has potential to prevent the negative impacts of pathogens and free radicals. A study was conducted on grape pomace inclusion in the feed of broiler chicks with the aim of evaluating its effects on their growth, digestibility of nutrients, blood parameters and meat quality [167]. Grape pomace supplementation showed positive effects on body weight gain during early growth stages, it reduced serum cholesterol levels and improved meat quality in broilers.

In addition, Kara & Kocaoglu-guclu evaluated grape pomace's supplementation in the diet of egg-laying hens and evaluated the egg production and quality parameters [168]. The study results indicated that grape pomace enhanced the overall chicken productivity as well as the production and quality of eggs. Also, overall blood levels of proteins, triglycerides and total serum cholesterol were improved in egg-laying hens [168]. In a study made by Lichovnikova and co-researchers, it was shown that supplementation of broiler feed with 1.5% red grape pomace did not lead to detrimental effects on their growth [169]. However, it increased the digestion of nutrients and the metabolisable energy and it also increased levels of antioxidants in the blood and the number of "good" bacteria *Lactobacillus* spp. in the ileum of broiler chicken.

Pumpkin waste inclusion in poultry feed has been shown to prevent certain degenerative diseases and oxidative stress. It is believed it also helps in the treatment of diabetes [163]. In regard to pumpkin seed, when added 6% into the diet of broiler chicken, it shows increased weight gain of broiler chicken, a decrease in abdominal fat and improved quality of breast meat [170]. Also, pumpkin seed oil does not have an adverse effect on productive performance [171]. Adding pumpkin leaf meal in the diet of broilers results in increased body weight gain and in a decrease of total serum cholesterol and fat content in the heart, gaster and muscles. Chickens' diet can also be supplemented with pumpkin seed oil, which extends the animals' life by decreasing phospholipids, triglyceride and cholesterol concentrations in the blood. In addition, it increases the chicken's weight and it can result in more eggs per hen weekly. This can be explained by the presence of phytochemicals in pumpkin, which stimulate the secretion of gastric juices, and enzymes, improve the intestinal mucosa, increase feed intake by stimulating olfactory receptors and enhance reproductive performances [163].

Dried tomato pomace is often used in poultry feed, however, it has low energy value which needs to be taken into account when added into feed formulations so that adverse effects are minimized. It is recommended that tomato pomace is added at the level of 15 or 20% in grown chicken. In the diet of layers that require less energy, it can be more successfully incorporated and replace wheat bran. Tomato pomace has a high amount of lycopene, a natural antioxidant, which is health beneficial for poultry. Lycopene and other carotenoids can also positively affect egg yolks' colour [25,172].

It is reported that sea buckthorn (SBT) pomace influences the colour, pH and rheological properties of eggs [173]. It can be used as a natural preservative rich in antioxidants and to inhibit lipid oxidation in breast muscles without altering the physicochemical properties [174]. In a study undertaken by Sharma et al. 20% of the crude protein of the traditional concentrate has been replaced with sea buckthorn cake in layer birds to evaluate its effect on egg production [175]. The inclusion of SBT cake in poultry feed by 20% improved egg production and had no negative impact on the quality traits of eggs. Contrary to this, Dvořák and co-workers showed that supplementation of SBT pomace could result in a more intense and darker colour of egg yolk [176]. In addition, SBT leaves, cake and pomace were added to broiler feed at different levels in the study conducted by Mushtaq and co-researchers [177]. This study showed that broilers' growth weight, feed intake and feed conversion ratio were not altered with the inclusion of sea buckthorn pomace, cake, and leaves in the poultry diet. It also did not alter mortality or serum mineral levels. It has been concluded that SBT leaves, cakes and pomace can be exploited as a non-conventional feed resource that can be included in the broiler diet without any adverse side effects.

5. Safety and Regulations

Materials which are not specifically produced for the purpose of developing animal feed can sometimes have unacceptable levels of residuals that can negatively affect animals' health and animal products. Feeding animals with these materials therefore has to be done considering regional regulations and with caution. FVWs can often be contaminated by heavy metals, toxins, mycotoxins, pesticides and chemical residues. If FVWs are used for the development of animal feed, their presence can negatively affect animal

health [28]. Therefore, following safety regulations, quality control systems and good practices for use of agricultural wastes as animal feed are necessary for ensuring the quality and safety of animal feed [36]. There are also legal restrictions regarding feeding animals with raw materials in order to prevent the spread of various pathogenic diseases. However, complicated safety regulations and legislation regarding the utilization of FVWs can sometimes intimidate farmers and feed technologists from using them as reliable feed material [14]. Worldwide, there are various systems used for ensuring the safety of feed ingredients as well as lists of ingredients which can be used and their limits and lists of ingredients which ought to be avoided [36]. Strict adherence to these safety norms and regulations is necessary.

6. Conclusions

Agri-food industrial wastes and by-products represent an unconventional but very promising alternative to current feed materials available in the market. They are a rich source of valuable bioactive compounds that exhibit a range of health-promoting properties that can contribute to overall animal welfare. In addition, certain bioactive compounds have also shown the ability to decrease both nitrogen (N) and methane (CH₄) emissions, therefore, mitigating environmental pollution. However, there are certain limitations in the valorization of wastes and by-products for the development of animal feed that still need to be considered such as a possible decrease in nutrient digestibility, complicated safety regulation and the high cost of waste treatment and transportation involved. In addition, there may always be concerns over high chances of microbial contamination, the occurrence of mycotoxins, the presence of heavy metals, pesticides or other chemical residuals, toxins and unwarranted anti-nutrient compounds. Besides, the cost-effectiveness of converting waste biomass to value-added products like that of animal feed also needs to be carefully designed.

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Article

Sustainable Utilization of Hemp Press Cake Flour in Ice Cream Production: Physicochemical, Rheological, Textural, and Sensorial Properties

Mirela Lučan Čolić ¹, Marko Jukić ^{1,*}, Gjore Nakov ², Jasmina Lukinac ^{1,*} and Martina Antunović ¹

¹ Faculty of Food Technology Osijek, Josip Juraj Strossmayer University of Osijek, 31000 Osijek, Croatia; mirela.lucan@ptfos.hr (M.L.Č.); martina.antunovic@ptfos.hr (M.A.)

² College of Sliven, Technical University of Sofia, 59 Bourgasko Shaussee Blvd., 8800 Sliven, Bulgaria; gnakov@tu-sofia.bg

* Correspondence: marko.jukic@ptfos.hr (M.J.); ptfosptfos2@gmail.com (J.L.); Tel.: +385-31-224-308 (M.J.)

Abstract: The aim of this study was to investigate the influence of replacing skim milk powder with hempseed press cake on the quality properties of ice cream. Four ice cream mix formulations were developed, three with hemp press cake (25.0%, 37.5% and 50.0% milk powder replacement) and one control sample. The physicochemical (basic composition, pH, titratable acidity, water activity) and rheological properties of the ice cream mixes and the fat destabilization index, overrun, texture profile, colour, and sensory attributes of the ice cream were analysed. The results showed that the partial replacement of milk powder with hemp flour had no significant effect on the total values of the main components of the ice cream; only the origin of the nutrients was changed, which affected the properties of the samples. In the enriched samples, a decrease in acidity (from 0.146% to 0.133% LA) and fat destabilization (43.70 to 26.84%); an increase in viscosity (from 1.319 to 1.908 Pa sⁿ), thixotropy (from 1682.00 to 2120.50 Pa/s), overrun (from 26.83 to 35.00%) and hardness (from 6833.12 to 14,660.06 g); as well as a change in colour to darker shades of red were observed. Although the incorporation of hempseed cake led to a decrease in sensory scores (from 7.57 to 6.47–5.63 on the hedonic scale), all samples were rated as acceptable. This study demonstrated that hemp press cake can be utilized as a functional and sustainable ingredient in ice cream production, providing additional nutritional benefits and creating a novel sensory experience for consumers.

Keywords: ice cream; by-product utilization; sustainable production; hemp press cake; physicochemical; rheological properties; texture; colour; sensory evaluation

1. Introduction

The increasing global population has prompted a demand for more efficient utilization of food and its by-products [1]. In addition, consumer awareness of the nutritional benefits of food by-products and their health-promoting properties has increased [2]. Due to beneficial health and functional properties, interest in the consumption of cold-pressed oils is driving the growth of this market [3].

A valuable by-product of cold-pressed oil is oilseed cake, which is often used as feed for livestock due to its considerable carbohydrate and gluten-free protein content [4–6]. In addition, oilseed cakes are rich in vitamins and minerals and contain valuable substances with antioxidant activity [7–10]. The cold-pressed cakes can be converted into value-added ingredients (hydrolysates, protein concentrate and isolate, and flour) Nowadays, cold-pressed seed cake obtained by cold pressing of hemp seeds presents an interesting and valuable by-product that is used in food fortification [11–14].

Known primarily as industrial hemp, *Cannabis sativa* L. is a herbaceous plant that is classified within the *Cannabaceae* family. Hemp is cultivated in numerous countries across different continents. According to the FAO [15], Canada is the leading producer of

hemp seed worldwide, with a total output of 32,988 tonnes in 2022. Australia, the Russian Federation, Chile, and the United States follow, with annual production ranging from 3600 to 1102 tonnes. The growing popularity of industrial hemp and its by-products is supported by data from Valuates Reports [16], which notes that the global hemp seed cake market was valued at 59 million US\$ in 2023 and an increase of 6.2% is predicted during the period 2024–2030.

Hemp seeds are considered a highly nutritious food due to their content of polyunsaturated fatty acids, essential amino acids, and insoluble fibre, along with vitamin E and mineral (phosphorus, potassium, sodium, magnesium, sulphur, calcium, iron, and zinc) content. Furthermore, they are also rich in several compounds that promote health, including phenolic compounds, tocopherols, and phytosterols [9,17,18]. After cold pressing of hemp seeds, a wide range of these compounds, including the oil, remain in the press cake, which offers a great opportunity for its utilization in the production of foods with potential health benefits [19,20].

Hemp, as well as its by-products, possess significant potential for application in the food sector across various industries. For example, there are some studies about the possibility of sustainable hemp flour [11,21–24] and hemp seed oil [25] applications in the bakery industry. These studies reveal favourable results concerning both the quality of the products and the acceptance by consumers when this ingredient is integrated into different baked items. Furthermore, hemp flour has been used in the production of gluten-free products, such as bread [26–28], crackers [29], and biscuits [30]. Its rich protein content, healthy fats, vitamins, minerals, and fibre make it a valuable addition to numerous food formulations designed to promote better health for individuals with gluten sensitivities. An interesting approach to hemp and its by-product use is focused on the production of products suitable for vegan and vegetarian diets, i.e., hemp drinks [31,32], hemp drink-based ice cream [33], or even vegan “meat” made from hemp protein [34]. These innovations such as beverages, frozen desserts, and meat substitutes not only fulfil dietary preferences but also enhance health benefits. Thereby, hemp and its by-products are lauded for their use in many industries and for improving the nutritional value of products, referring to their antioxidant potential and fatty acids content.

The composition of ice cream is intricate, comprising ice crystals, air bubbles, and fat droplets spread throughout a serum phase [35]. Due to its delicious sensory properties and popularity, it represents a great opportunity for food fortification, with the aim of increasing the intake of bioactive compounds by consumers [36,37]. However, the ingredients used in the production of ice cream, as well as the manufacturing process and conditions, have a significant impact on its quality [38–41], which represents a challenge for the food industry. Although some researchers have investigated the possibility of utilizing hemp press cake flour in some dairy products, such as fermented beverages [19,42,43], to the best of our knowledge, there is a scarcity of literature regarding hemp press cake utilization in ice cream production. With this in mind, this research was conducted to investigate the extent to which skim milk powder can be replaced by hemp press cake in ice cream with potential functional properties without compromising its physicochemical and sensory properties. Furthermore, such a replacement could be a trustworthy solution for the utilisation of by-products from hemp oil production.

2. Materials and Methods

2.1. Materials

The following ingredients were procured from a local shop: UHT milk with a fat content of 2.8% (Vindija d.d. Varaždin, Croatia), UHT cream with a fat content of 36.0% (Dukat d.d. Zagreb, Croatia), skim milk powder with a max 1.5% milk fat (95.00% total solids, 34.00% proteins, 1.50% fat, 50.00% carbohydrates; Dukat d.d. Zagreb, Croatia), and sucrose (Viro d.d. Zagreb, Croatia). Hemp press cake flour (92.27% total solids, 38.64% protein, 9.16% fat, 39.03% carbohydrates, 19.37% fibre), obtained by grinding the hemp seed cake following the cold pressing process, was gifted by a private industry (BioHill

BB oil d.o.o. Bijelo Brdo, Croatia). Soy lecithin was acquired from BDH Prolabo (VWR International GmbH, Darmstadt, Germany), and guar gum was sourced from Sigma–Aldrich (Saint Louis, MO, USA).

2.2. Ice Cream Production

Ice cream samples with the addition of hemp cake press flour, as well as control ice cream, were prepared as explained by Goff [44], with slight modifications (Figure 1). All ingredients were weighted separately according to the formulations reported in Table 1.

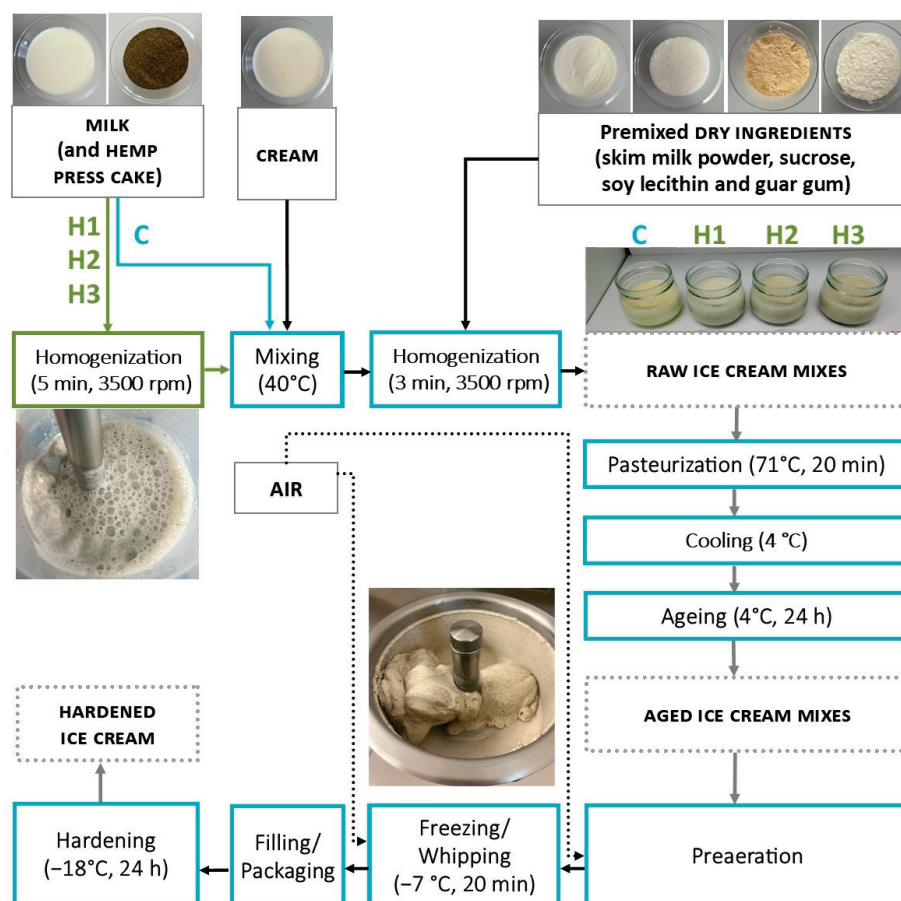


Figure 1. Flowchart of ice cream production.

Table 1. Ice cream sample formulations.

Ingredients (%)/Samples	C	H1	H2	H3
UHT milk	55.85	55.85	55.85	55.85
UHT cream	23.30	23.30	23.30	23.30
Skim milk powder	5.35	4.01	3.35	2.67
Sucrose	15.00	15.00	15.00	15.00
Soy lecithin	0.30	0.30	0.30	0.30
Guar gum	0.20	0.20	0.20	0.20
Hemp press cake flour	0	1.34	2.00	2.68
Replacement level (%)	-	25.0	37.5	50.0

C—control ice cream; H1, H2, and H3—ice cream with 25.0%, 37.5%, and 50.0%, respectively, skim milk powder replaced by hemp press cake flour.

The control sample (C) was prepared without the replacement of skim milk powder with hemp press cake flour. In the samples labelled as H1, H2, and H3, skim milk powder was replaced with hemp press cake flour at levels of 25.0%, 37.5%, and 50.0%, respectively. The minimum and maximum amount of hemp cake press flour was determined in preliminary sensory research with seven trained panellists.

Milk and hemp press cake flour were mixed (except for the control sample) using an IKA T 18 basic ULTRA-TURRAX homogenizer (IKA®-Werke GmbH & Co. KG, Staufen, Germany) at 3500 rpm for 5 min. Afterwards, the milk with hemp cake press flour and cream was heated up to 40 °C, and the previously mixed dry ingredients were added. Then, all components were mixed using an IKA T 18 basic ULTRA-TURRAX homogenizer at 3500 rpm for 3 min and pasteurized at 71 °C for 20 min. The ice cream mixes were aged at 4 °C for 24 h. Before the start of ice cream production, the ice cream mixes were pre aerated. An ice cream machine (GELATO 5K CREA i-Green, Nemox International S.R.L., Pontevico, Italy) was used to make the ice cream at $-7\text{ °C} \pm 1\text{ °C}$ for $20\text{ min} \pm 2\text{ min}$. The ice cream samples were sealed in plastic bags and hardened at -18 °C for 24 h prior to analysis.

2.3. Analysis of Ice Cream Mixes

2.3.1. Physicochemical Analysis

The evaluation of fat, protein, carbohydrates and total solids content were conducted using official methods of analysing [45]. The water activity (a_w) was determined using a water activity analyser HygroLab 3 Set (Rotronic AG, Bassersdorf, Switzerland) at $25\text{ °C} \pm 1\text{ °C}$. The pH values of the ice cream mixes were measured at $25\text{ °C} \pm 1\text{ °C}$ using a pH meter (WTW ProfiLine pH 3210, Wissenschaftlich-Technische Werkstätten GmbH, Weilheim, Germany). The determination of titratable acidity (TA) in the ice cream mixes was performed according to AOAC [45] by titrating the sample with 0.1 M NaOH solution, with phenolphthalein serving as the indicator. The calculation of TA was performed using Equation (1) [46].

$$\text{TA}(\%) = \frac{0.009 \times \text{Volume of NaOH (mL)}}{\text{Weight of the sample (g)}} \times 100 \quad (1)$$

All measurements were conducted in triplicate and the data are presented as mean $\pm$ standard deviation (SD).

2.3.2. Rheological Parameters

Rheological measurements of the produced ice cream mixes following the aging period were conducted utilizing a HAAKE™ Viscotester™ iQ Rheometer (Thermo Scientific™, Karlsruhe, Germany), which featured a temperature module controller. Utilizing coaxial cylinder measuring geometry (cylinder CC25 DIN/Ti), the measurements were taken at 4 °C within the shear rate of 0 to 300 s^{-1} and down from 300 to 0 s^{-1} at intervals of 6 s^{-1} [47]. All measurements were performed in triplicate; the data were obtained from the RheoWin Job Manager and reported as the mean $\pm$ standard deviation (SD).

The consistency coefficient K (Pa s^n), as well as flow behaviour index n , were analysed and the data were adjusted to align with the Ostwald de Waele model [48]:

$$\sigma = K\gamma^n \quad (2)$$

where σ is shear stress (Pa) and γ is a shear stress rate (s^{-1}).

Furthermore, the apparent viscosity η_{50} (Pa s) of the produced ice cream mixes was determined at a share rate of 50 s^{-1} , mainly known as the Kokini viscosity.

The thixotropic areas A_t (Pa/s) were derived from the areas under the ascending (A_{up}) and descending (A_{down}) flow curves [49]:

$$A_t = \frac{(A_{up} - A_{down})}{A_{up}} \times 100 \quad (3)$$

2.4. Analysis of Ice Cream Samples

2.4.1. Fat Destabilization Index Determination

The evaluation of fat destabilization was conducted following the method specified by Goff [50]. A weight of 3 g was measured for the samples of melted ice cream and mixes, followed by the addition of 27 mL of distilled water. Then, 1 mL of this solution was transferred into a 50 mL volumetric flask and diluted using distilled water. Centrifugation of the solution was performed at 1000 rpm for 5 min (Heraeus Multifuge 3SR Centrifuge, Thermo Scientific™, Waltham, MA, USA). Subsequently, the absorbance was measured at 540 nm after a 10 min period using a UV spectrophotometer (Shimadzu UV-1280, Shimadzu, Japan). Distilled water served as the control. The fat destabilization index (FDI) was calculated with Equation (4). The measurements were taken three times, and the results are reported as the mean value $\pm$ standard deviation (SD).

$$\text{FDI} = \frac{(A - A_0)}{A} \times 100 \quad (4)$$

where A is the absorbance of the diluted ice cream mix and A_0 is the absorbance of the diluted melted ice cream sample.

2.4.2. Overrun Determination

Overrun (OR) values of ice cream samples were measured using a 100 mL cup. Ice cream mixes (100 mL) and ice cream samples (100 mL) were weighed and the overrun (OR) was computed using the following equation:

$$\text{OR}(\%) = \frac{(w - w_0)}{w_0} \times 100 \quad (5)$$

where w is the weight of the ice cream mix and w_0 is the weight of the ice cream [40]. The assessments were carried out in three replicates, with the results reported as the mean value $\pm$ standard deviation (SD).

2.4.3. Instrumental Texture Analysis

The hardness, adhesiveness, gumminess and cohesiveness of the ice cream samples were analysed using the TA.XT Plus Texture Analyser (Stable Micro Systems, Great Britain, Godalming, UK), which was fitted with a Delrin cylinder of 10 mm diameter ($p/10$). The pre- and post-test speeds were 3.0 mm s^{-1} , the probe speed during the penetration was 3.3 mm s^{-1} , the penetration distance was set at 15.0 mm and the force was 5.0 g [51]. For every sample, seven measurements were carried out, and the data are represented as the mean value $\pm$ standard deviation (SD).

2.4.4. Instrumental Colour Analysis

The determination of colour parameters included the lightness value L^* (100, white; 0, black) and chromatic variables a^* (+, red; −, green) and b^* (+, yellow; −, blue) and was performed using a MiniScan WE colourimeter (Hunter Associates Laboratory, Inc., Reston, VA, USA, MiniScan XE Plus) based on the CIE-Lab colour space (CIE, 1976). A white and black plate was used for calibrating the instrument. Each sample underwent ten measurements with the outcomes presented as the mean value $\pm$ standard deviation (SD). The colour difference (ΔE) was calculated as follows:

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \quad (6)$$

where L^* , a^* , and b^* represent the values for the control sample, and L_0^* , a_0^* , and b_0^* the values for the samples with hemp press cake addition.

Furthermore, the hue angle (h^*), colour intensity-Chroma (C^*), whiteness index (WI), browning index (BI), and yellowness index (YI) were computed using Equations (7)–(11) [52].

$$h^* = \tan^{-1} \left(\frac{b^*}{a^*} \right) \quad (7)$$

$$C^* = \left[(a^*)^2 + (b^*)^2 \right]^{\frac{1}{2}} \quad (8)$$

$$WI = 100 - \sqrt{(100 - L^*)^2 + (a^*)^2 + (b^*)^2} \quad (9)$$

$$YI = \frac{142.86b^*}{L^*} \quad (10)$$

$$BI = 100 \times \left(\frac{X - 0.31}{0.17} \right) \quad (11)$$

where

$$X = \frac{(a^* + 1.75L^*)a^*}{(5.645L^* + a^* - 3.012b^*)} \quad (12)$$

2.4.5. Sensory Evaluation

The overall acceptability of the ice cream was assessed by a hedonic scale of 9 points, ranging from 1 (dislike extremely) to 9 (like extremely) [53]. Furthermore, acceptance of sensory properties, including appearance, scoopability, mouthfeel, taste, aroma and aftertaste was assessed using a 5-point hedonic scale, ranging from 1 (dislike very much) to 5 (like very much). A group of 30 semi-trained assessors (24 women and 6 men), including both students and academic personnel from the Faculty of Food Technology Osijek, Josip Juraj Strossmayer University of Osijek, Croatia, participated in the sensory evaluation. Participants were chosen based on their frequent consumption of ice cream and the absence of any known allergic reactions to hemp press cake and the standard ingredients of dairy ice cream.

The Faculty of Food Technology's Ethics Committee at Josip Juraj Strossmayer University of Osijek, Croatia granted approval for this study (Class number 602-04/23-08/01). Furthermore, all participants provided informed consent and confirmed that they had no known food allergies.

Prior to the evaluation, the ice cream samples were taken from a freezer maintained at -18°C , and allowed to temper at room temperature for 5 to 10 min to attain a temperature of -12°C . The samples were served in clear 40 mL plastic cups (Figure 2) marked with unique three-digit codes. To facilitate palate cleansing between testing, participants received crackers and water.



Figure 2. Ice cream samples presented to assessors during sensory evaluation.

2.5. Data Analysis

The analysis of the data was conducted using ANOVA, and the means were compared through the Tukey test at a 5% significance level, utilizing XLSTAT software version 2019.2.2 in Microsoft Excel (Addinsoft, New York, NY, USA). To analyse the relationships among the properties, the Pearson correlation coefficients (R^2) were determined.

3. Results and Discussion

3.1. Physicochemical Properties of Aged Ice Cream Mixes

3.1.1. Chemical Composition

Table 2 shows the chemical composition of the ice cream samples. The total solids, carbohydrates, fat, and protein, together with the incorporated air, can strongly influence the physical and sensory characteristics of ice cream. The results show that the partial replacement of skimmed milk powder with hemp cake had no significant effect on the change in the total content of the main components of ice cream. The composition of the ice cream mixes is characteristic of standard ice cream recipes. The values of the total solids, carbohydrates, fat, and protein ranged from 37.38–37.29%, 20.84–20.65%, 10.13–10.32%, and 4.38–4.32%, respectively.

Table 2. Chemical composition, acidity and water activity of ice cream mixes.

Parameter/Samples	C	H1	H2	H3
Total solids (%)	37.38 ± 0.46 ^a	37.33 ± 0.48 ^a	37.31 ± 0.48 ^a	37.29 ± 0.49 ^a
Carbohydrates (%)	20.84 ± 0.30 ^a	20.74 ± 0.29 ^a	20.70 ± 0.29 ^a	20.65 ± 0.28 ^a
Fat (%)	10.13 ± 0.11 ^a	10.22 ± 0.11 ^a	10.27 ± 0.11 ^a	10.32 ± 0.11 ^a
Protein (%)	4.38 ± 0.17 ^a	4.35 ± 0.16 ^a	4.33 ± 0.15 ^a	4.32 ± 0.15 ^a
pH	6.66 ± 0.00 ^d	6.74 ± 0.00 ^c	6.81 ± 0.00 ^b	6.90 ± 0.00 ^a
Titrateable acidity (%)	0.146 ± 0.000 ^a	0.142 ± 0.000 ^{ab}	0.140 ± 0.000 ^b	0.133 ± 0.000 ^c
a _w	0.946 ± 0.000 ^c	0.948 ± 0.001 ^b	0.949 ± 0.000 ^{ab}	0.950 ± 0.001 ^a

The results are shown as mean ± SD. Means in the same line with different superscripts are significantly different according to the Tukey HSD test ($p < 0.05$). C—control ice cream; H1, H2, and H3—ice cream with 25.0%, 37.5%, and 50.0%, respectively, skim milk powder replaced by hemp press cake flour.

These findings are partially consistent with those reported by Sakr et al. [54], who investigated the impact of substituting skim milk powder with *Adansonia digitata* pulp flour on the physicochemical characteristics of ice cream. Namely, they reported that the chemical characteristics of such ice cream were not significantly affected, with the exception of protein and ash content. Pereira et al. [55] reported that the total solids and fat content of ice cream samples did not change significantly when skim milk powder was partially replaced by soy extract. Conversely, Merlino et al. [13] noted that the partial replacement of wheat flour with hemp seed flour in *gnocchi* resulted in improved nutritional characteristics.

It is important to mention that the results of the chemical composition in this study are based on the total values of the parameters. The reason why the chemical characteristics of the hemp press cake samples in our research did not differ significantly from the control sample could be that skim milk powder and hemp flour have a very similar basic composition. According to the nutritional values declared by the manufacturer (specified in Section 2.1), it is evident that the hemp press cake, which partially replaced the powdered milk in the basic recipe of the ice cream, has a slightly different composition regarding its main components. Indeed, hemp flour has a slightly lower proportion of total solids and carbohydrates, and a slightly higher declared proportion of fat and protein. However, the overall composition of the ice cream mixes (Table 2) was not significantly influenced by the proportions in which the hemp flour was added to the ice cream mixes.

3.1.2. pH, Acidity and a_w Values

The pH value correlates with the composition of the ice cream mix [40] and is an important property in terms of ensuring the stability of the ice cream mix [56], and it influences the taste, texture and overall product quality [57]. According to Trejo-Flores et al. [57], the optimum pH range for ice cream is between 6 and 7, which is consistent with the results of this study. The pH values of the samples were changed by increasing the proportion of skim milk powder substitute (Table 2). The pH values of samples H1, H2, and H3 were 6.74, 6.81, and 6.90, respectively, and these values were significantly higher than for the control sample (6.66). Similar results were reported by Güven et al. [58] and Markowska et al. [59], who found pH values for ice cream samples in the range of 6.61–6.64 and 6.58–7.10, respectively. These results, i.e., the trend towards increasing pH values, are in agreement with those reported by Nakov et al. [42] who investigated the possibility of adding hemp press cake flour to bovine and ovine yoghurts. In addition, Nissen et al. [31] reported that among the investigated plant-based beverages in their study, the pH value for hemp beverages was generally the highest, because the hemp seed matrices possess buffering capacity. However, Xu et al. [60] reported that the addition of hemp protein to plant-based yoghurt resulted in a decrease in pH values, probably due to ingredients from hemp seed that promote the growth of lactic acid bacteria. Furthermore, as expected, the TA values were significantly decreased because of the hemp press cake addition (from 0.146% in the control sample to 0.142, 0.140, and 0.133% in the fortified samples). The alkaline nature of the hemp press cake may help to balance the acidity of the ice cream mixture, resulting in a reduction in titratable acidity.

Water activity is a characteristic that influences the food's shelf life [61]. Increased water activity can facilitate the growth of microorganisms, which may affect the quality and safety of the food product [62]. All samples enriched with hemp press cake had significantly higher a_w values (0.948–0.950) compared to the control sample (0.946). The increased water activity in these samples could be due to the moisture-retaining properties, i.e., the hygroscopic nature of the hemp-based ingredients [63]. This change in a_w values may affect properties other than shelf life, including texture and sensory properties.

The correlations calculated using Pearson's method between the analysed characteristics of the ice cream samples are illustrated in Figure 3. The correlation coefficients between the added hemp flour and the pH value and water activity were 0.987, and 0.995, respectively, while the titratable acidity showed a high negative correlation (−0.956) according to the Pearson correlation coefficients.

3.1.3. Rheological Properties

Viscosity, which refers to a liquid's resistance to flow, is an essential factor influencing the body and texture of ice cream [64]. This property is determined by the mix's composition, which includes the levels of total solids, stabilizers, proteins, fats, and salts, along with the processing methods utilized [40].

The rheological characteristics of aged ice cream mixes are given in Table 3, while the rheological behaviours are shown in Figure 4. The power law model yielded R^2 values exceeding 0.9989, indicating its effectiveness in analysing the rheological characteristics of ice cream mixes. The values for the flow behaviour index, n , were in the range of 0.622 to 0.681, which shows that all analysed ice cream mixes belong to the group of non-Newtonian pseudoplastic fluids.

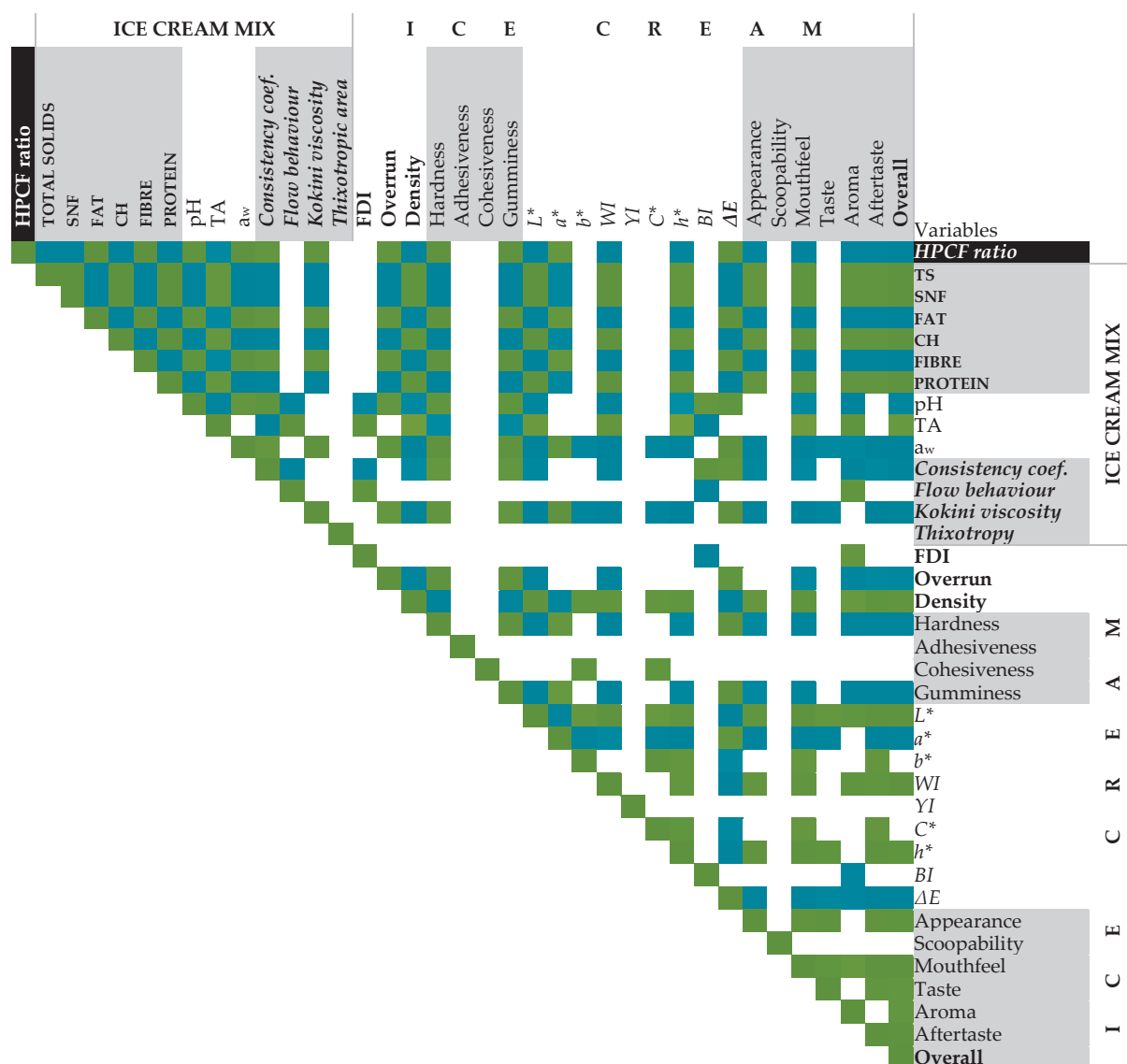


Figure 3. Pearson's correlation matrix. Coloured boxes indicate a significant correlation ($p < 0.05$); green boxes signify the positive and blue the negative correlations.

Table 3. Rheological properties of ice cream mixes.

Parameter/Samples	C	H1	H2	H3
K (Pa s ⁿ)	1.319 ± 0.028 ^b	1.570 ± 0.099 ^{ab}	1.649 ± 0.241 ^{ab}	1.908 ± 0.074 ^a
n	0.681 ± 0.005 ^a	0.661 ± 0.011 ^a	0.656 ± 0.016 ^{ab}	0.622 ± 0.010 ^b
R ²	0.9989	0.9990	0.9993	0.9999
η ₅₀ (Pa s)	0.379 ± 0.001 ^a	0.415 ± 0.008 ^a	0.434 ± 0.001 ^a	0.424 ± 0.035 ^a
A _t (Pa/s)	1682.00 ± 4.90 ^b	1656.50 ± 68.18 ^b	1630.00 ± 60.42 ^b	2120.50 ± 105.74 ^a

The results are shown as mean ± SD. Means in the same line with different superscripts are significantly different according to the Tukey HSD test ($p < 0.05$). C—control ice cream; H1, H2, and H3—ice cream with 25.0%, 37.5%, and 50.0%, respectively, skim milk powder replaced by hemp press cake flour. K—Consistency coefficient, n—Flow behaviour index, η₅₀—Kokini viscosity, A_t—Thixotropic area.

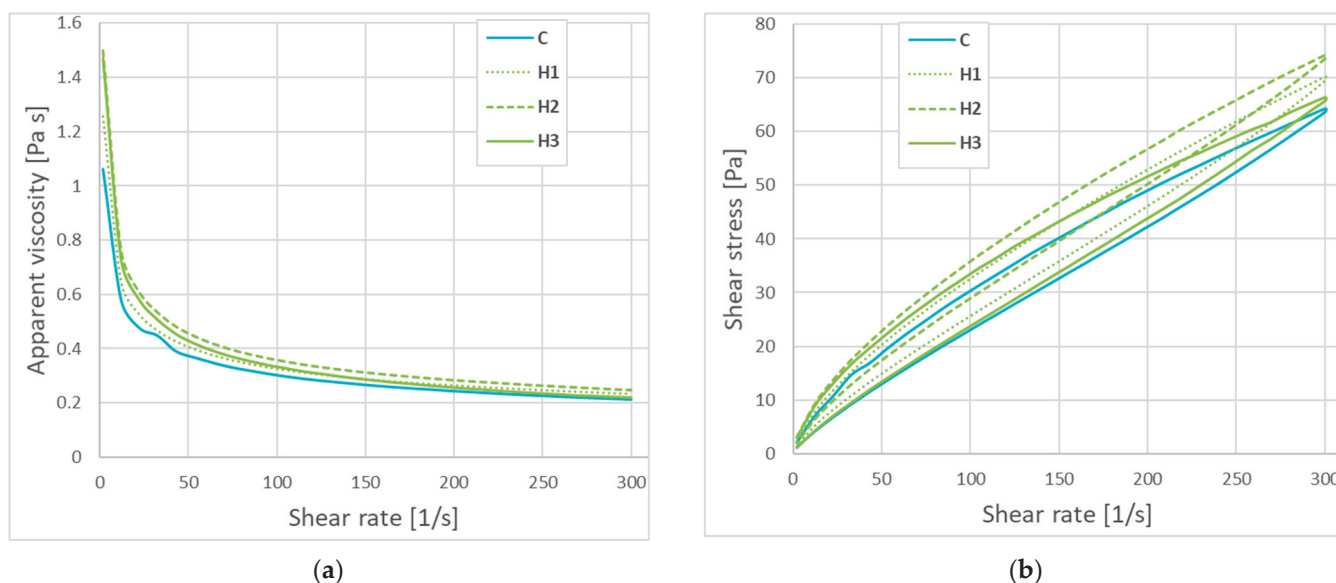


Figure 4. Flow behaviour of ice cream mixes: (a) apparent viscosity (Pa s) and (b) flow curves (shear stress in Pa at different shear rates in 1/s) of ice cream samples. C—control ice cream; H1, H2, and H3—ice cream with 25.0%, 37.5% and 50.0%, respectively, skim milk powder replaced by hemp press cake flour.

Figure 4a also shows that all samples exhibited pseudoplastic behaviour, as their viscosity decreased when increasing the shear rate. These findings are consistent with the results reported by Kasapoglu et al. [3] and Kurt et al. [65]. This investigation revealed that the control sample exhibited the lowest value for the K (1.319 Pa s^n). As the proportion of hemp press cake increased, the K values also increased (1.570 Pa s^n – 1.908 Pa s^n). However, the only significant difference was observed between the control sample and H3. In this study, a positive correlation (Figure 3, 0.978, 0.984) was found between the hemp press cake ratio, the consistency coefficient, and the Kokini viscosity values. It can be assumed that an increased substitution rate of skim milk powder by hemp press cake affected the rheological behaviour of ice cream mixes. Xu et al. [60] reported that the consistency coefficients in yoghurt samples with hemp protein were higher than in the control sample and that hemp protein could be used in order to improve the viscosity of yoghurt. The trend of increasing K values with the addition of cold-pressed coconut oil by-product [3] and cold-pressed chia-seed oil by-product [66] was also observed. In addition, they concluded that these by-products could be utilized to enhance the structural quality of some ice creams. Sakr et al. [54] reported that in ice cream with 25% and 50% baobab (*Adansonia digitata* L.) pulp instead of skim milk powder, K values were significantly increased, while this was not observed in samples with a higher replacement (75% and 100%).

The values of viscosity calculated at a Kokini shear rate of 50 s^{-1} (η_{50} , Pa s) are presented in Table 3. The Kokini viscosity values were 0.379 Pa s – 0.434 Pa s . According to Goff and Hartel [67], it is not possible to define an ideal mix viscosity; however, the apparent viscosity values are generally observed to range from 0.1 Pa s to 0.8 Pa s after the maturing process, which is in accordance with the results of this research. In a study performed by Hidas et al. [33], the apparent viscosity of a vegan ice cream mix made from hemp drink and stabilized with guar gum was 0.294 Pa s . Although there were no significant differences between the samples in the η_{50} value, as can be observed from Figure 3, there was a strong positive correlation between this value and the hemp flour content, indicating that the Kokini viscosity of the ice cream samples in this study was significantly influenced by the replacement of skimmed milk powder with hemp press cake.

Table 3 and Figure 4b show the hysteresis area, which refers to the difference in energy required for deformation and recovery, which is indicative of thixotropy. A larger hysteresis

area suggests a more pronounced thixotropic behaviour of ice cream [68]. All samples showed thixotropic behaviour, which is highly desirable for ice cream, as it indicates the ability to recover the viscoelastic character after deformation during processing [67,69]. The partial replacement of milk powder by hemp cake had no significant effect on the hysteresis area of the ice cream samples, with the exception of the sample containing the largest quantity of hemp cake (H3), which showed the highest thixotropy (2120.50 Pa/s). This observation is corroborated by Atik et al. [66], who reported a similar finding when they investigated the addition of coconut press cake to ice cream, as well as Saraiva et al. [70], who enriched ice cream with protein from brewing waste.

It is known that hemp flour contains a large amount of dietary fibre [43], which can have thickening properties when added to liquid mixes such as ice cream bases. The fibre in hemp flour absorbs water and swells, creating a gel-like consistency [63], which can enhance the viscosity of the ice cream mix. The obtained results of rheological properties show that the replacement of skimmed milk powder with hemp cake can be used to improve the rheological characteristics and thixotropy of ice cream. The specific mechanisms by which hemp cake influences the rheology and thixotropy of ice cream require detailed scientific analysis. By altering the rheological behaviour of the ice cream mix, the hemp flour could have influenced how the mix flowed during freezing and whipping, ultimately affecting the final texture and structure of the ice cream.

3.2. Ice Cream Properties

3.2.1. Overrun

Overrun is a function of the quantity of air integrated into the ice cream throughout its production. The degree of air incorporation is influenced by the composition of the mix, mostly by the fat and total solids content. The choice and quantity of stabilizers and emulsifiers are also critical factors. Protein source and content also play a role in determining overrun values, since proteins, due to their emulsifying capabilities, aid in the creation of air bubbles [71–73]. Although manufacturers often prefer a higher overrun to enhance profitability, both excessively high and low overruns can lead to an undesirable texture of ice cream. Namely, an overrun that is too high results in a light and airy body with a foamy consistency, whereas an overrun that is too low leads to a dense and heavy texture [64], accompanied by an unpleasant cold sensation in the mouth [54].

Table 4 displays the overrun values for the ice cream samples. The overrun for the control sample was 26.83% and it gradually increased with increasing concentration of the hemp press cake, reaching the highest level of 35.00% for sample H3. The overrun values in this study were lower than those reported by other authors [64,74]. This discrepancy could be due to production in a batch type of freezer where the air incorporation level is limited [75–77]. However, the overrun results from this study are still close to the values reported by Kot et al. [78], Nazarewicz et al. [79] and Lučan Čolić et al. [80].

Table 4. Overrun, fat destabilization index and textural properties of ice cream.

Parameter/Samples	C	H1	H2	H3
Overrun (%)	26.83 ± 1.94 ^b	30.37 ± 0.99 ^{ab}	34.04 ± 0.78 ^{ab}	35.00 ± 3.93 ^a
Fat destabilization index (%)	43.70 ± 1.80 ^a	40.12 ± 0.46 ^{ab}	36.94 ± 2.50 ^b	26.84 ± 2.67 ^c
Hardness (g)	6833.12 ± 807.75 ^c	10,749.42 ± 802.55 ^b	13,213.63 ± 199.89 ^a	14,660.06 ± 1472.34 ^a
Adhesiveness (g·s)	−532.22 ± 74.11 ^a	−594.97 ± 54.85 ^a	−687.53 ± 83.60 ^a	−581.40 ± 86.85 ^a
Gumminess	514.36 ± 121.97 ^d	753.00 ± 72.61 ^c	903.95 ± 71.39 ^b	1021.31 ± 58.64 ^a
Cohesiveness	0.076 ± 0.006 ^a	0.070 ± 0.004 ^{ab}	0.068 ± 0.001 ^b	0.070 ± 0.003 ^{ab}

The results are shown as mean ± SD. Means in the same line with different superscripts are significantly different according to the Tukey HSD test ($p < 0.05$). C—control ice cream; H1, H2, and H3—ice cream with 25.0%, 37.5% and 50.0%, respectively, skim milk powder replaced by hemp press cake flour.

An increase in overrun with an increasing concentration of hemp press cake could be related to the composition of the hemp protein. The two most important proteins

in hemp seeds are globulin (edestin), which accounts for about 70% of the total protein content, and albumin. Albumin has a more flexible structure than edestin, which allows it a higher solubility and foaming capacity [81]. Raikos et al. [82] investigated the functional properties of some plant flours and concluded that hemp flour has promising emulsifying and foaming properties at alkaline pH. It was also found that viscosity has an important influence on the aeration capacity, i.e., overrun of ice cream. According to Wang et al. [83], an increase in apparent viscosity allows the formation of a greater number of smaller air chambers and provides a higher overrun in ice cream, which could be a probable reason for the change in overrun in this study. On the other hand, Ghaedrahmati et al. [84] reported that the replacement of milk cream in ice cream with jaban watermelon exocarp powder up to 40% resulted in an increase in viscosity, which limited the proper incorporation of air and negatively affected the overrun.

The results clearly showed that increasing concentrations of hemp press cake correlate (Figure 3, 0.985) with higher overrun values in ice cream samples. This suggests that hemp press cake can improve aeration during freezing, possibly due to its unique composition or functional properties that facilitate better incorporation of air into the mixture.

3.2.2. Fat Destabilization Index

An essential parameter in ice cream formulation is the degree of fat destabilization, affecting its melting behaviour, stiffness, creaminess, and ice cream structure stabilization [67]. The index of fat destabilization as a result of partial fat coalescence depends on many factors, such as the addition of emulsifier, the shear forces applied during whipping and freezing, ice crystals, and the formation air cells [85].

In this study, the rate of fat destabilisation was found to be significantly higher in a control sample (43.70%) than in samples with the addition of hemp press cake (26.84–40.12%), as shown in Table 4. As the hemp protein content increased with increasing hemp press cake concentration, there was a significant decrease in the fat destabilisation index, although the total protein content in the ice cream samples was not statistically different. Similar findings were reported by Daw and Hartel [73], who investigated the effects of different protein types and contents on the fat destabilisation index in ice cream. In addition, the altered, i.e., reduced level of fat destabilisation can be attributed to the fibre content of hemp, which is in accordance with the results of a study in which ice cream was fortified with dietary fibre [86].

The analysis revealed an inverse relationship between the fat destabilization index and overrun (Figure 3), which is consistent with the conclusions drawn by Liu et al. [87]. According to the Chang and Hartel [71], the level of fat destabilization depends on shear forces and freezing time. On the contrary, Warren and Hartel [88] noticed higher degrees of fat destabilization for samples with higher overrun values.

3.2.3. Texture

The ability of ice cream to resist deformation when subjected to an external force, commonly referred to as hardness, is a critical quality parameter. Several factors contribute to the hardness of ice cream, such as the total solids content, the specific stabilizer, the overrun level, the size of the ice crystals, and the fat destabilization degree [89,90]. In this research, the hemp press cake ratio determined the texture of the ice cream samples (Table 4). The hardness of the control sample was the lowest (6833.12 g) and it significantly increased ($p < 0.05$) as the level of hemp press cake increased, reaching values of 10,749.42 g–14,660.06 g.

Xu et al. [60] reported that the supplementation of 5% hemp protein to plant-based yoghurt caused a decrease in its hardness, while the opposite was observed with higher hemp protein concentrations. Indeed, hemp is known to be rich in fibres [18], and this could be associated with increased hardness values in the tested samples through the mechanisms of water binding and network formation [91]. Similar results were reported by Crizel et al. [92] and Tolve et al. [93], who added various fibres to ice cream.

Although it is mainly found that samples with higher overrun values have lower hardness values [55,90], in this study, a strong positive correlation between the hardness of ice cream and overrun was noticed (Figure 3, 0.993), which is consistent with the results reported by Prindville et al. [47]. Muse and Hartel [90] found that ice cream samples were harder when the apparent viscosity was higher, and this could also be the case in this study. In addition, it is reported that ice crystal size also affects the hardness of ice cream [90]. Although not measured, it can be assumed that the ice crystal size influenced the hardness of the analysed samples more than the overrun.

The control sample had a slightly lower adhesiveness than the hemp-enriched formulations, indicating that less force is required to remove them from packaging, spoons or other materials. However, this difference was not statistically significant, and the values ranged from $-532.22 \text{ g}\cdot\text{s}$ to $-687.53 \text{ g}\cdot\text{s}$.

In terms of gumminess, the hemp press cake significantly increased this value from 514.36 for the control sample to 1021.31 for the sample with the highest hemp content, as confirmed by Pearson's correlation test (Figure 3). Gumminess is a textural attribute that describes the chewiness or elasticity of a food product. A strong positive Pearson correlation (0.999) was found between hardness and gumminess (Figure 3). The cohesiveness of ice cream refers to how well a food product holds together or retains its structure during consumption. The addition of pressed hemp cake to the ice cream reduced cohesiveness, but the decrease was not significant. Similar trends, i.e., not affected cohesiveness and increased gumminess, were found in studies in which yoghurt made from soybean powder was enriched with hemp protein [60].

The addition of hemp flour to ice cream had a significant impact on its textural properties. The Pearson correlation coefficients (Figure 3) showed a significant positive correlation between the hemp flour content and the hardness (0.997) and gumminess (0.999) of the enriched ice cream samples, as well as between these two texture parameters (0.999). In addition, the correlation coefficients of hardness and gumminess with the consistency coefficient, Kokini viscosity and overrun were 0.962, 0.973; 0.982, and 0.977; and 0.993 and 0.991, respectively.

The increase in hardness and gumminess values in enriched samples can be attributed to the presence of protein and carbohydrates, but especially dietary fibre, from the hemp cake [94]. The fibre in the hemp flour can interact with other ingredients in the ice cream mix and thus influence the overall texture and firmness of the ice cream. This change in composition can lead to an increase in the hardness of the final product. Hemp flour, which is a source of plant-based protein and fibre, can potentially affect the gumminess of ice cream due to its water-binding properties. When hemp flour is added to ice cream formulations, it can contribute to increased water immobilisation in the product. This increased water retention can lead to a stickier and more cohesive texture that resembles gumminess [33].

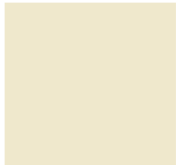
3.2.4. Colour

Colour is considered an important sensory parameter that influences consumer perception and acceptability of food [54]. Instrumental colour analysis is crucial for understanding how ingredients affect the visual attributes of food products. The measured values of the colour parameters are presented in Table 5. The addition of hemp flour significantly affected all tested colour properties.

It has been shown that the addition of hemp press cake to ice cream formulations has a significant effect on the lightness and overall colour characteristics of the final product. Specifically, as the proportion of skim milk powder was replaced with hemp press cake, there was a notable decrease in the lightness value (L^*). Enriching the samples with hemp flour reduced the whiteness index (WI), which was also reflected in an increasing browning index (BI). The whiteness index is a measure of how white or light a food product appears, while the browning index indicates the degree of brown colouring present. The decreasing trend of the lightness value indicates that replacing milk powder with hemp flour makes

the ice cream darker. The L^* values, which indicate the lightness on a scale from 0 (black) to 100 (white), ranged from 73.11 to 80.91 for the samples containing different amounts of hemp press cake. In contrast, the control sample, which contained no hemp flour, had a significantly higher L^* value of 91.04. The decrease in lightness could be due to the darker nature of the hemp cake compared to conventional ice cream ingredients. A decrease in the lightness of foods due to the use of hemp or its by-products has been reported previously [11,33,42,60]. Sakr et al. [54] also reported a significant increase in browning index when skim milk was replaced with baobab fruit pulp flour.

Table 5. Colour parameters of ice cream.

	C	H1	H2	H3
Parameter/Samples				
L^*	91.04 ± 0.23 ^a	80.91 ± 0.46 ^b	77.00 ± 0.32 ^c	73.11 ± 0.74 ^d
a^*	−1.95 ± 0.12 ^c	0.36 ± 0.04 ^b	0.23 ± 0.16 ^b	0.15 ± 0.03 ^a
b^*	12.87 ± 0.40 ^a	11.12 ± 0.24 ^b	10.62 ± 0.19 ^b	10.73 ± 0.22 ^b
WI	84.20 ± 0.42 ^a	77.90 ± 0.48 ^b	74.67 ± 0.35 ^c	71.05 ± 0.68 ^d
YI	20.19 ± 0.66 ^{ab}	19.64 ± 0.50 ^b	19.70 ± 0.42 ^b	20.96 ± 0.47 ^a
BI	13.27 ± 0.60 ^c	14.11 ± 0.39 ^{bc}	14.27 ± 0.18 ^b	15.65 ± 0.40 ^a
C^*	13.01 ± 0.38 ^a	11.13 ± 0.24 ^b	10.62 ± 0.20 ^b	10.73 ± 0.22 ^b
h^*	98.64 ± 0.74 ^a	91.84 ± 0.21 ^b	91.19 ± 0.85 ^b	89.19 ± 0.14 ^c
ΔE	-	10.41 ± 0.47 ^c	14.34 ± 0.45 ^b	18.19 ± 0.74 ^a

The results are shown as mean ± SD. Means in the same line with different superscripts are significantly different according to the Tukey HSD test ($p < 0.05$). C—control ice cream; H1, H2, and H3—ice cream with 25.0%, 37.5% and 50.0%, respectively, skim milk powder replaced by hemp press cake flour. L^* —lightness, a^* —green/red, b^* —blue/yellow, C^* —chroma, h^* —hue, ΔE —colour difference, WI—whiteness index, YI—yellowness index, BI—browning index.

The degree of redness is quantified using the a^* value from the CIELAB colour space, with negative values indicating green hues and positive values indicating red hues. For the control sample, the a^* value was measured at −1.95, indicating a predominantly green colouration. This is in line with expectations for many dairy products, which do not naturally exhibit significant red hues [95]. After the addition of hemp press cake, particularly in the H3 sample, the a^* value increased significantly to 0.15. This change marks the transition from a greenish hue towards a slight red colour. As hemp press cake is typically characterised by its greenish–brown appearance, the increase in red colour with increased hemp press cake content was not expected. However, these results are in agreement with those reported by Nakov et al. [42], who investigated the characteristics of a probiotic yoghurt enriched with honey and hemp press cake. It can be assumed that the compounds present in the hemp cake may interact with other ingredients within the ice cream matrix, resulting in changes in light absorption and reflectance properties. While it was expected that the addition of a greenish–brown ingredient such as hemp cake would maintain or deepen the green tones in the ice cream, the observed increase in redness indicates the need for further research to explain this phenomenon.

The b^* value is a critical metric that indicates the yellow to blue chromaticity of a sample. A higher b^* value indicates a more pronounced yellow colouration, while lower values indicate a shift towards blue. In our study, the control sample of ice cream had the highest b^* value at 12.87, indicating a slight yellow hue. This yellow coloration can be attributed to various factors, including the ingredients used and their inherent colour properties. The addition of hemp press cake resulted in a decrease in the b^* value in all samples tested. As the proportion of skim milk powder replacement increased, the yellow

coloration decreased but had no significant influence on the yellowness index (YI). YI is another measure used to quantify colour perception, but it does not always correlate (Figure 3) directly with changes in specific chromatic variables such as b^* . This result indicates that although there was a visual change in colour due to changes in ingredients, this did not lead to a significant change in the overall perception of yellowness. These results contradict those of Nakov et al. [42], who found an increase in the yellowness of probiotic yoghurt with the addition of hemp cake, which they explained by the presence of γ -tocopherols. This discrepancy raises the question how different food matrices (ice cream versus yogurt) interact with similar ingredients such as hemp press cake. It suggests that factors such as fat content, moisture content, and other compositional differences could play an important role in how these ingredients affect colour characteristics.

Chroma (C^*) is a quantitative parameter that refers to the saturation or intensity of a colour. A higher chroma value indicates a more vivid or intense colour, while a lower value indicates a more muted or dull appearance. Hue (h^*), on the other hand, is a qualitative parameter that describes the type of colour based on its position on the colour wheel, which is represented by an angular measurement. The angles correspond to specific colours: 0° , $+a^*$ —red; 90° , $+b^*$ —yellow; 180° , $-a^*$ —green; and 270° , $-b^*$ —blue [52]. In our study, the C^* value was significantly affected ($p < 0.05$) by replacing skimmed milk powder with hemp flour. The chroma value decreased from 13.01 to 11.13–10.62, indicating a decrease in the colour intensity of the enriched ice cream sample as perceived by humans. In this case, the addition of hemp flour had an effect not only on the chroma value but also on the hue values. The addition of hemp flour significantly lowered the hue value, changing the shade of the colour from a greenish–yellowish to reddish–yellowish range. Although a significant ($p < 0.05$) difference was found between the control sample and enriched samples, they are all perceived in the yellowish hue range (98.64 for the control sample; 91.84–89.19 for the enriched samples).

Based on the values of L^* , a^* , b^* , C^* and h^* , it can be confirmed that the addition of hemp press cake to ice cream had a medium–dark colour shade of yellow and red. The decrease in colour saturation and the increase in the reddish hue of ice cream when hemp flour is added can be attributed to various factors. Hemp flour contains compounds that can interact with the pigments responsible for the colour of the ice cream [96], resulting in a decrease in colour intensity or saturation. The specific mechanisms behind this colour change would require further investigation and analysis of the interactions between the components of the hemp flour and those of the ice cream.

The absolute colour change parameter (ΔE) is a quantitative measure used to express the difference in colour between two samples. It is particularly useful in food science to assess how modifications in formulations affect the visual characteristics of products. In this context, ΔE values help to determine whether changes in ingredients lead to perceptible colour differences that can be detected by the human eye. According to the literature, values for ΔE greater than three are differences in colour that the human eye can distinguish [52]. Ice cream samples with partially replaced skim milk powder exhibited significant variations in colour compared to the control sample, as demonstrated by the total colour difference values (ΔE). The ΔE values were found to be 10.41 for H1, 14.34 for H2 and 18.19 for H3, confirming that colour variations between the control and the enriched samples are noticeable to the human eye.

The Pearson correlation coefficients (Figure 3) confirmed a significant correlation between the colour parameters and milk powder replacement ($p < 0.05$). For example, the hemp flour content had a high positive correlation with the red chromatic value and total colour differences (0.961 and 0.997), but the lightness value, whiteness index and hue angle had a negative correlation (-0.994 , -0.999 , and -0.961) with the hemp cake addition. This indicates that as more hemp flour is incorporated, the redness of the product increases significantly and the colour variations become more pronounced. In addition, the correlation coefficients of lightness with redness and yellowness were -0.978 and 0.955 , respectively, while the correlation coefficient between these two chromatic variables was

−0.977. These results illustrate how the addition of hemp flour to products significantly alters their colour profile.

3.2.5. Sensory Characteristics

The results of the sensory evaluation of the ice cream samples are presented in Figure 5. In general, the standard ice cream sample received the highest score for overall acceptability (7.57/9.00; Figure 5b) and for all attributes evaluated (4.40–4.83/5.00; Figure 5a). This high score indicates that the standard recipe is well received by consumers, probably due to the balanced flavour profile, texture, and other sensory characteristics.

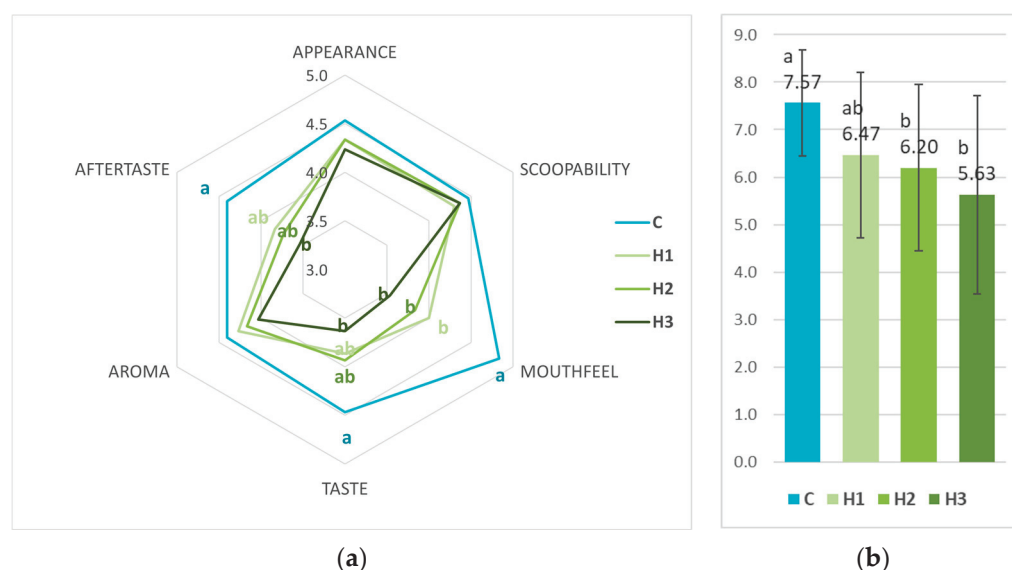


Figure 5. Sensory scores for sensory attributes (a) and overall acceptance (b) of ice cream samples: C—control ice cream; H1, H2, and H3—ice creams with 25.0%, 37.5% and 50.0%, respectively, skim milk powder replaced by hemp press cake flour. The results are shown as mean ($\pm$ SD). The same attributes with different superscripts are significantly different according to the Tukey HSD test ($p < 0.05$).

The incorporation of hemp cake in the ice cream recipe resulted in a noticeable decline in sensory scores for all characteristics assessed. Despite this decrease, it is noteworthy that appearance, scoopability, and aroma showed no statistically significant differences ($p > 0.05$). The scores for these attributes remained within a range of 4.00 to 4.50, which corresponds to consumer perceptions ranging from “like slightly” to “like very much”. This indicates that while the addition of hemp cake negatively affected some aspects, it did not significantly affect these particular sensory attributes.

It was observed that the addition of hemp cake to ice cream formulations significantly changed the colour profile of the final product (Table 5). Specifically, the addition of hemp cake resulted in a darker, uncharacteristic brownish hue. This change was quantitatively evaluated by instrumental measurements in which various colour parameters were determined. This revealed a clear difference between standard ice cream and the products enriched with hemp flour. Despite these significant instrumental colour changes, the sensory evaluations indicated that consumers did not perceive these changes as negative in terms of the appearance of the enriched ice cream. Nevertheless, a strong positive correlation was found between the appearance score and the instrumental values for lightness, whiteness index, and hue (Figure 3, 0.978, 0.968, and 0.992, respectively), and a negative correlation between the score for appearance and the values for a^* and ΔE (−0.986, and −0.979, respectively). This indicates that consumers generally prefer lighter-coloured products when it comes to visual appeal.

Furthermore, the increase in the instrumentally determined hardness had no influence on the decrease in the ice cream's scoopability rating. The hardness of ice cream is primarily determined by the formulation, including the type and quantity of ingredients used (e.g., fat, sugar, stabilizers), as well as the freezing process. In our study, it was found that an increase in instrumentally measured hardness did not correlate with a decrease in scoopability ratings (Figure 3). Scoopability refers to how easily a portion of ice cream can be removed from the container with a scoop or spoon. It is influenced by several factors including temperature, composition (such as fat content and air incorporation), and physical structure. The fact that the higher hardness had no effect on scoopability suggests that other textural characteristics play a more important role in how easily ice cream can be scooped. For example, if the ice cream contains sufficient air incorporation or has an optimal serving temperature, it may still maintain good scoopability despite higher hardness. These results showed that although the instrumentally determined hardness increased, this did not lead to a decrease in the scoopability rating of the hemp cake ice cream. However, a negative correlation was found between the values for hardness and gumminess and the ratings for appearance, mouthfeel, and overall acceptability (Figure 3). Hardness refers to the force required to deform the ice cream—higher values indicate a firmer product. Gumminess refers to the texture's chewiness or resilience; higher gumminess often leads to a less desirable mouthfeel. This relationship suggests that consumers prefer softer textures that are perceived as more palatable. A harder or gummier ice cream can lead to negative perceptions in terms of its appearance (perhaps too dense), mouthfeel (less smooth), and overall acceptability (leading consumers to rate it lower). While increased hardness might not directly affect scoopability, it does have a negative impact on other critical sensory attributes such as appearance and mouthfeel, which ultimately influence overall consumer acceptance.

In contrast to the ratings for appearance, aroma and scoopability scores, replacing powdered milk with hemp flour led to a significant reduction in the scores for mouthfeel, taste and aftertaste.

Mouthfeel is a crucial aspect of ice cream quality that influences consumer enjoyment and preference. The control sample, which contained powdered milk, received a high mouthfeel score of 4.83, indicating that consumers liked it very much. However, as the proportion of hemp flour increased in the samples labelled H1, H2, and H3, the mouthfeel scores dropped to 4.00, 3.83, and 3.53, respectively. The texture of hemp-enriched products may not be as smooth or creamy as traditional dairy products. This could be due to the fibrous nature of the hemp press cake or other components used in the formulations.

Taste is another essential factor in determining consumer acceptance of food products. The control sample received a score of 4.47 for taste, reflecting a positive perception by the tasters. However, with the addition of hemp press cake flour, this score decreased significantly to 3.63 for the H1 sample and further down to 3.53 for the H3 sample, which contained higher concentrations of hemp flour. The distinct flavour profile of hemp press cake can have a negative impact on overall taste perception due to its inherent bitterness and earthy notes, which can overshadow other flavours in the ice cream.

The aftertaste plays a crucial role in the overall experience of eating; it can enhance or detract from the initial flavour impression. In this study, the control sample had an aftertaste score of 4.40, indicating a pleasant aftertaste after consumption. Conversely, as more hemp flour was added (H1 with 3.63 and H3 with 3.53), tasters reported a less favourable aftertaste experience likely due to the bitterness associated with a higher proportion of hemp cake.

According to a study by Nakov et al. [43], the addition of hemp press cake flour to yogurt also resulted in negative effects across all analysed sensory properties. These results suggest that consumers may find the flavour of hemp flour unfamiliar or unappealing when compared to traditional yogurt flavours. Further studies by Sakr et al. [54] and Saraiva et al. [70] investigated the fortification of ice cream with various plant-based protein and fibre supplements, including brewing waste/trub and baobab pulp. Similar to our findings, these studies reported a reduction in the overall acceptability and sensory

characteristics of ice cream when these additives were added. The unfamiliar taste profiles and altered mouthfeel associated with these ingredients likely contributed to lower consumer acceptance. In addition, Bürck et al. [97] also stated that the subjects in their study showed a relatively conservative behaviour regarding their ice cream purchasing habits. This suggests that consumers are generally hesitant to try new products that contain unconventional ingredients such as those mentioned above. The lack of familiarity with the specific tastes and textures introduced by these plant-based additives could make them reluctant to embrace such innovations in their food choices.

Figure 5b shows the ratings for the overall acceptability of the ice creams produced. The results show a clear relationship between the sensory properties and overall acceptability. In our study, the lower sensory scores for taste, aftertaste, and mouthfeel correlated directly (0.974–0.996, Figure 3) with the lower overall acceptability. This correlation suggests that improving a particular sensory attribute could lead to improved overall acceptability of ice cream with a higher hemp cake content.

The control sample received an overall acceptability score of 7.57, which was categorised as “like very much”. The overall score of 6.47 for sample H1 indicates a sensory evaluation result that falls between “like slightly” and “like moderately” and no significant difference was found compared to the control sample. The evaluation indicates that this alternative ice cream formulation, in which 25% of the milk powder is replaced by hemp flour, is generally well accepted by consumers and can be considered comparable to traditional ice cream formulations. In contrast, samples H2 and H3 scored significantly lower at 6.20 and 5.63, respectively, and therefore fall into the “like slightly” category. Nevertheless, the results showed that despite the significantly ($p < 0.05$) lower scores for mouthfeel, taste, and aftertaste compared to the control samples, these formulations achieved an overall acceptability rating above 5.00. This indicates that consumers are willing to accept hemp-enriched products even if certain sensory attributes do not meet their expectations.

Hemp press cake has proven to be a promising substitute for milk powder in ice cream formulations. However, despite its potential, improvements are still needed to increase its acceptance on the market. For example, microencapsulation can contribute to masking off flavours and controlling the intensity of bioactive compounds release. In addition, the use of some sweeteners or fruity aromas could play an important role in minimizing impaired sensory properties, while utilization of press cake with a lower particle size could positively affect the ice cream texture and mouthfeel.

3.2.6. The Relationship between the Characteristics of Ice Creams and Mixes

Investigating the impact of substituting skim milk powder with hemp press cake flour in ice cream mixes provides important insights into how this replacement affects various properties of the final product. The Pearson correlation coefficients (Figure 3) calculated in this study provide a quantitative measure of the relationships between different parameters, allowing for a deeper understanding of the interactions among these ingredients.

The most important correlations are highlighted in the Results and discussion section, under the parameters to which they relate. In conclusion, the substitution of skimmed milk powder with hemp press cake flour has a significant effect on most of the parameters studied, including the acidity and viscosity of the ice cream mixes, as well as the overrun, texture, colour parameters and sensory acceptability of the ice cream samples. While this substitution offers benefits such as improved nutritional value and unique flavours, it also poses a challenge to consumer acceptance due to the altered flavour profiles.

4. Conclusions

Due to the growing interest in functional foods and the use of food industry by-products, in our study we investigated the possibility of replacing milk powder with hemp flour in ice cream. Hemp cake, derived from the extraction of hemp seed oil, is a nutrient-dense by-product that contains significant amounts of protein and fibre. Adding hemp

cake to ice cream recipes can not only improve the nutritional profile but also increase the sustainability of food production.

The results obtained indicate that the addition of hemp press cake significantly influenced the physical properties and sensory attributes of the ice cream. Replacing milk powder with this valuable by-product improved the rheological properties and thixotropy of the ice cream mix. The higher the proportion of hemp flour, the higher the water activity, overrun, hardness, and gumminess of the ice cream samples, while the acidity and fat destabilisation decreased. The enrichment also affected the colour parameters, giving the ice cream a darker reddish-brownish hue. Although a higher proportion of hemp cake resulted in lower sensory acceptability, consumers accepted all hemp-enriched formulations, indicating its potential for use in commercial ice cream products. The alternative ice cream formulation, in which 25% of the milk powder is replaced with hemp flour, is likely to be well accepted by consumers and considered comparable to traditional ice cream formulations.

The introduction of hemp cake flour to ice cream recipes could change production costs. Skim milk powder prices are subject to fluctuations influenced by market conditions and generally average around 2.50 euros per kilogram. In contrast, the price of hemp cake flour is more variable, mainly due to the dynamics of the supply chain. It is usually between 1.50 and 3.00 euros per kilogram. This indicates that substituting milk powder with hemp cake flour is unlikely to have a substantial impact on ingredient costs. However, the use of hemp cake flour could require adjustments in the production process, which could result in additional costs for specialised equipment or processes. Nevertheless, this product would have a higher nutritional value, including a higher concentration of fibre and unsaturated fatty acids, as well as possible antioxidant properties. Given the growing consumer interest in functional products, ice cream products with hemp ingredients have the potential to attract health-aware consumers. In addition, this substitution plays an important role in promoting the principles of the circular economy, as it offers a viable approach to the sustainable use of by-products, which could appeal to consumers who value environmental responsibility.

Overall, this study concluded that hemp press cake could be a valuable ingredient in ice cream formulation, offering both nutritional benefits and sustainability advantages. Further research and experimentation would be necessary to fully understand the underlying mechanisms and optimize formulations for commercial production.

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Article

Influence of Psychological Factors on Dairy Farmers' Intentions to Adopt Environmental Sustainability Practices in Paraná State, Brazil

Jessica Ortega de Jesus Sangali ¹, Ferenc Istvan Bánkuti ^{1,2,*}, Julio Cesar Damasceno ² and Henrique Leal Perez ²

¹ Programa de Pós-Graduação em Produção Sustentável e Saúde Animal—PPS/UEM, Departamento de Medicina Veterinária, Universidade Estadual de Maringá, Estrada da Paca, S/N, Umuarama 87507-190, PR, Brazil; jehortega_jesus@hotmail.com

² Programa de Pós-Graduação em Zootecnia—PPZ/UEM, Departamento de Zootecnia, Universidade Estadual de Maringá, Av. Colombo, 5790, Bloco J45, Maringá 87020-900, PR, Brazil; jcdamasceno@uem.br (J.C.D.); hlperez2@uem.br (H.L.P.)

* Correspondence: fibankuti@uem.br

Abstract: Efforts worldwide have been dedicated to developing strategies for reducing the environmental impacts arising from agricultural production. In developing countries, such as Brazil, where agricultural production stands as one of the most important economic sectors, meeting institutional and market requirements for sustainability is essential for ensuring the country's competitiveness. This study investigated the intention of Brazilian dairy farmers to adopt environmental sustainability practices. The sample comprised 100 dairy farms in Paraná State, Brazil. The data were analyzed using structural equation models and discussed from the perspective of the Theory of Planned Behavior. The results showed that farmers' intentions to adopt sustainability practices is not associated with socioeconomic or production characteristics. Structural equation modeling identified three constructs explaining farmers' intentions to adopt sustainability practices, namely attitude (ATT), subjective norms (SN), and perceived behavioral control (PBC). ATT and SN had a positive and significant influence, explaining 90% ($R^2 = 0.90$) of the farmers' intentions toward sustainability adoption. The lack of influence of the PBC construct suggests that farmers perceive themselves as having limited ability to adopt sustainability practices, mainly attributed to a lack of knowledge and financial resources, low self-confidence, and a heavy reliance on others for the implementation of sustainability actions.

Keywords: environmental adequacy; family farming; Theory of Planned Behavior

1. Introduction

Globally, agricultural production has struggled to find a balance between economic, social, and environmental sustainability. From an economic perspective, crop production generates jobs and foreign exchange for producing countries. Socially, it contributes to food security and domestic development. Environmentally, however, agriculture can exert negative impacts on a global scale. Several countries have implemented public policies aimed at achieving a balance between sustainability dimensions, demonstrating the need to reduce the environmental impacts of crop production [1,2]. In Europe, for instance, failure to comply with institutional and market requirements for sustainability has caused many farmers to leave the agricultural sector [3]. In developing countries such as Brazil, where crops are produced on a large scale and the economy is strongly dependent on agricultural production, achieving sustainability is a significant concern. Failure to meet sustainability requirements may have serious economic and social impacts for the country.

Among the three pillars of sustainability, namely economic, social, and environmental sustainability, environmental factors appear particularly relevant in the context of agricultural systems, given the direct relationship between crop production and environmental

conditions. Agricultural production can have deleterious effects on natural resources, such as water and soil, as it is associated with increased greenhouse gas emissions, deforestation, biodiversity loss, and climate change [4]. Studies have shown that the adoption of sustainable practices is a crucial strategy to mitigate the negative impacts of crop production, warranting high priority from farm managers [1,4,5]. Here, sustainable practices are defined as actions that, when implemented in place of others, result in reduced environmental impacts [1,2,4].

Some investigations suggested that institutional efforts have been ineffective in steering animal production systems toward sustainability. As extensively documented, farmers only adopt environmental sustainability practices in food production systems if they perceive such practices as important, accept them, and show the intention of implementing behavioral changes [1,2,6]. The Theory of Planned Behavior (TPB) has been widely used in studies assessing farmers' intentions to adopt less-common behaviors [6–9]. The TPB posits that individual behavior is influenced by intention, which, in turn, is governed by three psychological constructs, namely attitude, subjective norms, and perceived behavioral control [10].

This study examined the intention of dairy farmers in Paraná State, Brazil, to adopt environmental sustainability practices. The following three hypotheses were proposed based on the TPB [10]: H_1 , attitude has a positive and significant influence on farmers' intentions to implement environmental sustainability actions on the farm; H_2 , subjective norms have a positive and significant influence on farmers' intentions to implement environmental sustainability actions on the farm; and H_3 , perceived behavioral control has a positive and significant influence on farmers' intentions to implement environmental sustainability actions on the farm.

2. Materials and Methods

2.1. Study Site

Agricultural production is one of the most important sectors of the Brazilian economy, accounting for almost a quarter of the country's gross domestic product [11]. Brazil ranks among the world's largest producers of several agricultural commodities, including beef, chicken meat, coffee, and sugarcane [12]. Despite this, most Brazilian farms (77%) are family farms with small-to-medium scales of production. Family farms occupy 23% of the total agricultural land available in the country and represent the main source of income for both farmers and their families [13].

Dairy production holds significant economic and social importance in Brazil. The country boasts more than 1 million dairy farms, which together produced 34.6 billion liters of milk in 2022, placing the country as the third largest milk producer in the world [12,14]. Among the Brazilian states, Paraná (24°36' S 51°23' O) ranks as the second largest in terms of milk production volume, accounting for 13% of the national production. As in other regions of the country, the Paraná dairy sector is mainly represented by small- and medium-scale family farms [14]. This study was conducted in the northwest region of Paraná State (Figure 1). The area comprises 7900 dairy farms and about 105,000 dairy cows, which account for about 7% of the state's milk production [14].

Although small-scale family farms are predominant, important dairy corporations operate in the state, mainly in the southeast and southwest. The municipalities of Castro, Carambeí, Ponta Grossa, Toledo, and Marechal Cândido Rondon have the highest milk production in the country. In these large-scale systems, milk production is highly specialized and characterized by high technology adoption and hired labor, unlike other regions of the state. These dairy basins account for 75% of the total milk volume and house 60% of the dairy farms in Paraná State [2].

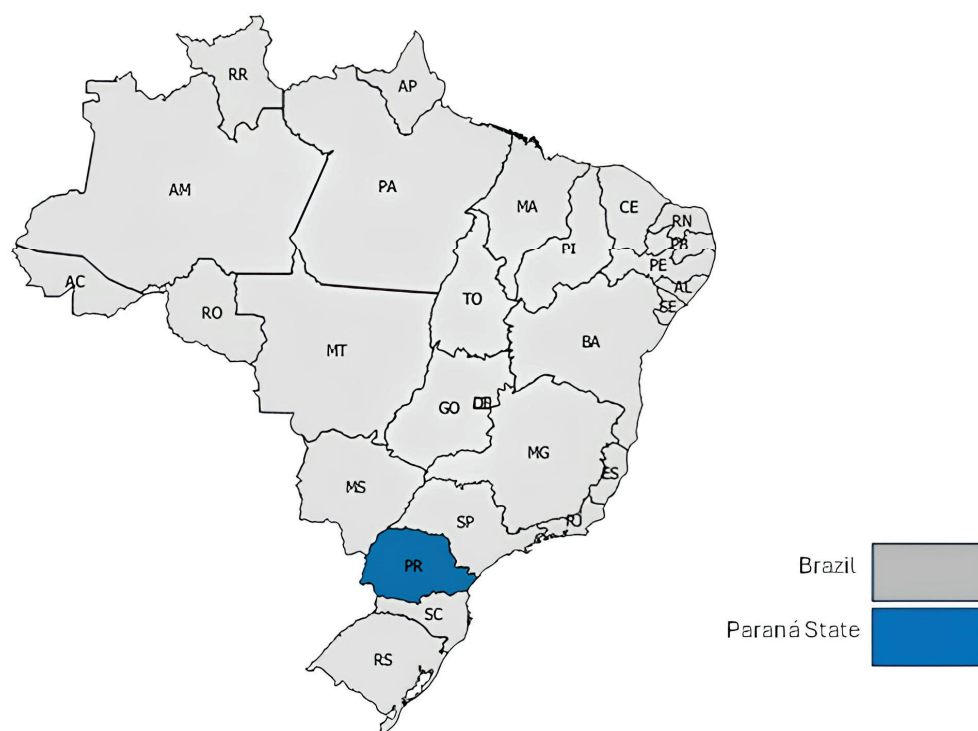


Figure 1. Brazil and Paraná State.

2.2. Data Collection

Data were collected between February and December 2023. Dairy farmers were selected from contact lists provided by technical assistance and public rural extension companies operating in Paraná State. Additionally, farmers previously contacted by the research team were also included in the list. Farmers were randomly selected and invited to participate in the study. During the first contact, the dairy farmers received an explanation and were presented with some examples of environmental sustainability practices. These included (i) reducing the use or ensuring the rational use of natural resources, such as water and soil; (ii) reducing, eliminating, and properly disposing of elements that pose a risk of environmental, human, and animal contamination, such as pesticide and medication packaging and animal carcasses; and (iii) reducing greenhouse gas emissions or enhancing greenhouse gas capture through conservation practices, such as crop–livestock integration, rotational grazing, utilization of animal waste as biofertilizers, and preservation of forested areas.

Data collection was performed by a single researcher (the first author) by using two semi-structured questionnaires. The first questionnaire was administered to 15 dairy farmers. The aim of this step was to identify the main advantages, disadvantages, challenges, capabilities, and social groups influencing farmers' intentions to adopt sustainability practices in their dairy system. This qualitative survey allowed us to better understand the barriers and facilitators for the study sample, as performed in previous studies [15]. The data collected using the first questionnaire were used to formulate quantitative questions for the second questionnaire. The quantitative questionnaire was administered to 100 dairy farmers in northwest Paraná State, Brazil. About 70% of the responses were collected on site (at the farm). The remaining responses were obtained remotely via video calls because of schedule incompatibilities with the farmers. The questionnaires were approved by the Standing Committee on Human Research Ethics (COPEP, CAAE protocol No. 50176121.3.0000.0104) at the local university.

The quantitative questionnaire was divided into two sections. The first section assessed structural and production variables of dairy systems and social variables related to farmers and their families. The second section of the questionnaire measured farmers' intentions to

adopt sustainability practices based on TPB assumptions [10]. According to the TPB, an agent's intention (dependent construct) is influenced by three (independent) constructs, that is, attitude, subjective norms, and perceived behavioral control [10]. In the context of the current study, the TPB constructs are defined as follows: intention (INT), which refers to farmers' intentions to adopt environmental sustainability practices on the farm; attitude (ATT), which describes farmers' attitudes toward environmental sustainability practices, whether favorable or not; subjective norms (SN), which indicate farmers' perceptions of social pressures from relevant persons (family members and technical advisors) to adopt environmental sustainability practices; and perceived behavioral control (PBC), which describes farmers' perceptions of their own capacity to implement environmental sustainability practices.

The TPB constructs were measured from the responses to eighteen questionnaire items, including four for INT, four for ATT, five for SN, and five for PBC. These questions were rated on a Likert scale, as recommended [10]. Responses ranged from 1 to 5, with 1 being the most negative and 5 the most positive [3] (Table 1).

Table 1. Questionnaire used to measure intention (INT), attitude (ATT), subjective norm (SN), and perceived behavioral control (PBC) constructs of the Theory of Planned Behavior.

Item	Question	Responses (1–5)
INT1	Do you intend to increase the use of environmental sustainability practices in dairy production?	Definitely no–definitely yes
INT2	How strong is your intention to increase the use of environmental sustainability practices in dairy production in the coming years?	Very weak–very strong
INT3	How likely are you to increase the use of environmental sustainability practices in dairy production in the coming years?	Not likely–very likely
INT4	Do you plan to increase the use of environmental sustainability practices in dairy production in the coming years?	Definitely no–definitely yes
ATT1	How good would it be for you to increase the use of environmental sustainability practices in dairy production in the coming years?	Very poor–very good
ATT2	How beneficial would it be for you to increase the use of environmental sustainability practices in dairy production in the coming years?	Not advantageous–very advantageous
ATT3	How necessary is it for you to increase the use of environmental sustainability practices in dairy production in the coming years?	Not necessary–very necessary
ATT4	How important is it for you to increase the use of environmental sustainability practices in dairy production in the coming years?	Not important–very important
SN1	Do most people who are important to you think you should increase the use of environmental sustainability practices in dairy production in the coming years?	Strongly disagree–strongly agree
SN2	Would most people whose opinion you value approve if you increased the use of environmental sustainability practices in dairy production in the coming years?	Not likely–very likely
SN3	Would most farmers who are like you approve if you increased the use of environmental sustainability practices in dairy production in the coming years?	Not likely–very likely

Table 1. Cont.

Item	Question	Responses (1–5)
SN4	Would most rural technical advisors approve if you increased the use of environmental sustainability practices in dairy production in the coming years?	Not likely–very likely
SN5	Would most dairies in your area approve if you increased the use of environmental sustainability practices in dairy production in the coming years?	Not likely–very likely
PBC1	If you wanted to increase the use of environmental sustainability practices in dairy production in the coming years, would you have enough knowledge?	Definitely no–definitely yes
PBC2	If you wanted to increase the use of environmental sustainability practices in dairy production in the coming years, would you have enough resources?	Definitely no–definitely yes
PBC3	How confident are you that you can overcome the barriers that prevent you from increasing the use of environmentally sustainable practices in dairy production in the coming years?	Definitely not confident–definitely confident
PBC4	Is the increased use of environmental sustainability practices in dairy production in the coming years solely dependent on you?	Definitely no–definitely yes
PBC5	Is increasing the use of environmental sustainability practices in dairy production in the coming years under your control?	Definitely no–definitely yes

2.3. Data Analysis

For the general characterization of the sample, structural, production, and social data were analyzed using descriptive statistics (mean, standard deviation, maximum, minimum, and mode). Then, the relationship between the INT construct and structural, production, and socioeconomic variables was assessed using Spearman’s correlation (ρ) analysis [9]. Confirmatory factor analysis was used to determine the variables composing INT, using factor loadings (>0.5) and Cronbach’s alpha (>0.7) as criteria [16].

Structural equation modeling was used to assess the TPB constructs. This method provides a preliminary assessment of the measurement model. The model was subjected to confirmatory factor analysis and assessed for reliability. The following reliability measures were evaluated: the average variance extracted (AVE), where values above 50% were deemed acceptable; construct reliability (CR), which must be greater than 0.7; and Cronbach’s alpha, which must be greater than 0.7 [16,17]. Model validation included the assessment of the following fit indices: the root mean square error of approximation (RMSEA), 95% confidence intervals (CI), the comparative fit index (CFI), the Tucker–Lewis index (TLI), and the standardized root mean squared residual (SRMR). The CFI and TLI should be greater than 0.95, whereas the RMSEA and SRMR should be less than 0.08. The chi-squared (χ^2) value was also evaluated; χ^2 values of less than 5.0 were deemed acceptable [16].

Following validation of the measurement model, the next step was to assess the structural model. This model should adequately represent relationships between constructs, allowing for the measurement of multiple regressions and the evaluation of their strengths [16]. The structural model was assessed by determining the coefficient of determination (R^2) and beta coefficient (β). Hypotheses were accepted or rejected at a significance level of $p < 0.05$. The collected variables were tabulated and analyzed using the Jamovi software version 2.3.21.

3. Results

3.1. Socioeconomic and Production Characteristics

The mean age of the interviewed dairy farmers was 49.93 ± 12.32 years. The farmers had a mean of 18.63 ± 12.41 years of experience in dairy farming. The sample included

farmers with different levels of education, with a mean of 7.98 ± 3.86 years. The majority of the farmers (62.0%) reported not receiving any form of technical assistance for dairy production, such as those offered by public agencies, cooperatives, and dairies.

The dairy farms were highly heterogeneous with regard to production characteristics. The mean daily production was 165.92 ± 246.47 L of milk. The mean farm size was 31.36 ± 72.33 ha. The area used specifically for milk production, including pasture and animal handling areas, was 19.74 ± 44.12 ha. The mean number of lactating cows was 16.06 ± 12.45 cows. As for herd characteristics, the farmers reported that 90.0% of their cows were crossbreds, mostly Dutch or Jersey cows crossed with zebu bulls (e.g., Nellore), and 10.0% were purebreds (Girolando, Dutch, or Jersey).

Regarding milking systems, 25.0% of the farmers reported using manual milking, 44.0% used mechanical bucket milking, 21.0% used pipeline milking systems, and only 10.0% used a fully closed milking system. Milk cooling was performed in immersion tanks by 4.0% of the farmers, community cooling tanks by 33.0% of the farmers, and individual cooling tanks by 63.0% of the farmers.

No significant correlations were found between INT and age ($\rho = 0.008$, $p = 0.936$), education ($\rho = 0.017$, $p = 0.870$), experience in dairy activity ($\rho = -0.056$, $p = 0.580$), total farm area ($\rho = -0.008$, $p = 0.938$), milk production area ($\rho = 0.048$, $p = 0.638$), number of lactating cows ($\rho = -0.106$, $p = 0.295$), and production volume ($\rho = 0.068$, $p = 0.501$).

3.2. Measurement Model

For the validation of the measurement model, the items INT1, SN1, PBC1, and PBC3 were removed because they had factor loadings lower than $|0.5|$. The retained items had a reliability index of 95% and factor loadings equal to or greater than $|0.58|$ (Table 2). The consistency measures of the measurement model indicated that all indicators were adequate. The AVE was greater than 0.5, and CR and Cronbach's alpha were greater than 0.7. The measurement model also had adequate fit indices [4], namely $\chi^2 = 106$, $df = 69$, $p < 0.003$, RMSEA = 0.07 (95% CI = 0.04–0.09), CFI = 0.96, and TLI = 0.95.

Table 2. Standardized factor loadings, Cronbach's alpha, average variance extracted (AVE), and reliability of the constructs included in the measurement model.

	INT		ATT		SN		PBC	
Factor loading	INT2	0.80	ATT1	0.92	SN2	0.70	PBC5	0.58
	INT3	0.87	ATT2	0.91	SN3	0.61	PBC4	0.87
	INT4	0.87	ATT3	0.89	SN4	0.92	PBC2	0.59
			ATT4	0.94	SN5	0.69		
Cronbach's alpha	0.89		0.95		0.85		0.72	
AVE	0.85		0.91		0.71		0.59	
Construct reliability	0.91		0.95		0.86		0.77	

INT, intention; ATT, attitude; SN, subjective norm; PBC, perceived behavioral control. INT 2, 3, and 4; ATT 1, 2, 3, and 4; SN 2, 3, and 4; and PCB 2, 4, and 5 are shown in Table 1.

3.3. Structural Model

For the structural model, there were positive interaction coefficients between INT and ATT, SN, and PBC. The strongest correlation was observed between INT and ATT (0.75). Among the three constructs, the interaction was only non-significant for PBC ($p > 0.05$) (Table 3). Therefore, hypotheses H_1 (attitude has a positive and significant influence on farmers' intentions to implement environmental sustainability actions on the farm) and H_2 (subjective norms have a positive and significant influence on farmers' intentions to implement environmental sustainability actions on the farm) were accepted, and hypothesis H_3 (perceived behavioral control has a positive and significant influence on farmers' intentions to implement environmental sustainability actions on the farm) was rejected (Table 3).

Table 3. Results of the structural model.

H	Relationship	Estimate	SD	Lower 95% CI	Upper 95% CI	Standardized β	z	p	Outcome
H ₁	ATT→INT	0.75	0.04	0.66	0.84	0.81	15.8	<0.001 *	Accepted
H ₂	SN→INT	0.21	0.06	0.09	0.34	0.21	3.47	<0.001 *	Accepted
H ₃	PBC→INT	0.02	0.04	−0.06	0.11	0.03	0.59	0.55	Rejected

INT, intention; ATT, attitude; SN, subjective norm; PBC, perceived behavioral control; H, hypothesis; SD, standard deviation; CI, confidence interval. * $p < 0.05$.

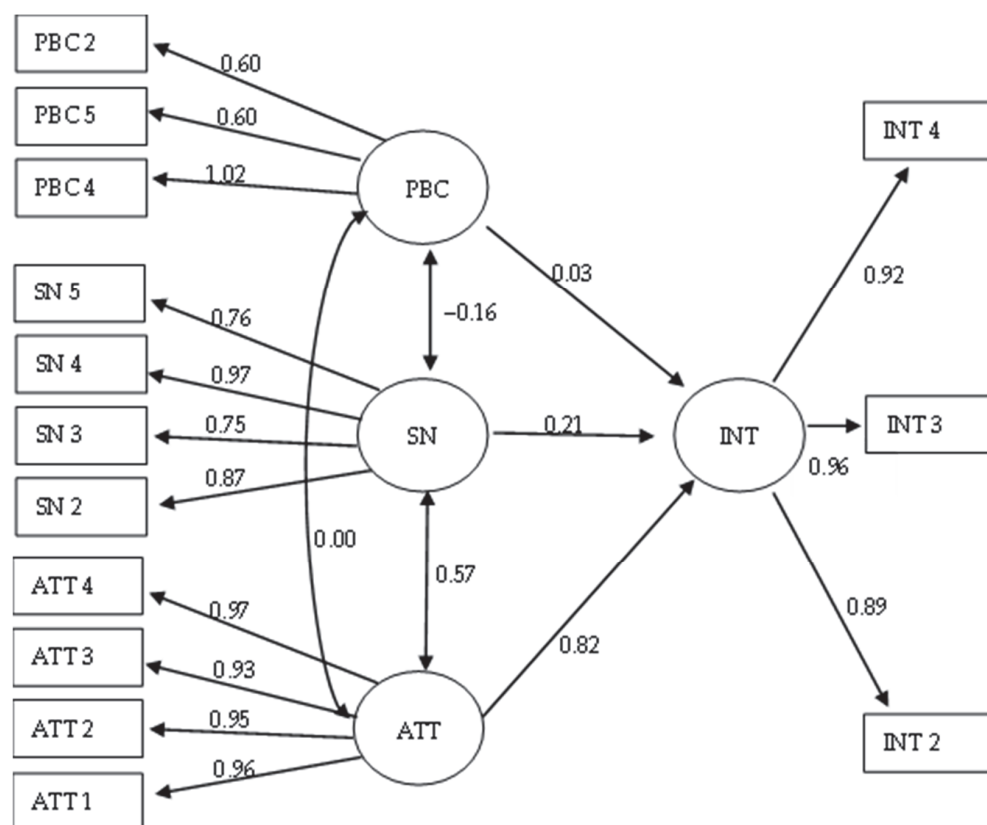


Figure 2. Relationship of intention (INT) with attitude (ATT), subjective norm (SN), and perceived behavioral control (PBC). Rectangles represent the items used to assess dairy farmers' intentions to adopt environmental sustainability practices in the coming years. Circles represent latent constructs. Arrows represent dependency relationships between constructs and measured items. The values in each arrow represent the β value and express the strength of the relationship between items and constructs and between constructs.

The fit index of the model was adequate ($R^2 = 0.90$), indicating that ATT and SN together explained 90% of the farmers' intentions to adopt sustainability practices in milk production. Complementarily, Figure 2 shows the strengths of the relationships between the items and their respective constructs. For ATT, the lowest β was 0.93 (ATT3). For SN and PBC, the lowest β values were 0.75 (SN3) and 0.60 (PBC2 and PBC5), respectively. For INT, the lowest β was 0.89 (INT2).

3.4. Data Analysis

Structural equation modeling was used to assess the TPB constructs. This method provides a preliminary assessment of the measurement model. The model was subjected to confirmatory factor analysis and assessed for reliability. The following reliability measures were evaluated: the average variance extracted (AVE), where values above 50% were deemed acceptable; construct reliability (CR), which must be greater than 0.7; and Cronbach's alpha, which must be greater than 0.7 [16,17]. The model validation included

the assessment of the following fit indices: the root mean square error of approximation (RMSEA), 95% confidence intervals (CI), the comparative fit index (CFI), the Tucker–Lewis index (TLI), and the standardized root mean squared residual (SRMR). The CFI and TLI should be greater than 0.95, whereas the RMSEA and SRMR should be less than 0.08. The chi-squared (χ^2) value was also evaluated; χ^2 values of less than 5.0 were deemed acceptable [16].

Following validation of the measurement model, the next step was to assess the structural model. This model should adequately represent relationships between constructs, allowing for the measurement of multiple regressions and the evaluation of their strengths [16]. The structural model was assessed by determining the coefficient of determination (R^2) and beta coefficient (β). Hypotheses were accepted or rejected at a significance level of $p < 0.05$. The collected variables were tabulated and analyzed using the Jamovi software version 2.3.21.

4. Discussion

4.1. Production and Socioeconomic Characteristics

The age (49.93 ± 12.32 years) and education level (7.98 ± 3.86 years) of the analyzed farmers were in agreement with those of dairy farmers in Paraná State [18]. The dairy farms were found to be heterogeneous with regard to structural and production characteristics, as reported in similar studies conducted in Paraná State [19]. The milk production (165.92 ± 246.47 L/day), number of lactating cows (16.06 ± 12.45), farm area (31.36 ± 72.33 ha), and milk production area (19.74 ± 44.12 ha) of the analyzed farms were higher than those of other dairy production systems in the state [18]. Therefore, the studied farmers had a higher degree of adaptation to market demands, particularly the concerning minimum production volume.

These results can be explained in part by the farmers' needs to meet current institutional and market demands, which have evolved over the past 20 years [18]. The current demands aim at professionalization of dairy activity, as exemplified by the increase in production scale and product quality. Such factors have led many farmers to abandon the activity. Those who managed to adapt remained in the market. These farmers are generally younger, with a higher level of education and greater use of production technologies, which allow for achieving a greater production scale and milk quality [19].

4.2. Correlation between INT and Socioeconomic and Production Characteristics

No significant correlations were found between INT and the variables age, education level, experience in dairy activity, total farm area, milk production area, number of lactating cows, or production volume. This finding shows that the intention to adopt sustainability practices in dairy production is not associated with the socioeconomic characteristics of farmers, nor the production or structural characteristics of dairy farms.

4.3. Farmers' Intentions to Adopt Sustainability Practices in Dairy Production

A positive and significant relationship was found between the variables that defined INT, ATT, and SN. Thus, the structural model indicated that two constructs (ATT and SN) had a positive and significant influence on the farmers' intentions to adopt environmental sustainability practices. PBC did not exert a significant influence (Table 3). Non-validation of the three TPB constructs has been observed in several studies about farmers' intentions [6,8], representing a common situation for TPB models. The two constructs explained 90% of the variance in the farmers' intentions, which was considered an adequate result. Hair et al. (2009) argued that structural models explaining more than 75% of the variance in a dataset are considered highly satisfactory. Previous studies using the same method and theoretical input to analyze dairy farmers' intentions in Brazil reported variances (R^2) of from 49.3% to 76.0% [20].

ATT was the most important factor determining farmers' intentions to adopt environmental sustainability practices in the coming years (Table 3). Other studies have

also reported the great importance of attitudes in determining farmers' intentions to use technologies and conservation practices in production systems. Given the importance of the ATT factor, it is recommended to adopt practices designed to encourage farmers to make better decisions [21,22]. Therefore, it can be inferred that farmers perceive the adoption of sustainability practices in a positive/favorable way, not representing barriers to their adoption.

The high β values of the ATT items are further evidence of the importance of this construct to farmers. ATT4 (How important is it for you to increase the use of environmental sustainability practices in dairy production in the coming years?) had the highest β value (0.97). By contrast, ATT3 (How necessary is it for you to increase the use of environmental sustainability practices in dairy production in the coming years?) had the lowest value (0.93). This result, although quite positive, may indicate that the need to adopt environmental sustainability practices is relatively less important than the other items comprising ATT (Figure 2). Thus, according to farmers' perceptions, the need for changes in environmental sustainability practices stemming from standards or explicit requirements by buyers (e.g., the dairy industry) is less important than farmers' beliefs. Such a relationship is supported by the lack of contracts between dairy farmers and the industry throughout Brazil [23].

The poor enforcement of production standards within the Brazilian dairy sector may contribute to farmers' perceptions of the low importance of adopting sustainability practices in the face of institutional demands. The study [1] argued that issues related to regulatory compliance are less important than production factors in the decisions of farmers to use sustainable production practices. The study [2] considered that although the institutional environment has directed efforts toward mitigating the environmental impacts of agricultural production, positive results will only be seen if farmers adopt sustainable practices. Overall, it can be said that dairy farmers' intentions to adopt sustainability practices is more related to their own beliefs about environmental issues than to the need to comply with laws and regulations.

There was a positive and significant relationship between the variables that defined INT, ATT, and SN. Therefore, SN had a positive and significant effect on the farmers' intentions to adopt environmental sustainability practices, being the second most important construct (Table 3). This finding indicates that people who are important to farmers influence them in a positive way to adopt environmental sustainability practices. Previous studies analyzing subjective norms found that family, other farmers, and technical advisors can influence farmers' intentions and decisions [24–26]. The studies [26,27] identified the importance of subjective norms in determining farmers' intentions toward adopting environmental sustainability practices.

The high β values of the SN items (Figure 2) indicate that the dairy farmers believed that individuals who hold importance in their lives would support them in the adoption of environmental sustainability practices. This group of individuals includes family members, other farmers, and members of associations and cooperatives. SN4 (Would most rural technical advisors approve if you increased the use of environmental sustainability practices in dairy production in the coming years?) had the highest score among the SN items (Figure 2). Thus, it is shown that technical advisors are important to farmers and bear responsibility as catalysts of changes in the milk production system. The study [28] demonstrated that public or private technical assistance programs can be determinant of the behavior of farmers toward the adoption of sustainability practices. The study [25] stated that technical assistance aims to facilitate interactions, learning, and innovation in agricultural systems and is therefore useful in the development of agricultural production.

The lowest score among the SN items was that of SN3 (Would most farmers who are like you approve if you increased the use of environmental sustainability practices in dairy production in the coming years?) (Figure 2). Although the β value of SN3 (0.75) was the lowest among the SN items, it is still considered high, indicating that other farmers have a positive perception about the adoption of environmental sustainability practices. Some authors demonstrated the influence of peers, technical advisors, and

family members on farmers' intentions to adopt environmental sustainability practices. The study [26] found that the decision of farmers to adopt such practices was influenced only by subjective norms, not being influenced by attitude or perceived behavioral control. The cited study observed that close farmers were the most influential, followed by experts and technical assistance professionals. Similarly, [6] reported that farmers' intentions to adopt sustainability practices is mainly influenced by the opinions of other farmers.

Among the three constructs analyzed in this research, PBC was the only one to not significantly influence the farmers' intentions (Table 3). PBC allows for analyzing farmers' perceptions about their own capacity to adopt environmental sustainability practices. The higher and more positive the perception, the greater the tendency to adopt such practices. This result indicates that farmers do not perceive themselves as having the capacity to adopt sustainability practices in their farms, as exemplified by PBC1, PBC2, PBC3, PBC4, and PBC5 (Table 1).

Some studies also reported a low importance of PBC in determining farmers' intentions [8,9]. However, others observed a greater importance of PBC in the intention to incorporate sustainability practices [28]. Therefore, barriers to the adoption of such practices may vary depending on the analyzed group, region, production characteristics, and cultural aspects, among others. The study [4] stated that the economic benefits of sustainable practices, resulting, for example, from the reduced use of inputs and increased yields, are not yet clear to farmers, reducing their adoption. For the farmers surveyed, the low perception of financial returns or the need to increase costs may be an obstacle to the adoption of sustainable practices in dairy production. In this sense, public and private information and training actions could be defined. Besides that, the farmers' perceived lack of capacity to adopt environmental sustainability practices indicates the need for public and private actions aimed at developing capacity, training, and support. An example of such an effort is the provision of specific credit lines for environmental sustainability projects. Furthermore, actions that promote knowledge and understanding of such practices can help farmers meet institutional and market demands.

The results of this research allow us to suggest public or private actions to increase the adoption of sustainability practices by dairy farms, namely the generation of financial incentives, such as credit subsidized by the government or partner companies (e.g., dairy industries) for the adaptation of farms; farmer training and qualification; and acquisition of technologies. Such actions can be facilitated by their promotion through organized collectives, such as cooperatives and associations. Several authors argued that information exchange and knowledge generation are greater when farmers participate in collective production arrangements. The study [18] stated that information exchange and training through collective arrangements can increase the competitiveness of dairy farms. Furthermore, training, awareness, and incentives for the adoption of environmental sustainability practices should also be directed to the group of people considered important by farmers, such as family members and rural technical advisors. Thus, positive reinforcement of these groups may contribute to the adoption of sustainability actions in the analyzed dairy farms.

4.4. Study Limitations

This study has some limitations. The results cannot be extrapolated to other production systems or regions, as different groups of farmers may respond differently to the adoption of sustainability measures. Another limitation is the possibility that the farmers misinterpreted the items of the questionnaire. We are aware that although explanations and examples about sustainability practices were provided, errors in interpretation might have occurred. Another limitation of this study is that the data collection was performed in a single event, thus not allowing for a temporal analysis. Time series studies in dairy farms could provide more realistic results about farmers' intentions to adopt environmental sustainability practices. Limitations of this kind are inherent in any research that focuses on issues that are difficult to measure and are fundamentally less objective in nature. Other studies have already identified such limitations [29].

5. Conclusions

A positive and significant relationship was observed between the variables INT, ATT, and SN. Therefore, ATT and SN had a positive and significant effect on the intention (INT) of dairy farmers to adopt environmental sustainability actions in the coming years. PBC did not exert such an effect on INT. The greater importance of the INT construct indicates that farmers have a positive perception of adopting sustainability practices in dairy production. In addition, the importance of the SN construct represents reinforcement from people important to the farmers to adopt sustainability practices in dairy production. These results suggest that there is a good chance that dairy production systems will change in the coming years, making them more responsive to current institutional and market demands and thus more viable in the medium and long term. The results also showed that, for the evaluated sample, the farmers' intentions to adopt such measures in dairy production was not associated with socioeconomic or production characteristics.

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Article

Optimization of Ultrasonic-Assisted Extraction of Antioxidants in Apple Pomace (var. *Belorusskoje malinovoje*) Using Response Surface Methodology: Scope and Opportunity to Develop as a Potential Feed Supplement or Feed Ingredient

Dunja Malenica ^{1,2,*}, Larissa Silva Maciel ³, Koit Herodes ³, Marko Kass ^{2,4} and Rajeev Bhat ^{1,*}

¹ Food (By-) Products Valorisation Technologies (ERA-Chair in VALORTECH), Estonian University of Life Sciences, Fr. R. Kreutzwaldi 1, 510014 Tartu, Estonia

² Institute of Veterinary Medicine and Animal Science, Estonian University of Life Sciences, Fr. R. Kreutzwaldi 1, 51006 Tartu, Estonia; marko.kass@emu.ee

³ Institute of Chemistry, University of Tartu, Ravila 14a, 50411 Tartu, Estonia; maciel@ut.ee (L.S.M.); koit.herodes@ut.ee (K.H.)

⁴ Centre of Estonian Rural Research and Knowledge (METK), J. Aamisepa 1, 48309 Jõgeva, Estonia

* Correspondence: dunja.malenica@student.emu.ee (D.M.); rajeev.bhat@emu.ee (R.B.)

Abstract: Apple pomace represents an underexploited source of bioactive compounds. This study examines the optimization of total phenolic content (TPC) and antioxidant extraction yield of apple pomace (variety: *Belorusskoje malinovoje*) using response surface methodology. The green extraction technique used was ultrasound-assisted extraction, and it was compared with conventional solvent extraction. The impact of extraction time and amplitude of ultrasound-assisted extraction on the yield of polyphenols and antioxidants has been evaluated. Total phenolic content was determined using an established TPC assay. The antioxidant activity of the apple pomace was determined using established assays 2,2-diphenyl-1-picrylhydrazyl (DPPH•) and 2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid (ABTS^{•+}). Furthermore, the potential of apple pomace as a feed material was explored by assessing its nutritional composition, vitamins, minerals, fatty acids, and amino acid content. The extraction of antioxidants and phenolic compounds was efficiently optimized using RSM. The optimal conditions for TPC and DPPH• analyses were achieved with an extraction time of 17.5 min and an ultrasound-assisted extraction amplitude of 20%. Optimal conditions for ABTS^{•+} were 5 min extraction time and 20% amplitude. Conventional and ultrasound-assisted extraction methods yielded comparable results. Moreover, apple pomace exhibits potential as a feed ingredient despite its modest protein content. This study contributes to the utilization of apple pomace by providing additional information on its antioxidant content and nutritional composition, thus contributing to its sustainable utilization in various industries, especially the livestock feed sector.

Keywords: apple pomace; green extraction; optimization; antioxidants; RSM; animal feed

1. Introduction

Utilization of fruit and vegetable waste as livestock feed offers a potential solution for global challenges such as climate change, urbanization, resource scarcity, and increase in current feed prices [1–6]. One of the common by-products of the fruit industry—apple pomace—exhibits promise as an alternative feed ingredient [5–12]. Apple pomace represents solid residue created during the extraction of juice from the apple. It consists of pulp, skin, seeds, and stalk [7,13]. It has been estimated that the annual production of apple pomace can lead to up to 4 million tonnes [12]. This extensive production of apple pomace is especially alarming considering the high moisture content of apples, which makes them more prone to microbiological contamination and, consequently, environmental pollution [1,3,14–16]. Utilization of apple pomace as animal feed material

could help alleviate the negative environmental impact caused by its unsustainable discarding while simultaneously benefiting the animal feed sector, which has been facing numerous challenges [4–6].

Research findings on the inclusion of apple pomace in animal diets are mixed; however, the health properties of apple pomace, like prebiotic and antioxidant effects, are encouraging [6,7,11,12,17–21]. Antioxidant compounds protect animal health by detoxifying harmful free radicals [22,23]. In high-stress situations or during pathological or physiological changes, animals may not be able to produce sufficient amounts of antioxidants to neutralize excess free radicals [22–25]. Adding antioxidant-rich ingredients to diets can prevent the accumulation of free radicals and, therefore, benefit animal health [26–29]. While synthetic antioxidants have proven to be effective, they are also believed to be carcinogenic, toxic, and cause lipid alteration [23,30,31]. Hence, there is a growing interest in utilizing natural antioxidants, which are commonly present in agro-industrial waste [23,32,33]. Choosing the appropriate extraction method is essential for obtaining bioactive compounds. Green extraction techniques aim to reduce environmental impact but are costly compared to conventional methods. Ultrasound-assisted extraction, a novel and efficient technique, has been utilized in this research because of its ability to maximize the yield of specific compounds while saving both time and energy [34–39]. Moreover, the conventional solvent extraction method was employed, and an equivalent volume of solvent was used, thereby demonstrating a comparable environmental impact to ultrasound-assisted extraction. However, it is important to emphasize one of the limitations of solvent extraction, which is that it is time-consuming, especially compared to ultrasound-assisted extraction [40–42].

Extraction optimization of antioxidants has been carried out on apple pomace before [43–52]. While previous studies have investigated antioxidant extraction from apple pomace using different technologies, solvents, and apple cultivars, numerous additional parameters and their corresponding values remain that could potentially impact the extraction process and warrant further exploration. Specifically, for ultrasound extraction of phenolic compounds and antioxidants from apple pomace, parameters such as temperature, concentrations of ethanol, power, and extraction time have been explored [53–55]. Amplitude and time were explored along with different factors involved, including different varieties of apples, temperatures, solvents, and concentrations of solvents used [50,56]. Based on the literature, the antioxidant content depends largely on the variety of apples [44,51,52,57].

To the best of our knowledge, comprehensive research on the nutritional and bioactive properties of the variety *Beloruskoja malinovoje* has yet to be undertaken. Even though certain studies have touched upon the extraction of antioxidants from this variety, a comprehensive investigation into its nutritional properties remains unexplored [52]. Furthermore, the vitamin content within apple pomace is an understudied area since previous studies mainly focused on vitamins C and E [58–61]. A thorough study of the vitamin content in apple pomace is necessary, as it could add to its nutritional value and hold implications for potential applications of this by-product in various industries.

Further study on the valorization of apple pomace in livestock feed production presents an opportunity to reduce fruit waste and benefit animal health. A comprehensive study with a wide range of analyses involving chemical composition and bioactive compounds for apple pomace felt necessary as the information on this has been scattered among several articles [7,43–49,51,57–61]. The main objective of the present research was to optimize the extraction yield of antioxidant compounds from a local variety of apple by-products, which previously exhibited promising antioxidant activity, using response surface methodology (RSM) to assess the impact of different extraction parameters.

The sub-objective of this study was to compare relationships between extraction yield achieved by green extraction and conventional extraction. This comparison aimed to determine whether costly extraction procedures are truly superior and essential and to provide valuable perspectives on perhaps more cost-effective but equally sustainable alternative methods. Proximate analyses have been conducted, followed by analyses of the

mineral, vitamin, fatty acid, and amino acid content, aiming to evaluate its potential as a feed ingredient and to compare it with existing feed ingredients.

2. Materials and Methods

2.1. Sample Selection and Collection

Apple pomace was collected from the Polli Horticulture Research Centre located in Viljandi County in Estonia. The pomace was air-dried using condensing dehydrator CFD 1400, Alpfrigo, at the temperature of +50 °C for 78 h and then ground and packaged in vacuumed polythene bags. The ground material was stored at refrigeration temperature (+4–7 °C) until further analysis.

The studied variety “*Belorusskoje malinovoje*” is cultivated in Estonia but is initially bred in Belarus as a winter variety. The variety was chosen based on a literature review where among 11 cultivars of 3 seasonal groups (autumn, autumn–winter, and late winter) in Latvia, the cultivar *B. malinovoje* exhibited the highest antioxidant results [52]. Given Estonia’s close geographical proximity to Latvia, we found this study particularly important when considering the cultivar selection for further research. Several other Estonian cultivars have been considered; however, based on their antioxidant content and also seasonality, the choice remained with *B. malinovoje* [44]. The apple tree variety of *B. malinovoje* is a winter variety with high yield and early fruiting [62,63]. It has good disease and good winter resistance potential [62]. The identification of this particular variety is based on the fruit: The ripe fruit of this variety is medium to large sized, round, and almost entirely crimson red, while the flesh is white [62,63]. It is juicy with a sweet and sour taste [62,63].

2.2. Proximate Analyses and Fatty Acid Content

Standard methods of the Association of Official Analytical Chemists were used to determine the moisture, crude protein, crude fat, crude fiber, and crude ash of apple pomace [64]. Dry matter (DM) content was determined by heating a feed sample for 2 h at +130 °C to constant weight. Crude ash was determined after ignition at 550 °C for 18 h. Analysis for ether extract content was performed by petroleum ether extraction with the Soxtec System 2043 Extraction Unit (FOSS, Hillerød, Denmark). Crude protein content was analyzed by the Kjeldahl method with a Kjeltec 2300 analyzer (FOSS, Hillerød, Denmark). For determination of crude fiber, ISO 6865:2000 was used [65]. The following calculation was applied for the determination of nitrogen-free extractives (NFE):

$$\text{NFE (\%)} = \text{dry matter} - (\text{crude ash} + \text{crude protein} + \text{crude fiber} + \text{crude fat}).$$
 Feed metabolizable energy was calculated according to Oll and Tölp (1995) and metabolizable protein (MP), as described by Kärt et al. [66,67].

The fatty acid profile was determined using a method described by Sukhija and Palmquist [68].

2.3. Mineral and Vitamin Content

To determine the mineral content of apple pomace, established methods were used. Calcium content was determined flame-photometrically using the EVS-EN ISO 6869:2001 method [69]. Phosphorus content was determined spectrophotometrically using AOAC Official Method 965.17 [62]. The following mineral contents were determined with flame atomic absorption spectroscopy (EVS-EN ISO 6869:2001): calcium (Ca), potassium (K), magnesium (Mg), sodium (Na), iron (Fe), copper (Cu), manganese (Mn), and zinc (Zn).

Vitamin content analysis was performed at the Veterinary and Food Laboratory under the Estonian University of Life Science (Tartu, Estonia) using Agilent HPLC 1200 equipped with degasser, quaternary pump, autosampler, column thermostat, DAD, and FLD detectors for vitamins A, D, E, B1, B2, and B6. B5 was detected by liquid chromatography with tandem mass spectrometry (LC-MS-MS). The column used for all the vitamins was C18. For B vitamins, the mobile phase consisted of acidic water and methanol. For fat-soluble vitamins, the mobile phase contained water–methanol–acetonitrile. Water-soluble vitamins and B1–4 were detected with diode-array detection (DAD) and B6 by using a fluorescence

detector (FLD). The flow rate was 0.5 mL/min. The LC-MS-MS instrument operated in positive ionization mode: capillary voltage 3500 V. The methods used were as follows: EVS-EN 12821:2009 for vitamin D [70], EVS-EN 12822:2014 for vitamin E [71], EVS-EN 12823-1:2014 for vitamin A [72], EVS-EN 14152:2014 for vitamin B2 [73], EVS-EN 14122:2014 for vitamin B1 [74], and EVS-EN 14663:2006 for vitamin B6 [75]. The concentrations were calculated based on the peak area detected in the sample using external calibration.

2.4. Amino Acid Content

For the analysis of amino acid content, a liquid chromatography-tandem mass spectrometry (LC-MS/MS) system was used featuring an Agilent 1290 Infinity II quaternary pump, a column thermostat, an autosampler, and an Agilent 6460 Triple Quadrupole (QqQ) mass spectrometer (MS) with Agilent Jet Stream Technology electrospray ionization source (ESI). The chromatographic column was a Zorbax Eclipse Plus C18 (3.0×100 mm, $1.8 \mu\text{m}$) equipped with a guard column (3.0×5 mm, $1.8 \mu\text{m}$). The mobile phase consisted of 0.1% aqueous formic acid (A) and acetonitrile (B) at a flow rate of 0.4 mL/min with the following gradient: 0–2 min, 10%; 2–27 min, 10–98%; 27–29 min, 98%; 29–31 min; 98–10% (B). Analysis was carried out in positive ionization mode with a capillary voltage of 3000 V in dynamic multiple reaction monitoring (dMRM) mode. More details regarding the MS parameters, dMRM transitions, and hydrolysis conditions have been published [76]. However, the mass of the sample was modified, and approximately 100 mg of apple pomace was utilized.

2.5. Extraction Procedure

Antioxidants from apple pomace were extracted using both ultrasound-assisted and conventional extraction procedures. The conventional procedure was solvent extraction, during which 96% ethanol, 70% ethanol, and distilled water were used to determine which of the mentioned solvents gives the highest extraction yield. While we initially considered using smaller concentrations of ethanol as well, we chose to use 70% ethanol due to a literature review, which, in general, proved that 70% ethanol is favored over smaller concentrations for the extraction of polyphenols and antioxidants in various plant materials [77,78]. The goal of this study was to compare the highest yield achieved using ethanol to yields achieved with water. We chose 70% ethanol as we anticipated it would yield the highest results over lower ethanol concentrations. Grounded pomace 5 g was mixed with 100 mL of solvent in a glass beaker. After this, the extracts were left for 24 h in a shaker (Thermo Scientific MaxQ 6000 Shaker, Waltham, MA, USA).

The sample powder (5 g) was once again mixed with 100 mL of solvent. For comparison, the sample-to-solvent ratio was the same for both conventional and ultrasound extraction. For ultrasound extraction, 70% ethanol was used based on our results of conventional extraction. The choice was also made based on a literature review, which showed that a similar concentration of ethanol was the most optimal for ultrasound-assisted extraction of antioxidants and phenolic compounds from apple pomace [53]. Before ultrasound extraction, apple pomace samples with solvent were mixed using a magnetic stirrer with no heating applied to samples for 1 h. The ultrasound-assisted extraction of antioxidants was carried out using a UP 400St ultrasonic processor ($\varnothing 7$ mm titanium horn; Hielscher GmbH, Chamerau, Germany). The conditions for the ultrasound extraction were chosen based on the literature review with some modifications [79]. The number of runs was determined by RSM.

The beaker with the sample was put in a larger beaker with ice to avoid overheating and degradation of the phenolic compounds during the extraction process. In general, the temperature was kept below $+30^\circ\text{C}$ degrees.

After both conventional and ultrasound extraction, the extracts were separated from the residue by filtration using Whatman filter paper. Paper filtration was performed several times until the extract and the residual plant material were properly separated. Recovered extracts were placed in the refrigerator until antioxidant analysis was performed.

Extracts were analyzed for total phenolic content, DPPH• free radical scavenging activity, and ABTS•⁺.

2.6. Response Surface Methodology

For this particular study, response surface methodology coupled with the central composite design was used to evaluate the effect of two independent variables of the UAE process on the extraction yield of total phenolic content (TPC), DPPH• radical scavenging activity, and ABTS•⁺. The significance of the prediction model and the impact of variables were assessed using *p*-values and *R*². Model terms with *p*-values less than 0.0500 are considered statistically significant. The parameters for optimization were extraction time (*A*, min) and sonicator amplitude (*B*, %). The ranges of factors were 5–30 min for extraction time and 20–50% for amplitude. In Table 1, the observed responses (TPC, DPPH• and ABTS•⁺) are presented. In Table 2 and Table S1, observed levels of independent variables, determined by RSM, are shown. Table 3 presents an overview of the experimental design for ultrasound-assisted extraction.

Table 1. Responses observed for the central composite design.

Response	Name	Units
R1	TPC	mg GAE eq./g DW
R2	DPPH•	μM TE eq./g DW
R3	ABTS• ⁺	μM TE eq./g DW

mg GA eq./g DW-mg of gallic acid equivalents per g of dry weight; μM TE eq./g DW-μM TE Trolox equivalent (TE) per g of dry weight sample.

Table 2. Observed levels of independent variables.

Name	Units	Type	Min	Max	Coded Low	Coded High	Mean
Time	Min	Numeric Continuous	5.00	30.00	−1↔5.00	+1↔30.00	17.50
Amplitude	%	Numeric Continuous	20.00	50.00	−1↔20.00	+1↔50.00	35.00

Table 3. The experimental design matrix for ultrasound-assisted extraction.

Run	Time (min)	Amplitude (%)
1	30 (+1)	35 (0)
2	5 (−1)	35 (0)
3	5 (−1)	20 (−1)
4	30 (+1)	20 (−1)
5	5 (−1)	50 (+1)
6	30 (+1)	50 (+1)
7	17.5 (0)	20 (−1)
8	17.5 (0)	35 (0)
9	17.5 (0)	50 (+1)

The coded levels are designated as follows: +1 represents the highest observed level, 0 corresponds to the medium observed level, and −1 indicates the lowest observed level of the independent variable.

2.7. Total Phenolic Content

Total phenolic content was measured using the Folin–Ciocalteu (FC) method described by Song et al. (2010) with some modifications [80]. The gallic acid solutions used for the calibration curve were prepared at the following concentrations: 25, 50, 75, 100, 125, 150, 175, 200, 250, and 300 μg/mL. For the calibration curve, 40 μL of each standard was pipetted along with 200 μL of FC (0.2 N) reagent and 160 μL Na₂CO₃ (75 g/L) into a 96-well microplate with 400 μL volume. The microplate was incubated for 30 min in the dark. After that, the microplate was inserted into a microplate spectrophotometer (Biotek, Epoch 2 microplate reader, Winooski, VT, USA), and the absorbance was read at 765 nm wavelength.

Once the calibration curve was made, TPC analyses of apple pomace extracts were performed. Before analyses, all the samples were diluted 40 times (12.5 μL of apple pomace extract + 487.5 μL of solvent used for extraction). The samples were then added the same way as it was carried out for the standard calibration: 40 μL of the diluted sample, 200 μL of FC (0.2 N) reagent, and 160 μL Na_2CO_3 (75 g/L) in microplate, which was then inserted into microplate spectrophotometer. The absorbance was read at 765 nm wavelength. Acquired TPC results were expressed as mg of gallic acid equivalents per g of apple pomace dry weight (mg GA eq./g DW) using regression equation ($R^2 = 0.9992$) acquired from the calibration curve. All chemicals were of analytical grade and were purchased from Stigma (Steinheim, Germany).

2.8. DPPH• Radical Scavenging Assay

DPPH• radical scavenging activity was determined using a spectrophotometric method of Brand-Williams et al. with some modifications [81]. For the calibration curve, 20 μL of Trolox standard, previously prepared in various concentrations, was pipetted, and then 360 μL of 0.1 mM DPPH• assay was added into a 96-well microplate. The microplate was left to incubate in darkness at room temperature for 30 min. After that, the reading was carried out at 515 nm wavelength using a microplate reader. Before the analyses, apple pomace extracts were diluted 10 times (50 μL of apple pomace extract + 450 μL of solvent used for extraction). The DPPH• procedure of apple pomace extracts was carried out in the same way as for the calibration curve described previously: 20 μL of sample and 360 μL of DPPH• assay were pipetted into the microplate, and the absorbance was read at 515 nm wavelength. The final DPPH• values were calculated using the regression equation ($R^2 = 0.9932$) obtained from the calibration curve. The antioxidant capacity of each sample is expressed as μM of Trolox equivalent (TE) per g of dry weight sample. All chemicals used for this experiment were of analytical grade and were purchased from Stigma (Steinheim, Germany).

2.9. ABTS•+ Radical Scavenging Assay

ABTS•+ analyses were performed using a method previously described by Re et al. (1999) with some modifications [82]. ABTS•+ radical cation was made by mixing 7 mM ABTS•+ with 2.45 mM potassium persulfate (1:0.5). After that, it was incubated for 12 h in the dark at room temperature. Prior to the analyses, the ABTS•+ assay was diluted 32 times with 70% ethanol. For the calibration curve, 3 μL of Trolox solutions at various concentrations were pipetted into 96-well microplates, and then 300 μL of diluted reagent was added. The microplate was incubated for 30 min in the dark. Reading was performed at 734 nm wavelength using a microplate spectrophotometer (Biotek, Epoch 2 microplate reader, USA). The ABTS•+ measurement procedure of apple pomace extracts was carried out in the same way as for the calibration curve described previously: 3 μL of sample and 300 μL of assay were pipetted into the microplate, and the absorbance was read at 734 nm wavelength. The final ABTS•+ values were calculated by using a regression equation ($R^2 = 0.9961$) obtained from the calibration curve. ABTS•+ results for each sample are expressed as μM TE Trolox equivalent (TE) per g of dry weight sample. All chemicals utilized for ABTS•+ analyses were of analytical grade and were purchased from Stigma (Steinheim, Germany).

2.10. Statistical Analyses

For statistical analyses, Design Expert 12 (Stat-Ease Inc., Minneapolis, MN, USA) software was used to determine whether factors were statistically significant for the optimization of antioxidant analyses. R Statistical Software (v4.1.2; R Core Team 2021) was used for the generation of plots. Correlations and *t* tests were performed in Microsoft Excel 2017 Data Analysis Add-in. In addition, to evaluate the significance of solvent impact on extraction yield, SAS OnDemand for Academics was used (SAS OnDemand for Academics,

Cary, NC, USA). All results are mean values of three replicate analyses calculated, apart from vitamin content analyses.

3. Results and Discussion

3.1. Proximate Analyses and Fatty Acid Content

Apple pomace showed a relatively low content of crude protein and a moderately low content of crude fiber compared to conventional feed material. The proximate content of this variety of apple pomace is presented in Table 3. Previous studies have reported similar results of proximate analyses of apple pomace, which include low crude protein and crude fat in apple pomace [57,83–91]. However, this variety of apple showed scanty crude fiber content, only up to 14.6%, which is significantly lower than previously reported crude fiber content of dehydrated apple pomace [92–94]. While apple pomace may have low protein and fat content, enhancing its nutritional profile by ensiling it with urea or ammonia or fermenting transforms it into a considerable alternative feed ingredient for ruminants. This process elevates its feeding value to a level comparable to that of grass silage for beef cattle [83]. Based on the literature review that has been carried out for this article, the content of protein and fat of apple pomace from variety *B. malinovje* is comparable to that of citrus pulp [95–97]. The crude fat and crude fiber content of apple pomace has shown to be more similar to pumpkin and citrus pulp; however, pumpkin peel has much greater protein content [95–100]. The results of metabolizable energy and metabolizable protein align with previously reported results and are presented in Table 4 [83,84,89–91].

Table 4. Proximate analysis, vitamin, fatty acid, and mineral content of apple pomace.

Traits		Vitamin Content		Fatty Acid Profile		Mineral Content	
Dry matter, %	89.4 ± 0.28	Vitamin A, Retinol µg/100 g	<2	C14:0	0.32 ± 0.03	Ca, g/kg	1.1 ± 0.08
Crude protein, %	3.0 ± 0.15	Vitamin A, Beta carotene µg/100 g	<20	C16:0	14.6 ± 0.95	P, g/kg	1.5 ± 0.2
Crude fiber, %	14.6 ± 0.25	Vitamin E mg/100 g	2.42	C16:1	0.2 ± 0.04	Na, g/kg	0.04 ± 0
Crude fat, %	3.1 ± 0.2	Vitamin D µg/100 g	<1	C18:0	4.15 ± 0.25	K, g/kg	10.6 ± 0.2
Content of NFE in feed, %	76.2 ± 1.3	B1 vitamin mg/100 g	<0.01	C18:1	17.1 ± 0.95	Mg, g/kg	0.6 ± 0.07
ME, MJ/kg	9.8 ± 0.55	B2 vitamin mg/100 g	0.29	C18:2	55.1 ± 1.4	Zn, mg/kg	10.1 ± 0.5
		B3 vitamin mg/100 g	0.6	C18:3	3.94 ± 0.3	Copper, mg/kg	6.7 ± 0.2
		B5 Vitamin mg/100 g	0	C18:4	0.09 ± 0	Manganese, mg/kg	5.6 ± 0.1
MP, g/kg	73 ± 0.8	B6 Vitamin mg/100 g	0.23	C20:0	2.12 ± 0.2	Fe, mg/kg	11.2 ± 0.28
				C20:1	0.34 ± 0.03		
				C20:2	0.35 ± 0.08		
				C22:0	0.61 ± 0.02		
				C22:1	0 ± 0		
				C24:0	0 ± 0		

ME = metabolizable energy, MP = metabolizable protein; fatty acid composition results are expressed as g/100 g of fatty acids. C14:0—myristic acid; C16:0—palmitic acid; C16:1—palmitoleic acid; C18:0—stearic acid; C18:1—oleic acid; C18:2—linoleic acid; C18:3—alpha-linolenic acid; C18:4—stearidonic acid; C20:0—arachidic acid; C20:1—eicosenoic acid; C20:2—eicosadienoic acid, C22:0—docosanoic acid, C22:1—erucic acid, C24:0—lignoceric acid. Vitamins are expressed in different units.

Regarding fatty acid content, linoleic acid and oleic acid are proven to be two major unsaturated fatty acids of apple pomace. These results align with previous studies on the fatty acid composition of apple pomace [7,101,102]. While oleic and linoleic fatty acids are dominant fatty acids in apple pomace, apple pomace's low-fat content means that this by-product is not considered a rich source of these fatty acids compared to other waste materials, which may yield higher amounts [7].

3.1.1. Minerals and Vitamin Content

Apple pomace measured a relatively high content of vitamin E when compared to conventional feed material [103]. To our knowledge, only a few studies on apple pomace included the vitamin content of apple pomace; thus, the vitamin results obtained in this study were difficult to compare with previous results. Previous studies of apple pomace mostly included vitamins C and E only and often with antioxidants, making it difficult to

understand the value obtained for individual vitamins [58–61,104]. However, based on the results, it can be concluded that pomace derived from this particular variety is a rich source of vitamin E, which is consistent with previous findings in apple pomace [7,102]. Vitamin E significantly influences animal health, particularly in dairy cows, by positively affecting reproductive function, bolstering the immune system, aiding in mastitis prevention, and enhancing milk quality [105]. Even though the concentration of vitamin E for this variety is still quite high, it is lower compared to previously reported vitamin E concentration for apple pomace [7,104]. The results of the vitamin content obtained for apple pomace are shown in Table 3. Moreover, the results of the mineral content of apple pomace are consistent with prior studies [7,11,55]. Based on our results, this variety of apple pomace exhibited high concentrations of potassium, while other minerals are present in lower or trace amounts [7,106].

3.1.2. Amino Acid Content

Based on our results, the amino acid concentration of this variety of apple pomace is low when compared to conventional feed material [103]. Our results showed that two major amino acids in apple pomace are glutamic acid and aspartic acid. The high concentration of glutamic acid in apple pomace is especially interesting, considering its importance for dairy cows. Glutamic acid plays a significant role in protein metabolism, and it is involved in various psychological processes in dairy cows, with a special emphasis on the synthesis of milk protein [107]. Providing an adequate amount of glutamic acid is essential for ensuring animal health and milk production. Amino acid content is presented in Figure 1 and in the chromatogram of amino acids after hydrolysis in dMRM mode, presented in Figure S5. Previous studies involving the amino acid content of apple pomace reported similar results, with general low protein content and glutamic acid and aspartic acid being major amino acids [108,109].

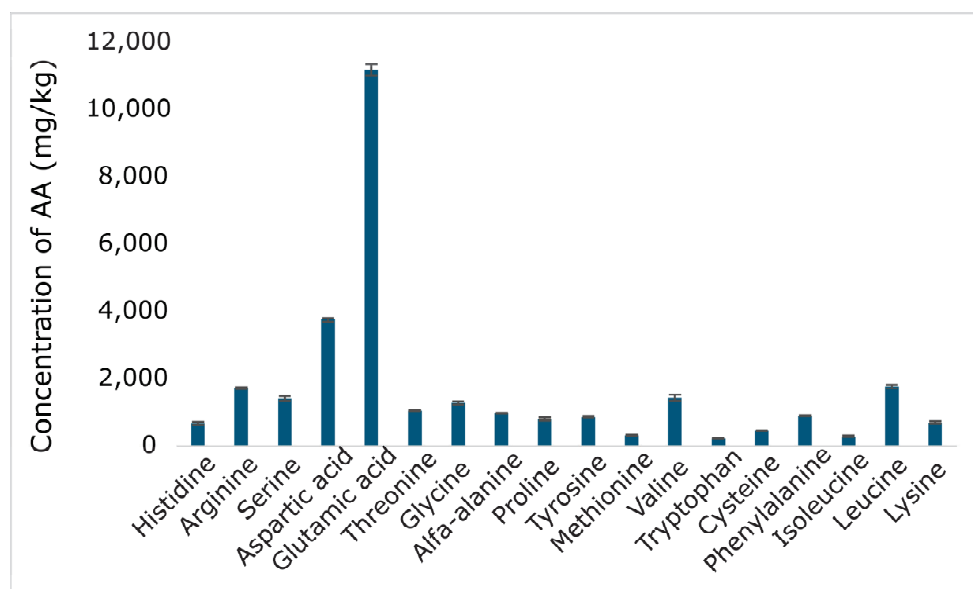


Figure 1. Total amino acid content (mg/kg) of apple pomace. Amino acid composition results are expressed as mg/kg of sample; all values are means $\pm$ standard deviation, $n = 2$.

3.2. Optimization of Conventional Extraction of TPC, DPPH $\bullet$, and ABTS $\bullet^{+}$

The solvent extraction efficiency was similar across three analyses: TPC, DPPH $\bullet$, and ABTS $\bullet^{+}$; 70% of ethanol in all three analyses showed the best results and highest yield of antioxidants. Before the analyses, distilled water was expected to show the lowest results; and it was chosen for this experiment to see whether distilled water extraction results could be comparable to the ethanol extraction results. The aim of including distilled water was to evaluate the possibility of eliminating the use of solvents that negatively affect the

environment, even though compared to other solvents (hexane, chloroform, methanol, etc.), ethanol is considered a green solvent and is environmentally preferable [110]. Besides looking from an environmental aspect, economically, it would also make more sense to use distilled water rather than ethanol. Distilled water, however, did not show the lowest results, as the smallest extraction yield for all three analyses was obtained when 96% ethanol was used. In Table 5, mean values of TPC, DPPH•, and ABTS•+ results are presented, respectively. Based on the obtained results and the highest yield for TPC, DPPH•, and ABTS•+ achieved by using 70% ethanol during conventional extraction, ultrasound-assisted extraction was carried out with this solvent. The effect of solvent on the extraction yield of all three analyses—TPC, DPPH•, and ABTS•+—was statistically significant: $p = 0.0006$, $p = 0.0010$, and $p = 0.0017$ respectively (Table S6, Table S7 and Table S8, accompanied by visual representation: Figure S2, Figure S3 and Figure S4 respectively).

Table 5. Mean values of TPC (mg GAE/g DW), DPPH• (μM TE/g DW), and ABTS•+ (μM TE/g DW).

	TPC	DPPH•	ABTS•+
APC96	2.9 ± 0.2	31.34 ± 1.7	84.86 ± 1.6
APC70	4.36 ± 0.1	43 ± 1.8	95.81 ± 1.18
APCW	3.15 ± 0.3	36 ± 2.2	90.7 ± 2.83

APC96 represents apple pomace extracted in 96% ethanol, APC70—apple pomace extracted in 70% ethanol, and APCW—apple pomace extracted in distilled water.

3.3. Optimization of Ultrasound-Assisted Extraction of TPC, DPPH•, and ABTS•+

For optimizing the yield of TPC, DPPH•, and ABTS•+, the chosen extraction method was ultrasound-assisted extraction as this technique is quite efficient, energy and time-saving, and it is suitable for extraction of heat-sensitive compounds. For this study, two independent variables were selected for the optimization of TPC, DPPH•, and ABTS•+ yield: extraction time and amplitude. RSM was employed to ascertain the optimal condition of independent variables, to create a prediction model, and to evaluate the impact of these two factors on the TPC and antioxidant yield. The independent variables are presented in Table 3. In Table 6, actual and predicted values of TPC, DPPH•, and ABTS•+ are displayed, with visual representation of the yields shown in Figure S1. Based on the data acquired and summary statistics involving p -value, F -value, and R^2 , the quadratic model was the best fit for maximizing all three yields (Tables S9–S11).

Table 6. Actual and predicted values of TPC (mg GAE/g DW), DPPH• (μM TE/g DW), and ABTS•+ (μM TE/g DW) of apple pomace extracted by ultrasound-assisted extraction.

Run Order	Time (min)	Amplitude (%)	TPC		DPPH•		ABTS•+	
			Actual Value	Predicted Value	Actual Value	Predicted Value	Actual Value	Predicted Value
1	30	35	3.65	3.66	26.3	24.7	96.0	96.2
2	5	35	2.55	2.68	17.5	17.9	95.7	94.2
3	5	20	3.65	3.50	35.2	34.4	100.7	101.8
4	30	20	4.24	4.15	43.6	43.9	98.4	98.7
5	5	50	1.50	1.52	20.0	20.3	88.0	88.4
6	30	50	2.75	2.83	23.2	24.5	95.9	95.4
7	17.5	20	4.26	4.45	44.4	45.0	98.0	96.6
8	17.5	35	3.95	3.80	26.0	27.1	90.2	91.5
9	17.5	50	2.90	2.80	30.0	28.2	88.0	88.2

All results are mean values of three replicate analyses calculated.

For the optimization of TPC extraction yield, the model p -value implies that the model is significant, as presented in Table 7 and Table S3. In this case, A, B, and A² are significant

model terms (factors) for the optimization of TPC yield, with A being time and B being the amplitude, as shown in Table 7. *p*-values indicate that both factors (time and amplitude) impact the yield of TPC. The predicted R^2 of 0.7614 is in reasonable agreement with the adjusted R^2 of 0.9401; i.e., the difference is less than 0.2 (Table S2). The high R^2 value of 0.9775 implies that approximately 97.75% of the variability in TPC results can be explained by independent variables in the model (Table S2). The adjusted R^2 is also very high, which suggests that even with multiple factors included, the model can explain about 94% of the variability of response (Table S2).

Table 7. *p*-values of the models for optimization of TPC, DPPH•, and ABTS•+ yield obtained by Analysis of variance (ANOVA) for quadratic model.

Model and Model Terms	Response 1: TPC	Response 2: DPPH•	Response 3: ABTS•+
	<i>p</i> -Value	<i>p</i> -Value	<i>p</i> -Value
Model	0.011 *	0.005 *	0.031 *
A-Time	0.013 *	0.019 *	0.236
B-Amplitude	0.003 *	0.002 *	0.008 *
AB	0.235	0.247	0.051
A ²	0.028 *	0.020 *	0.048 *
B ²	0.345	0.005 *	0.505

* Represent values which are statistically significant at $p < 0.05$.

Regarding the optimization of DPPH• yields, the model's F-value of 45.05 and *p*-value ($p = 0.0051$) indicate that the model is significant, as can be seen in Tables 7 and S4. A, B, A², and B² are significant model terms, which tells us that both time and amplitude influence DPPH• yield (Table 7). Just like in the results for TPC, the predicted R^2 is in reasonable agreement with the adjusted R^2 , with the difference being less than 0.2 (Table S2). In addition, high R^2 and adjusted R^2 values suggest that the model is a good fit and that it can explain a large percentage of variability of DPPH• extraction yield (Table S2).

For maximizing ABTS•+ yield, the *p*-value ($p = 0.03$) suggests the model created is significant, as presented in Table 7 and Table S5. In this quadratic model, B (amplitude) and A² are significant model terms. In addition, R^2 of the ABTS•+ optimization model is high: 0.9552, suggesting that 95% variability in ABTS•+ extraction yield can be explained by independent variables used in the model (Table S2). However, the predicted R^2 of 0.56 is not as close to the adjusted R^2 of 0.88 as one might normally expect (Table S2). For this model, reducing the number of terms could be helpful.

Final equations describing the extraction yield of TPC (mg GAE/g DW) (1), DPPH• (2), and ABTS•+ (3) were the following:

$$Y1 = 3.38 + (0.149 \times A) - (0.015 \times B) + (0.00088 \times A \times B) - (0.004019 \times A^2) - (0.000782 \times B^2) \quad (1)$$

$$Y2 = 77.84924 + (1.81633 \times A) - (3.38551 \times B) - (0.006917 \times A \times B) - (0.037173 \times A^2) + (0.042141 \times B^2) \quad (2)$$

$$Y3 = 120.5616 - (1.22422 \times A) - (0.784751 \times B) + (0.013556 \times A \times B) + (0.023644 \times A^2) + (0.003827 \times B^2) \quad (3)$$

where Y1 represents the yield of TPC (mg GAE/g DW), Y2 represents the yield of DPPH• (μM TE/g DW), Y3—ABTS•+ (μM TE/g DW), A—time, and B—amplitude.

In Figure 2, a three-dimensional (3D) response surface plot is represented to show the visual effect of factors on each response, TPC (a), DPPH• (b), and ABTS•+ (c) extraction yield, as well as the relationship between the two factors. From the plot, it can be concluded that increasing the amplitude negatively affected the yield of TPC (Figure 2a). This can also be concluded by Equation (1). At the same time, with the increase in the time of extraction, TPC extraction increased as well. The lowest amplitude (20%) and middle set time (17.5 min) provided the highest yield of TPC, while the lowest amplitude and highest set time were a close second.

Based on the given Equation (2), which helps us understand the impact of the independent variable on the response, in this case, DPPH•, we can conclude that increasing amplitude has a negative effect on DPPH• extraction yield. This has been further proved by a 3D response surface plot, which provides the visual of the factor's individual and combined influence on the response (DPPH•), which is shown in Figure 2b. Much like with the results of TPC, the lowest set amplitude (20%) accompanied by the middle set time 17.5 provided the highest DPPH• results. This also implies there is a positive correlation between TPC and DPPH• results.

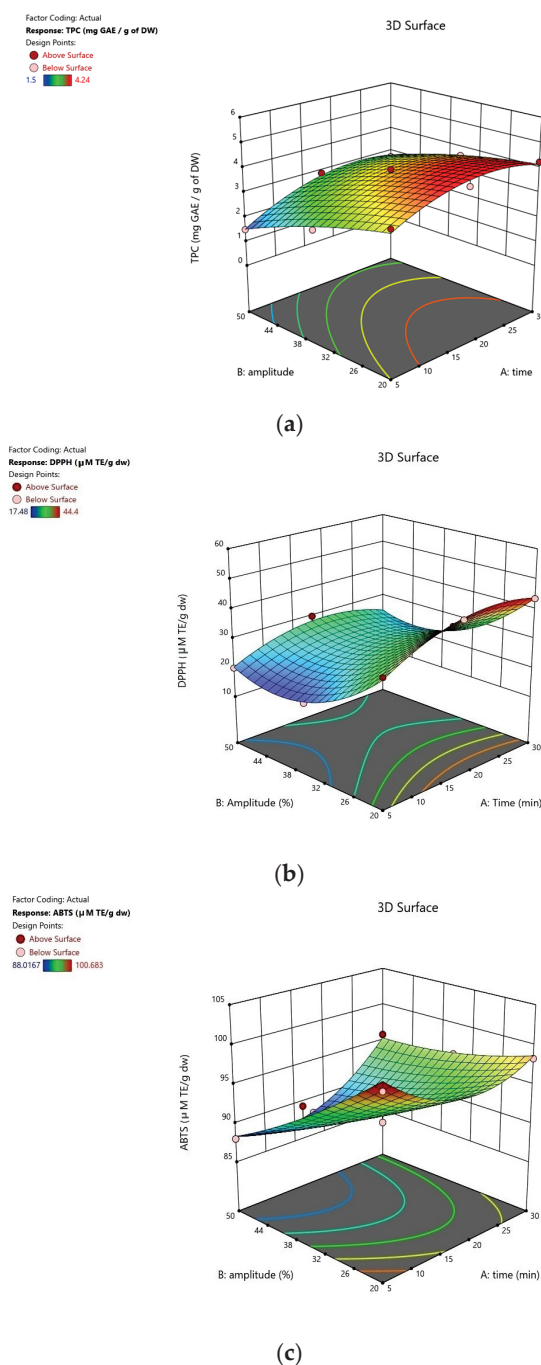


Figure 2. Three-dimensional response surface plot showing the effects of ultrasonic time (A) and amplitude (B) on TPC extraction yield (a), DPPH• extraction yield (b), and ABTS•+ extraction yield (c). Blue color presents the lowest results, and red color shows the highest results for TPC yields (mg GAE/g DW), DPPH•, and ABTS•+ (μM TE/g DW).

Looking at Equation (3), we can see that increasing both time and amplitude has a negative effect on ABTS^{•+} yield. This is visually shown in the 3D response surface plot, which is presented in Figure 2c. Based on this, we can also include that the correlation between ABTS^{•+} extraction yield and TPC and DPPH[•] is slightly less. The highest ABTS^{•+} yield was obtained with the lowest amplitude (20%) and lowest extraction time (5 min). The ABTS^{•+} assay yielded the highest results with the shortest extraction time, unlike TPC and DPPH[•], where the highest results were achieved with medium extraction time. The decline in ABTS^{•+} results associated with prolonged extraction time could be attributed to the decomposition of antioxidative compounds within the sample [111,112]. Furthermore, the highest ABTS^{•+} results obtained with the shortest extraction time could be attributed to the rapid response of certain antioxidants, leading to increased activity during shorter extraction time, while other antioxidants may require a longer period of time to reach their optimal antioxidant activity [113]. It is important to emphasize that while both DPPH[•] and ABTS^{•+} provide valuable information about the antioxidant capacity of the material, they might not extract the same antioxidants [113]. In addition, the antioxidants they extract could exhibit different response times influenced by their distinct chemical properties and interactions with other components in the matrix [113]. Moreover, some antioxidants could be more sensitive to certain extraction conditions such as ultrasound intensity, temperature, extraction duration, etc. [114–116]. Differences in assay conditions, especially the concentration of radicals and reaction kinetics, might contribute to the highest antioxidant yield being achieved with different extraction times [113].

3.4. Comparison between Conventional and Ultrasound-Assisted Extraction and Antioxidant Content of Apple Pomace

The results for TPC, DPPH[•], and ABTS^{•+} from apple pomace correspond with results reported in previous studies carried out on different varieties of apple pomace [47,50,53,56]. In this study, TPC values for the variety *B. malinovoje* were lower than the results previously presented for this variety; however, DPPH[•] results are in agreement [52]. While this study reports lower total phenolic content (TPC) results compared to previous findings, several factors might explain this variance. Differences in extraction techniques, methodologies, variations in the treatment of apple pomace, and seasonal variations could contribute to the observed differences in antioxidant content [117–120]. Understanding and recognizing the factors that influence is very important for the optimization of antioxidants of apple pomace.

In addition, the positive values of linear correlation coefficients indicate that analyses are positively correlated one with the other ($TPC \times DPPH^{\bullet} = 0.78$, p value: 0.01388; $DPPH^{\bullet} \times ABTS^{\bullet+} = 0.52$, p value: 0.1497 and $TPC \times ABTS^{\bullet+} = 0.57$ p value: 0.109); however, the correlation is not as high as expected. Previously reported correlation between results of TPC, DPPH[•], and ABTS^{•+} of apple pomace has been higher [47]. The correlation between TPC and DPPH[•] results is statistically significant. In addition, ABTS^{•+} results are higher than DPPH[•] results. This can be attributed to the fact that ABTS^{•+} assay applies to hydrophilic and hydrophobic antioxidant systems, while the DPPH[•] applies to hydrophobic systems only [121–123]. This can result in ABTS^{•+} capturing more antioxidant capacity, leading to higher readings [121–123].

In addition, the difference in results between ABTS^{•+} and DPPH[•] could be explained by higher radical reactivity and reaction kinetics in ABTS^{•+} assay than in DPPH[•] where the reduction in radicals occurs more slowly [124–127]. Due to higher radical reaction, absorbance decreases faster too, which may lead to higher antioxidant activity values observed in the ABTS^{•+} assay compared to the DPPH[•] assay [111–113,122]. Antioxidant compound solubility can also lead to differences in results [128,129]. In addition, ABTS^{•+} is more sensitive than DPPH[•] assay, and it can detect antioxidants with low concentrations, which can further explain the higher results obtained [122]. The choice of solvent can play a significant role and influence the results as well. ABTS^{•+} radicals are soluble in both organic and aqueous solutions, while DPPH[•] radicals are soluble in organic mediums

only [122,124,127]. Therefore, the choice of solvent can affect the solubility and reactivity of antioxidants and affect the results. Also, because the chemical structure of ABTS^{•+} and DPPH[•] radicals is different, it impacts their reactivity with antioxidants, so some antioxidants may be more efficient at scavenging ABTS^{•+} radicals compared to DPPH[•] radicals, which can result in higher readings in ABTS^{•+} assay [113].

The difference between TPC, DPPH[•], and ABTS^{•+} of apple pomace obtained by conventional extraction using 70% ethanol, and TPC, DPPH[•], and ABTS^{•+} results obtained by ultrasound extraction using optimal conditions is not statistically significant ($p = 0.368$, $p = 0.128$, and $p = 0.122$, respectively). Interestingly, TPC results from conventionally extracted apple pomace using 70% ethanol are higher than results acquired by using optimal conditions for ultrasound extraction. However, as previously mentioned, the difference between the two is not statistically significant. For both DPPH[•] and ABTS^{•+}, extraction yield was higher when optimal conditions for ultrasound-assisted extraction were used, compared to yield obtained by conventionally extracted apple pomace with 70% ethanol, but as previously stated, the difference was not statistically significant. Based on the results obtained, further research on extraction conditions and different extraction techniques is advised.

4. Conclusions

Based on our comprehensive investigation, it can be concluded that the apple pomace variety *B. malinovoje* has potential as a feed ingredient despite its low protein and fiber content. It is a rich source of vitamin E and glutamic acid, which could especially be beneficial to dairy cows. Moreover, the extraction yield of TPC, DPPH[•], and ABTS^{•+} has been optimized using RSM, and the impact of independent variables—time and amplitude—was established. The time and amplitude proved to be of high significance. The optimal conditions for TPC and DPPH[•] analyses were found to be an extraction time of 17.5 min and an ultrasound-assisted extraction amplitude of 20%. For ABTS^{•+}, optimal conditions were achieved with a 5 min extraction time and 20% amplitude. Further research is warranted to improve the nutritional content of apple pomace, especially in enhancing its protein and fiber content. Enhancing protein content could potentially be achieved through ensiling apple pomace with urea or by fermentation and cultivation of filamentous fungi with pomace. Fiber content could be enhanced by adding material rich in fiber with apple pomace. Besides enhancing fiber and protein content, we propose further research involving optimizing vitamin E yield, studying the effect of apple pomace on animal health, and determining the optimal percentage of incorporating apple pomace in the diets of different animals. By addressing these areas, apple pomace of var. *B. malinovoje* could be utilized as a sustainable and nutritious ingredient in animal feed production, contributing to both agricultural sustainability and animal wellbeing.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su16072765/s1>, Figure S1: Presentation of actual and predicted yield of TPC (a), DPPH (b) and ABTS^{•+} (c); Table S1: Independent variables and their levels; Table S2: R² values of the model predicting TPC, DPPH[•] and ABTS^{•+} extraction yield; Table S3: Analysis of variance (ANOVA) of model for the yield of TPC from apple pomace; Table S4: Analysis of variance (ANOVA) of model for the yield of DPPH[•] from apple pomace; Table S5: Analysis of variance (ANOVA) of model for the yield of ABTS^{•+} from apple pomace; Figure S2: Distribution of TPC results for apple pomace conventionally extracted using different solvents; Figure S3: Distribution of DPPH[•] results for apple pomace conventionally extracted using different solvents; Figure S4: Distribution of ABTS^{•+} results for apple pomace conventionally extracted using different solvents; Table S6: Results of ANOVA procedure for TPC results of apple pomace conventionally extracted using different solvents (96% ethanol, 70% ethanol, distilled water); Table S7: Results of ANOVA procedure for DPPH[•] results of apple pomace conventionally extracted using different solvents (96% ethanol, 70% ethanol, distilled water); Table S8: Results of ANOVA procedure for ABTS^{•+} results of apple pomace conventionally extracted using different solvents (96% ethanol, 70% ethanol, distilled water); Table S9: Model Summary Statistics for TPC results from apple pomace obtained

with ultrasound-assisted extraction; Table S10: Model Summary Statistics for DPPH• results from apple pomace obtained with ultrasound-assisted extraction; Table S11: Model Summary Statistics for ABTS•+ results from apple pomace obtained with ultrasound-assisted extraction; Figure S5: Chromatogram in MRM mode of amino acids after hydrolysis.

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Article

Digital Technology, Factor Allocation and Environmental Efficiency of Dairy Farms in China: Based on Carbon Emission Constraint Perspective

Chenyang Liu ¹, Xiuyi Shi ² and Cuixia Li ^{1,*}

¹ College of Economics and Management, Northeast Agricultural University, Harbin 150030, China

² School of Economics and Management, Southeast University, Nanjing 211189, China

* Correspondence: licuixia.883@neau.edu.cn

Abstract: The emission of carbon pollutants stemming from dairy farms has emerged as a significant obstacle in mitigating the effects of global warming. China, being a prominent nation in the field of dairy farming, encounters significant challenges related to excessive component input and elevated environmental pollution. Digital technology presents an opportunity to enhance the factor allocation of dairy farms and thus increase their environmental efficiency. This study utilizes survey data from 278 dairy farms in China to examine the effect of digital technology on the allocation of land, labor, and capital variables in dairy farms. The IV-Probit model, IV-Tobit model, treatment effect model, and two-stage least square technique are employed to empirically analyze these impacts. Simultaneously, the intermediate effect model was employed to examine the mediating function of factor allocation in the effect of digital technology on environmental efficiency. The findings indicate that digital technology has the potential to greatly enhance land transfer and land utilization rates in dairy farms. Additionally, it has been observed that digital technology may lead to a decrease in both the proportion and time of labor input. Furthermore, digital technology has the potential to decrease short-term productive input while simultaneously enhancing long-term productive input within dairy farming operations. Digital technology has been found to have an indirect yet beneficial influence on environmental efficiency. This is mostly achieved through the facilitation of resource allocation, specifically in terms of land, labor, and capital aspects. The article presents a set of policy recommendations, including the promotion of extensive integration of digital technology within dairy farms, the facilitation of optimal allocation of production factors in dairy farms, and the implementation of specialized training programs focused on digital technology.

Keywords: digital technology; factor allocation; environmental efficiency; carbon emission

1. Introduction

The dairy farming industry is recognized as a significant contributor to environmental pollution in agriculture, hence impeding the progress of global low-carbon green development [1,2]. It is observed that approximately 15% of carbon emissions can be attributed to animal husbandry. Within the domain of animal husbandry, dairy farming specifically contributes to 20% of the total emissions [3]. China holds the distinction of being the foremost global contributor to carbon dioxide emissions [4], while also maintaining a significant presence in the realm of dairy farming on a global scale. According to recent data, it is projected that China's dairy herd has reached 10.943 million head in 2021. Additionally, the milk output reached 36.827 million tons during the same period, reflecting year-on-year growth rates of 4.9% and 7.1%, respectively [5]. Nevertheless, the escalating issue of environmental pollution resulting from the emissions of cow dung and urine, as well as carbon dioxide emissions from intestinal fermentation, has grown more apparent. This has significantly intensified the challenges faced by China in its efforts to reduce carbon emissions in the agricultural sector [6,7]. The Chinese government formally announced the objective

of attaining the apex of carbon dioxide emission before 2030 and accomplishing carbon neutrality by 2060, referred to as the “double carbon” aim [8,9]. “The Opinions on Promoting High-quality Development of Animal Husbandry”, issued by The General Office of the State Council, emphasizes the importance of fostering a new model of high-quality development in China’s animal husbandry sector. This model should prioritize efficient output, resource conservation, and environmental sustainability. “The Implementation Plan for Carbon Emission Reduction and Sequestration in Agriculture and Rural Areas” explicitly emphasizes the need to enhance the per unit yield of livestock and poultry, while concurrently mitigating greenhouse gas pollution emissions, such as those arising from the intestinal tract and fecal methane emissions of ruminants. Given the “double carbon” objective and the escalating pollution caused by cattle and poultry, it has become imperative to enhance environmental efficiency as a means of aligning dairy farming with environmental preservation [10]. The concept of environmental efficiency involves maximizing production while minimizing both factor input and environmental degradation. Within the confines of the “double carbon” objective, enhancing the environmental efficiency of dairy farms entails optimizing the production efficiency of such farms, therefore minimizing carbon emissions and maximizing output [11].

The inherent conflict between economic development and the availability of resources and preservation of the environment is primarily determined by how different production elements are allocated, combined, and utilized efficiently [12]. The dairy farming model in China always experiences instances of over-input and under-input of production parameters within dairy farms [13]. The low production efficiency and significant environmental pollution in Chinese dairy farms can be attributed to inadequate factor allocation [14]. Hence, the allocation of factors has emerged as a crucial determinant impacting environmental efficiency. The method of factor allocation aims to optimize resource use and increase the utility of resource allocation when faced with limited resources [15]. Factor allocation in dairy farms pertains to the precise allocation and efficient usage of capital, land, and labor, intending to optimize resource utilization and enhance the welfare of dairy farmers. The optimization of component allocation in dairy farms has the potential to achieve Pareto optimization by effectively combining production factors, leading to a reduction in excessive carbon pollution. This is a crucial aspect of enhancing environmental efficiency [16].

The constraints posed by limited dairy farming resources in China, coupled with regional disparities in factor endowments, necessitate a multifaceted approach to the development of dairy farms. Relying solely on resource factors for input is insufficient, thus highlighting the need for the advancement of novel technologies that enhance production efficiency and environmental sustainability [17]. Digital technology has the potential to facilitate the greening of resource utilization within the agricultural factor allocation system [18]. This can be achieved by reducing resource waste, enhancing output efficiency, and mitigating non-essential carbon source pollution [19]. Consequently, the adoption of digital technology in factor allocation can contribute to the improvement of environmental efficiency [20]. In 2022, the State Council released “The 14th Five-Year Plan for the Advancement of the Digital Economy”, emphasizing the need for extensive and profound integration of digital technologies across economic, social, and industrial sectors. Additionally, the plan highlights the imperative to significantly enhance the level of digitalization in the agricultural domain. “The 14th Five-Year Plan for National Agricultural Green Development” was released. It outlines the objective of advancing the digitalization of agricultural production and achieving a thorough transition towards environmentally sustainable agriculture. Digital technology has emerged as a significant strategy for addressing the disparity in agricultural variables, enhancing productivity, and mitigating carbon emissions and pollution [21–23]. Dairy farms can leverage digital technology to facilitate the digital processing of data and information about production factors at each stage. This enables a gradual understanding of the underlying relationships between production factors, milk yield, and carbon emission pollution in dairy farms. Such insights

are beneficial for dairy farmers as they can enhance the input structure of production factors. The allocation of production components will progressively shift from production linkages with lower marginal benefits to those with higher marginal benefits. This will lead to greater optimization of the resource allocation and energy utilization structure. The reduction in environmental pollution resulting from the inequitable distribution of resources will lead to a substantial improvement in environmental efficiency.

Theoretical analyses have been conducted by several researchers to examine the effect of digital technology on component allocation and the environment [24–27]. However, there is a scarcity of empirical studies that investigate the specific action channel and transmission mechanism via which digital technology influences environmental efficiency. The effect of digital technology on factor allocation, particularly, is of significant importance. The effect of factor allocation on the environmental efficiency of dairy farms in relation to digital technology is a significant aspect to consider. This research aims to experimentally evaluate the dynamic interaction between digital technology, factor allocation, and environmental efficiency as a means to address the aforementioned issues. The study used the IV-Probit model, the IV-Tobit model, and the treatment effect model to assess the effect of digital technology on the allocation of resources. Furthermore, a theoretical framework was developed to examine the effect route of “digital technology-factor allocation-environmental efficiency”. The study employed the intermediate effect model to examine the effect of digital technology on factor allocation. Additionally, the intermediary effect model was utilized to empirically assess the function of factor allocation in the relationship between digital technology and environmental efficiency. The subsequent sections of this work are organized as follows. The subsequent section presents the theoretical framework and research hypothesis. The third section of the paper provides an introduction to the data source, outlines the process of variable selection, and establishes the model configuration. The fourth section of the paper presents the empirical findings and subsequent analysis. The fifth section of the study presents the research findings and offers policy recommendations.

2. Theoretical Basis and Research Hypothesis

The factor allocation of a dairy farm primarily entails the efficient allocation of three key production elements, namely land, labor, and capital. Digital technology in dairy farms, as a kind of agricultural technological advancement, has the potential to enhance regional production scale [28] and facilitate the commensurate increase in land allocation. Digital technology enables dairy farmers to effectively manage their dairy cows, while the strategic allocation of land in dairy farms may enhance the stocking density of dairy cows per unit area. Taking into account the postulation of the “rational economic man” theory [29], it can be inferred that dairy producers would progressively increase the magnitude of dairy farming operations until the land’s carrying capacity hits its maximum limit. In order to achieve the most effective distribution and productive exploitation of land resources in dairy farms, and to facilitate the enhancement of dairy farm production efficiency [30]. To enhance breeding income, dairy farmers should expand the land area of dairy farms to accommodate the growing number of dairy farms until they reach the maximum limit of land carrying capacity. This expansion facilitates the gradual formation of agglomeration effect and scale efficiency within dairy farms, resulting in reduced unit input costs for production factors and a significant decrease in pollution emissions. The factor that promotes the enhancement of both production efficiency and environmental efficiency has been identified [31].

Therefore, the paper suggests hypotheses as follows:

Hypothesis 1. *Digital technology has the potential to enhance decision-making processes for land transfer in dairy farms, leading to improved efficiency in land usage and facilitating the allocation of land elements.*

Hypothesis 2. *The distribution of land factors serves as an intermediary mechanism in the effect of digital technology on environmental efficiency.*

Digital technology has the potential to enhance the efficiency of labor capital allocation on dairy farms by mitigating temporal and spatial constraints, hence expanding employment and career opportunities for employees [32]. Digital technology could enhance the intelligence and modernization of dairy farming. It can also lead to a substantial substitution effect on the labor input [33], resulting in a reduction in labor requirements. Additionally, digital technology establishes a highly effective medium for communication among dairy farm workers. This serves to diminish the obstacles associated with disseminating contemporary agricultural knowledge and the intangible expenses related to exchanging information. Moreover, it facilitates the transmission of farming knowledge and encourages the sharing of information. Consequently, it enables swift enhancements in the labor skills and proficiency of dairy farm workers, thereby maximizing the inherent benefits of a skilled workforce. Dairy farms have recognized the shift in labor capital from a focus on quantity expansion to an emphasis on enhancing quality. This transition has facilitated the ongoing enhancement of labor efficiency [34], resulting in reduced labor requirements and overall labor duration within dairy farms. Consequently, this reduction in labor input costs has led to improved production efficiency and, correspondingly, enhanced environmental efficiency in dairy farming operations.

Therefore, the paper suggests hypotheses as follows:

Hypothesis 3. *Digital technology in dairy farms has the potential to decrease the proportion and duration of labor required, hence facilitating the efficient allocation of labor resources.*

Hypothesis 4. *The allocation of labor factors serves as an intermediary mechanism in the effect of digital technology on environmental efficiency.*

Digital technology, as a kind of technical advancement, has the potential to facilitate the efficient allocation of capital components, such as feed and energy, inside dairy farms. In the immediate term, the implementation of precise feed input and energy management in dairy farms can lead to cost savings in capital investment for dairy farming. Additionally, it can effectively mitigate excessive carbon emissions, thereby facilitating a mutually beneficial outcome of intensified dairy production and carbon emission reduction. The implementation of efficient resource allocation strategies, particularly in relation to feed and energy, can lead to substantial reductions in short-term agricultural production costs, specifically in terms of feed and energy expenses, within dairy farms. This, in turn, incentivizes farmers to decrease their short-term agricultural production investments. Additionally, such optimized resource allocation practices help mitigate the environmental effect of excessive factor input, specifically by reducing carbon emissions resulting from cow rumination and energy consumption. There is potential for enhancing both production efficiency and environmental efficiency [35]. Digital technology has the capacity to enhance the profitability and production efficiency of agricultural operations [36]. Simultaneously, it may effectively mitigate the financial limitations faced by farmers and establish favorable circumstances for productive investments. In contrast to conventional farming practices, digital technology enables the rational allocation of production factors. Additionally, it generates a labor substitution effect, leading to a gradual reduction in the long-term average cost of dairy farming. Consequently, this enhances production efficiency and profitability [37]. Dairy farmers, being rational economic actors, may choose to allocate the earnings generated from dairy farming towards the development of dairy farm infrastructure. This strategic reinvestment aims to facilitate the expansion of dairy farming operations and ultimately provide greater financial gains. To effectively address the demands posed by the extensive expansion of dairy farms, it is imperative to enhance the long-term productive investment in these farms. Concurrently, efforts should be made to gradually decrease the long-term average cost associated with dairy farming. One primary factor is the introduc-

tion of long-term productive investment, which establishes the fundamental prerequisites for the emergence of the “scale effect” and “agglomeration effect” within dairy farms. This leads to a reduction in the unit cost associated with dairy farming. Simultaneously, the steady enhancement of contemporary infrastructure and digital technological equipment in dairy farms is facilitated by sustained productive investment. The initial investment required for digital technology is substantial; however, it has the potential to consistently decrease the additional cost of production for producers [38]. This can facilitate the enhancement of production efficiency and the implementation of measures to control carbon emission pollution in dairy farms over an extended period. Consequently, it can drive the long-term improvement of environmental efficiency in dairy farms. The process flow chart is shown in Figure 1.

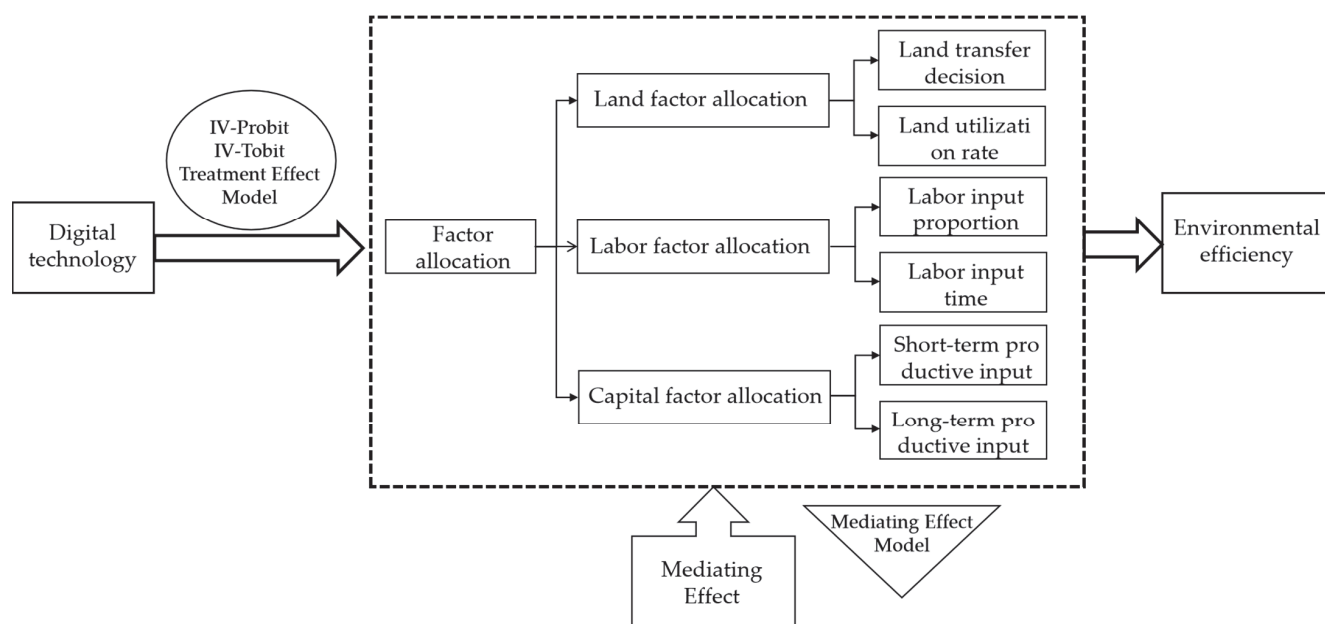


Figure 1. Process flow chart.

Therefore, the paper suggests hypotheses as follows:

Hypothesis 5. *Digital technology in dairy farms has the potential to decrease short-term productive input while simultaneously enhancing long-term productive input. This integration of technology enables the efficient allocation of capital components.*

Hypothesis 6. *The allocation of capital factors serves as an intermediary mechanism in determining the effect of digital technology on environmental efficiency.*

3. Methods and Data

3.1. Model Selection

3.1.1. IV-Probit and IV-Tobit Model

This study assesses the effect of digital technology on the allocation of land factors with the IV-Probit model and IV-Tobit model, specifically focusing on land transfer decisions and land utilization rates within these farms. The utilization of the ordinary least square approach in estimating the impact connection may introduce potential bias. The land transfer decision is a binary discrete variable, so the probit model was constructed to

analyze the land transfer decision on dairy farms. The formula may be expressed in the following:

$$\begin{aligned} Y^* &= \alpha_0 + \beta_1 DT_i + \beta_i X_i + \varepsilon \\ Y &= \begin{cases} 1, & Y^* > 0 \\ 0, & Y^* \leq 0 \end{cases} \end{aligned} \quad (1)$$

Y^* and Y represent the latent variables of land transfer decisions and actual behavior in dairy farms, respectively. α_0 indicates a constant term. DT_i represents the core explanatory variable of digital technology. X_i represents the control variable. ε indicates the residual of the model. The issue of endogeneity is a significant factor contributing to bias in estimates derived from models. Endogeneity of models can arise due to bidirectional causation, measurement error, selection bias, and the presence of missing variables. This research posits the existence of a bidirectional causal link between the utilization of digital technology and the decision-making process pertaining to land transfer. One potential benefit of incorporating digital technology in dairy farms is its potential to enhance decision-making processes related to land transfer. On the contrary, the conversion of dairy farm land may also enable the utilization of digital technologies for efficient land management and utilization. Hence, the primary explanatory factor examined in this study, digital technology, might potentially be an endogenous variable. To address the issue of endogeneity, this study introduced the variable “digital technology adoption ratio of other dairy farms in the same region” as an instrumental variable for digital technology. Subsequently, an IV-Probit model was constructed to estimate the effect of digital technology on land transfer decisions.

The values of land utilization rate fall between the range of 0 and 1, so classifying them as “restricted dependent variables”. To address the issue of limited dependent variables, the Tobit model is an appropriate method for resolution. This study employs the Tobit model to construct an empirical analytic framework examining the effect of digital technology on the land utilization rate. The formula may be expressed in the following:

$$Y = \begin{cases} \beta_0 + \sum_{i=1}^n \beta_i X_i + \varepsilon_i, & 0 \leq Y \leq 1 \\ 0, & Y < 0 \text{ or } Y > 1 \end{cases} \quad (2)$$

Y indicates the land utilization rate in a dairy farm. The regression coefficient, denoted as β_i , represents the relationship between the explanatory variable X_i and the error term, denoted as ε_i , which follows a normal distribution. To address the issue of endogeneity, this study still applied the variable “digital technology adoption ratio of other dairy farms in the same region” as an instrumental variable for digital technology. IV-Tobit model was constructed to estimate the effect of digital technology on land utilization rate. The formula may be expressed as follows:

$$\begin{aligned} Y_i^* &= \beta' x_i + \theta DT_i + \mu_i \\ DT_i &= \rho ODT_i + \gamma' x_i + \varepsilon_i \\ Y_i^* &= Y_i, Y_i^* > 0 \\ Y_i^* &= 0, Y_i^* < 0 \end{aligned} \quad (3)$$

Y_i denotes the land utilization rate in dairy farms, while the variable DT_i serves as the primary explanatory factor for digital technology. Additionally, the variable ODT_i represents the application of digital technology in dairy farms within the same area and serves as the instrumental variable for this study. The symbol μ_i denotes the error term associated with digital technology, whereas ε indicates the error term associated with the deployment of digital technology within an identical geographical area. The IV-Tobit model presents an appropriate approach to address the issue of endogeneity when estimating the effect of digital technology on the land utilization rate.

3.1.2. Treatment Effect Model

This study used the treatment effect model to assess the effect of digital technology on the distribution of labor and capital resources within dairy farms. The propensity score matching (PSM) method is commonly employed as a means to address the issue of selectivity bias in the model. Nevertheless, the PSM method is limited to addressing the effect of visible elements inside the model, neglecting the influence of unobservable factors. The allocation of labor and capital in dairy farms is influenced by a combination of observable and unobservable variables, which introduces bias in the estimation findings derived by the propensity score matching approach. This study utilizes scholarly research to construct a treatment effect model [39]. The treatment effect model assesses the effect of digital technology on the allocation of labor and capital elements in dairy farms, taking into account both observable and unobservable factors. It examines the marginal effect and average treatment effect of digital technology. In contrast to the propensity score matching technique, the treatment effect model offers a more comprehensive estimation of the association between digital technology and the allocation of labor and capital factors.

The treatment effect model may be delineated into two distinct components. The initial phase involves formulating a selection equation to estimate the elements that influence the application of digital technology in this context. The selection equation formula may be expressed in the following manner:

$$DT_i = \begin{cases} 1, DT_i^* > 0 \\ 0, DT_i^* \leq 0 \end{cases} \quad (4)$$

$$DT_i^* = Z_i\beta + \mu_i$$

The primary explanatory variable of dairy farm digital technology is denoted as DT_i , while the latent variable utilized by dairy farm digital technology is represented as DT_i^* . The coefficient vector to be estimated is denoted as β , and the error term is denoted as μ_i . The second phase involves the establishment of an outcome equation to assess the influence of digital technologies on the allocation of labor and capital elements within dairy farms. The outcome formula may be expressed as follows:

$$Y_i = X_i\beta + DT_i\gamma + \varepsilon_i \quad (5)$$

The variable Y_i denotes the dependent variables related to the allocation of labor and capital elements in dairy farms. X_i represents each independent control variable, while γ represents the vector of coefficients that are to be estimated. Lastly, ε_i represents the random error term. The treatment effect model necessitates the establishment of an instrumental variable that only impacts the utilization of digital technology within dairy farms while not influencing the allocation of labor and capital resources. In the present study, the variable denoting the percentage of other dairy farms within the same geographical region that employ digital technology continues to serve as the instrumental variable in assessing the effect of digital technology. The treatment effect model provides a clear means of demonstrating the marginal effect of digital technology on the distribution of labor and capital resources within dairy farms. To comprehensively assess the effect of digital technology on the allocation of labor and capital factors in dairy farms, it is imperative to compute the average treatment effect by estimating the treatment effect model. The formula is as follows:

$$ATE = E(Y_i|DT_i = 1) - E(Y_i|DT_i = 0) \quad (6)$$

This study examines the distribution of labor and capital factors that apply digital technology, as well as those that do not apply such technology. The utilization of the average processing impact serves to mitigate the bias arising from both observable and unobservable components. Consequently, this approach enhances the accuracy of digital technology in estimating the allocation of elements within dairy farms.

3.1.3. Mediating Effect Model

This research applies the concept of factor allocation as a mediating mechanism in examining the effect of digital technology on environmental efficiency. Digital technology is anticipated to alter the distribution of resources within dairy farms. This factor allocation, in turn, has the potential to influence the environmental efficiency of these farms. It can be inferred that digital technology may contribute to an enhancement in environmental efficiency by means of intermediary factor allocation. The mediating effect model is applied to examine the mediating effect of digital technology on environmental efficiency. The model is constructed as follows:

$$\begin{aligned} Y_i &= a_0 + a_1 DT_i + a_2 X_i + \varepsilon_1 \\ Z_i &= b_0 + b_1 DT_i + b_2 X_i + \varepsilon_2 \\ Y_i &= c_0 + c_1 DT_i + c_2 Z_i + c_3 X_i + \varepsilon_3 \end{aligned} \quad (7)$$

In Equation (7), Y_i indicates the environmental efficiency, DT_i indicates the value of digital technology, Z_i represents the factor allocation of the dairy farm, and X_i represents additional control factors such as dairy farm scale and breeding experience. The constant variables in the equation are denoted as a_0 , b_0 , and c_0 . The coefficients to be estimated are represented as a_1 , a_2 , b_1 , b_2 , c_1 , c_2 and c_3 . The error terms are shown as ε_1 , ε_2 and ε_3 . a_1 represents the overall effect of digital technology on the enhancement of environmental efficiency. b_1 denotes the influence of digital technology on the allocation of factors. c_1 signifies the direct effect of digital technology on environmental efficiency while considering the variables related to factor allocation. The intermediary effect is calculated as the multiplication of coefficients $b_1 c_2$, representing the indirect effect of digital technology on environmental efficiency through factor allocation. c_2 represents the effect of factor allocation on environmental efficiency while controlling for digital technology. This study employed the sequential test analysis method of stepwise regression and the bootstrap method to assess the statistical significance of the intermediate effect.

3.2. Data Source

The results were obtained from a micro survey conducted by our study group on dairy farms in Heilongjiang Province between January and July 2023. The chosen regions encompassed the primary distribution zones of dairy farms within Heilongjiang Province, serving as representative indicators of the broader dairy farm production landscape. Stratified and random sampling methods were used to select dairy farms for the survey, which included three types of dairy farms: small-scale, medium-scale, and large-scale. Therefore, dairy farms surveyed in this paper can basically represent the overall situation of dairy farms in China. The samples were delivered to various cities like Suihua City, Harbin City, Qiqihar City, Heihe City, Daqing City, Jiamusi City, Jixi City, Hegang City, Mudanjiang City, and so on. The dairy farms surveyed were mainly located in village and township areas far from the main urban areas, where the farmland, grassland, and construction land are vast and cheap. The structure of agricultural products is mainly composed of soya beans, wheat, maize, and rice in the survey area, which provide abundant feed and raw materials for dairy farming. A total of 291 questionnaires were gathered through the utilization of scientific random sampling and multi-layer sampling techniques. After excluding samples containing outliers and incomplete data, a total of 278 valid samples remained. The location and scope of the survey area are shown in Figure 2.

3.3. Variable Selection

- (1) Explained variable: The environmental efficiency of dairy farms. This paper draws on scholarly research [17] to examine various input variables in dairy farms, including roughage input, concentrate feed input, fixed asset input cost, water and electricity fuel cost, and medical and epidemic prevention cost. The expected output is milk production, while the non-expected output is carbon emissions. The environmental

efficiency of dairy farms may be conducted using the Undesirable Outputs-SBM model.

- (2) Explanatory variable: Digital technology refers to the use of electronic devices and systems that operate on binary code, enabling the processing, storage, and transmission of This study assesses the digital technology based on the criterion of whether or not dairy farms utilize such technology. A binary value of 1 is allocated to signify the utilization of digital technology in a dairy farm, whereas a binary value of 0 is assigned to indicate the absence of such technology.
- (3) Intermediary variable: The concept of factor allocation refers to the process of distributing resources or inputs among different factors of production in order to maximize efficiency and productivity. In the realm of agriculture, factors of production encompass the fundamental material resources that are necessary for sustaining agricultural progress. These factors typically encompass three key components: labor, land, and capital. In the context of dairy cow farms, the allocation of factors is primarily categorized into three components: land factor allocation, labor factor allocation, and capital factor allocation. The analysis of land factor allocation encompasses two key dimensions: the land transfer decision and the land utilization rate. Land transfer decision refers to the behavior of dairy farmers to transfer land to expand the scale of their farms. The land transfer decision is the basis for further expansion of dairy farms, and it can make full use of the unused land resources around dairy farms to achieve a rational allocation of land elements. The decision of land transfer is assessed based on the expansion of the dairy farm's land scale, while the land utilization rate is evaluated by the proportion of the dairy farm's land area to the overall land area. The analysis of labor factor allocation was conducted considering two dimensions: the labor input proportion and the labor input time. These dimensions were assessed by examining the ratio of individuals involved in dairy farming to the overall labor force within a household, as well as the average amount of time dedicated to labor input per cow. The allocation of capital factors in dairy farms primarily encompasses the allocation of short-term productive inputs and long-term productive inputs. The former is measured by the production and operational inputs of dairy farms, while the latter pertains to the inclination to invest in fixed assets, such as large-scale breeding machinery, in the future.
- (4) Control variables: This work provides a summary of the control factors categorized into three groups: household head characteristics, family characteristics, and organizational characteristics, as identified by researchers [40–42]. The attributes associated with the head of home encompass several factors such as educational attainment, age, village cadres, breeding experience, risk perception, and technical training of dairy farmers. Household characteristics encompass several factors such as the household registration type, the composition of income, and the endowment of household labor. Organizational aspects pertain to the dairy farm's involvement in a cooperative.
- (5) Instrumental variables: This article has chosen the "digital technology adoption ratio of other dairy farms in the same region" as the instrumental variable, based on scholarly research [43,44]. In the same geographical area, the adoption of digital technology by a particular dairy farmer might influence other dairy farmers to also embrace digital technology for their production processes. Consequently, the use of digital technology by other dairy farmers is associated with explanatory factors. Furthermore, the utilization of digital technology by fellow dairy farmers does not have a direct impact on the environmental efficiency of the specific dairy farmer in question, hence adhering to the requirement of exclusivity in instrumental variables. Hence, the utilization of digital technology inside dairy farms in the aforementioned area might be considered a viable instrumental variable. Table 1 presents the depiction and statistical summary of each variable.

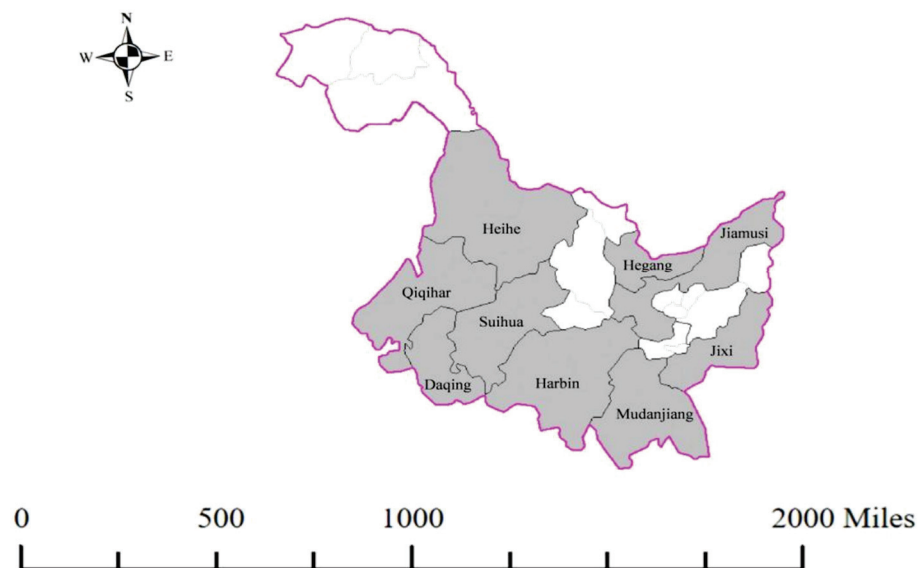


Figure 2. Location and scope of the survey area.

Table 1. Variable selection and descriptive statistics.

Variable Types	Variable Name	Variable Meaning and Assignment	Mean	Standard Deviation
Explained variable	Environmental efficiency	The results were calculated based on the Undesirable Outputs-SBM model	0.6222	0.1130
Core explanatory variables	Digital technology	Whether the dairy farm uses digital technology (no = 0, using 1 or more digital technologies is assigned a value of 1)	0.3669	0.4828
Mediating variables	Land factor allocation: land transfer decision	Whether the dairy farm expands the land scale (no = 0, yes = 1)	0.3597	0.4808
	Land factor allocation: land utilization rate	The ratio of utilized land area to total land area in dairy farms	0.6461	0.1443
	Labor factor allocation: labor input proportion	The number of people engaged in dairy farming as a share of the total labor force in a household	0.5550	0.1716
	Labor factor allocation: labor input time	The logarithm of labor input time (days/head)	1.4663	0.0250
	Capital factor allocation: short-term productive input	The logarithm of production and operation input of dairy farm (yuan/head)	9.3571	0.0531
	Factor allocation of capital: long-term productive inputs	The willingness to invest in fixed assets such as large-scale breeding machinery in the future	2.5501	1.2464
Control variables	Educational attainment	Years of schooling for dairy farmers	9.7230	1.2854
	Age	The age of the dairy farmer	46.6007	7.2288
	Village cadre	Is the dairy farmer a village cadre? Yes = 1, no = 0	0.0683	0.2528
	Breeding experience	The number of years a dairy farming household owner has kept cows	16.6835	9.8318

Table 1. Cont.

Variable Types	Variable Name	Variable Meaning and Assignment	Mean	Standard Deviation
	Risk perception	Are you concerned about the risks of dairy farming? Very not worried = 1, not worried = 2, generally = 3, worried = 4, very worried = 5	4.5540	0.6264
	Technical Training	Do dairy farmers participate in technical training? Yes = 1, no = 0	0.3705	0.4838
	Cooperatives	Does the dairy farm participate in a dairy farming Cooperative economic organization? Yes = 1, no = 0	0.4137	0.4934
	Household registration type	Rural registration = 0, urban registration = 1	0.3345	0.4727
	Composition of income	Income from dairy farming as a share of total household income	78.3453	21.1483
	Household labor endowment	Number of household members available for dairy farming	3.8705	1.3666
	Digital technology adoption ratio of other dairy farms in the same region	The proportion of other dairy farms in the same region utilizing digital technology	0.2212	0.3279

4. Results and Discussions

4.1. Multicollinearity Test

To mitigate the issue of multicollinearity across variables, this study used the variance inflation factor (VIF) approach to perform a multicollinearity test. The test results are presented in Table 2. The expansion factor of each variable in the regression equation is found to be less than 10, suggesting the absence of multicollinearity among the variables.

Table 2. Results of multicollinearity test.

Variables	VIF	Variables	VIF
Land transfer decision	1.88	Village cadre	1.59
Land utilization rate	1.71	Breeding experience	1.58
Labor input proportion	1.74	Risk perception	2.23
Labor input time	1.65	Technical training	2.02
Short-term productive inputs	1.33	Cooperatives	1.42
Long-term productive inputs	1.87	Household registration type	2.29
Digital technology	1.21	Composition of income	1.85
Education attainment	0.75	Household labor endowment	1.91
Age	1.21		

4.2. Effect of Digital Technology on Factor Allocation in Dairy Farm

4.2.1. Effect of Digital Technology on Land Factor Allocation in Dairy Farm

This article used the IV-Probit model and IV-Tobit model to assess the effect of digital technology on the allocation of land resources in dairy farms. The estimated outcomes are presented in Table 3. The regression findings indicate a statistically significant and favorable relationship between digital technology and land transfer choice as well as land utilization rate in dairy farms.

Table 3. Estimated results of the effect of digital technology on land factor allocation in dairy farms.

Variables	Probit	IV-Probit	Tobit	IV-Tobit
	Land Transfer Decision	Land Transfer Decision	Land Utilization Rate	Land Utilization Rate
Digital Technology	0.6644 *** (0.0485)	0.8912 *** (0.0610)	0.1762 *** (0.0155)	0.1985 *** (0.0181)
Education attainment	0.0527 ** (0.0225)	0.0206 (0.0244)	0.0346 *** (0.0074)	0.0313 *** (0.0074)
Age	−0.0022 (0.0030)	−0.0004 (0.0032)	0.0023 ** (0.0010)	0.0025 *** (0.0009)
Village Cadre	0.0883 (0.0736)	0.0771 (0.0782)	0.0358 (0.0240)	0.0347 (0.0236)
Breeding experience	0.0035 * (0.0019)	0.0030 (0.0020)	0.0031 *** (0.0006)	0.0031 *** (0.0006)
Risk perception	−0.1091 *** (0.0310)	−0.0932 *** (0.0330)	0.0014 (0.0100)	0.0031 (0.0099)
Technical training	0.2017 *** (0.0440)	0.1956 *** (0.0467)	0.0548 *** (0.0142)	0.0542 *** (0.0140)
Cooperatives	0.1086 ** (0.0532)	0.1756 *** (0.0572)	0.0441 ** (0.0172)	0.0504 *** (0.0171)
Household registration type	0.0340 (0.0451)	0.0219 (0.0479)	0.0388 *** (0.0144)	0.0376 *** (0.0142)
Composition of income	0.0004 (0.0009)	0.0001 (0.0010)	0.0005 * (0.0003)	0.0005 (0.0003)
Household labor endowment	0.0403 *** (0.0140)	0.0358 ** (0.0149)	0.0024 (0.0046)	0.0021 (0.0045)
Constant term	−0.0853 (0.3408)	0.0395 (0.3622)	0.0128 (0.1110)	0.0257 (0.1092)
N	278	278	278	278
Prob > chi2	0.0000	0.0000	0.0000	0.0000

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. The values in parentheses represent standard deviations.

The regression coefficient for digital technology in the Probit model is estimated to be 0.6644, with a statistically significant level of 1%. This suggests that as the application level of digital technology increases by 1%, the chance of land transfer is expected to increase by 0.6644%. Nevertheless, it is important to acknowledge that the Probit model is susceptible to endogeneity issues arising from sample selection bias, which can potentially introduce bias into the estimated findings of the model. Hence, the IV-Probit model is proposed in this study as a means to address the issue of endogeneity. The findings from the IV-Probit model indicate that the regression coefficient representing the effect of digital technology on the choice to transfer land in dairy farming is estimated to be 0.8912. This coefficient is somewhat greater than the coefficient obtained from the Tobit model and is statistically significant at the 1% level. This suggests that the adoption of digital technology inside dairy farms might effectively facilitate land transfer, therefore establishing a basis for farmers to attain economies of scale. The land transfer choice of dairy farms is positively influenced by control factors such as technical training, cooperative participation, and family labor endowment. There is a positive correlation between the size of dairy farmers' families and the likelihood of engaging in land transfer activities to expand their agricultural operations and enhance their revenue levels increases accordingly. The technical proficiency of dairy farmers has been significantly enhanced by their engagement in technical training programs and cooperatives. Consequently, they are more motivated to transition their operations to larger land areas in order to accommodate the demands of large-scale dairy farming.

The regression coefficients for digital technology in the Tobit model and IV-Tobit model are 0.1762 and 0.1985, respectively. Both values are statistically significant at the 1% level. This finding suggests that the implementation of digital technology inside dairy

farms has the potential to greatly enhance the efficiency of land utilization and facilitate the optimal exploitation of land resources in such farms. Regarding the effect of control factors, the IV-Tobit model revealed that variables such as education attainment, age, breeding experience, technical training, cooperatives, and household registration types had a statistically significant positive effect on land usage rate at a significance level of 1%. The age and experience of dairy farmers positively correlate with their ability to optimize land resources for dairy farming, resulting in a notable increase in land usage efficiency on dairy farms. The positive correlation observed between household registration type and land utilization rate of dairy farms may be attributed to the advantageous circumstances experienced by dairy farmers residing in urban areas. These circumstances include enhanced accessibility to contemporary breeding information and knowledge, which in turn facilitates the expansion of breeding scale and improvement of land utilization rate within dairy farms. Hypothesis 1 has been confirmed.

4.2.2. The Effect of Digital Technology on Labor Factor Allocation in Dairy Farms

This study employs the treatment effect model to assess the effect of digital technology on the allocation of labor factors. The estimated outcomes are presented in Table 4. The findings indicate that digital technology in dairy farms has a notable adverse effect on both the proportion and duration of labor input. The output equation reveals that the regression coefficient of digital technology on the proportion of labor input is -0.2622 , indicating statistical significance at the 1% level. This finding suggests that the utilization of digital technology in dairy farms is associated with a reduced proportion of labor input compared to dairy farms that do not employ digital technology. A positive correlation exists between the application of digital technology in dairy farms and the corresponding decrease in the proportion of labor input in these farms, with a fall of 0.2622% seen for every 1% rise in digital technology usage. This study examines the influence of digital technology on the number of worker input hours. The regression coefficient for the effect of digital technology on labor input time in dairy farming is estimated to be -0.0344 , indicating a statistically significant relationship at the 1% level. This finding suggests that digital technology within dairy farms has the potential to substantially reduce the amount of time required for manual input. One potential explanation for this phenomenon is that digital technology has resulted in the displacement of a portion of the workforce and the subsequent reduction in labor hours required. Hypothesis 3 has been confirmed.

Table 4. Estimated results of the effect of digital technology on labor factor allocation in dairy farms.

Variables	Selection Equation	Output Equation	Selection Equation	Output Equation
	Proportion of Labor Input	Proportion of Labor Input	Labor Input Time	Labor Input Time
Digital technology		-0.2622^{***} (0.0182)		-0.0344^{***} (0.0024)
Education attainment	0.0666^{***} (0.0169)	-0.0307^{***} (0.0074)	0.0666^{***} (0.0169)	-0.0073^{***} (0.0010)
Age	-0.0006 (0.0020)	-0.0033^{***} (0.0009)	-0.0006 (0.0020)	-0.0007^{***} (0.0001)
Village Cadre	-0.0305 (0.0504)	-0.1129^{***} (0.0236)	-0.0305 (0.0504)	-0.0149^{***} (0.0031)
Breeding experience	0.0003 (0.0013)	-0.0009 (0.0006)	0.0003 (0.0013)	0.0000 (0.0001)
Risk perception	-0.0175 (0.0210)	0.0461^{***} (0.0099)	-0.0175 (0.0210)	0.0088^{***} (0.0013)
Technical training	0.0677^{**} (0.0300)	-0.0060 (0.0140)	0.0677^{**} (0.0300)	-0.0043^{**} (0.0018)
Cooperatives	0.2243^{***} (0.0350)	-0.0682^{***} (0.0172)	0.2243^{***} (0.0350)	-0.0084^{***} (0.0023)

Table 4. Cont.

Variables	Selection Equation	Output Equation	Selection Equation	Output Equation
	Proportion of Labor Input	Proportion of Labor Input	Labor Input Time	Labor Input Time
Household registration type	0.0922 *** (0.0308)	−0.0203 (0.0142)	0.0922 *** (0.0308)	−0.0019 (0.0019)
Composition of income	0.0007 (0.0006)	0.0004 (0.0003)	0.0007 (0.0006)	0.0002 *** (0.0000)
Household labor endowment	−0.0504 *** (0.0099)	0.0128 *** (0.0045)	−0.0504 *** (0.0099)	0.0012 ** (0.0006)
Application of digital technology in dairy farms in the same region	1.4085 *** (0.0545)		1.4085 *** (0.0545)	
Constant term	0.9069 *** (0.2390)	0.8182 *** (0.1094)	0.9069 *** (0.2390)	1.5341 *** (0.0144)
Log likelihood		341.2348		930.2690
Residual covariance		0.0205		0.3881 ***
Wald value		653.65		980.18
N		278		278

Note: ** and *** indicate significance at the 5% and 1% levels, respectively. The values in parentheses represent standard deviations.

4.2.3. Effect of Digital Technology on Capital Factor Allocation in Dairy Farms

Table 5 displays the projected outcomes pertaining to the influence of digital technology on the distribution of capital factors. The regression coefficients for the effect of digital technology on the short-term and long-term productive input of dairy farms are −0.0524 and 0.4484, respectively. Both values are statistically significant at the 1% level. This finding suggests that the adoption of digital technology has the potential to decrease immediate input requirements while simultaneously enhancing long-term productivity in dairy farming operations. The potential factors may be attributed to the fact that the employment of digital technology in dairy farms enables precise and efficient resource management, leading to a reduction in immediate input requirements for dairy farming. In contrast, digital technology has been found to facilitate the enhancement of breeding income and breeding scale. This, in turn, encourages farmers to acquire large-scale breeding equipment to fulfill the enduring production requirements of dairy farms, thereby resulting in a notable augmentation of long-term productive input in such establishments. Hypothesis 5 has been confirmed.

Table 5. Estimated results of the effect of digital technology on capital factor allocation in dairy farms.

Variables	Selection Equation	Output Equation	Selection Equation	Output Equation
	Short-Term Productive Inputs	Short-Term Productive Input	Long-Term Productive Inputs	Long-Term Productive Input
Digital technology		−0.0524 *** (0.0078)		0.4484 *** (0.1450)
Education attainment	0.0666 *** (0.0169)	0.0002 (0.0032)	0.0666 *** (0.0169)	0.3553 *** (0.0590)
Age	−0.0006 (0.0020)	−0.0024 *** (0.0004)	−0.0006 (0.0020)	−0.0483 *** (0.0076)
Village Cadre	−0.0305 (0.0504)	0.0079 (0.0101)	−0.0305 (0.0504)	0.6623 *** (0.1884)
Breeding experience	0.0003 (0.0013)	−0.0001 (0.0003)	0.0003 (0.0013)	0.0189 *** (0.0048)
Risk perception	−0.0175 (0.0210)	0.0182 *** (0.0042)	−0.0175 (0.0210)	0.1160 (0.0788)

Table 5. Cont.

Variables	Selection Equation	Output Equation	Selection Equation	Output Equation
	Short-Term Productive Inputs	Short-Term Productive Input	Long-Term Productive Inputs	Long-Term Productive Input
Technical training	0.0677 ** (0.0300)	−0.0230 *** (0.0060)	0.0677 ** (0.0300)	0.2450 ** (0.1115)
Cooperatives	0.2243 *** (0.0350)	−0.0587 *** (0.0073)	0.2243 *** (0.0350)	0.6274 *** (0.1370)
Household registration type	0.0922 *** (0.0308)	0.0438 *** (0.0061)	0.0922 *** (0.0308)	0.9121 *** (0.1135)
Composition of income	0.0007 (0.0006)	0.0007 *** (0.0001)	0.0007 (0.0006)	0.0028 (0.0023)
Household labor endowment	−0.0504 *** (0.0099)	0.0073 *** (0.0019)	−0.0504 *** (0.0099)	0.1256 *** (0.0360)
Application of digital technology in dairy farms in the same region	1.4085 *** (0.0545)		1.4085 *** (0.0545)	
Constant term	0.9069 *** (0.2390)	9.2889 *** (0.0467)	0.9069 *** (0.2390)	−4.3277 *** (0.8728)
Log likelihood		588.90809		−202.84611
Residual covariance		0.2730 ***		0.4609 ***
Wald value		274.97		526.76
N		278		278

Note: ** and *** indicate significance at the 5% and 1% levels, respectively. The values in parentheses represent standard deviations.

4.3. The Effect of Digital Technology on the Environmental Efficiency in Dairy Farms under the Mediation of Factor Allocation

4.3.1. The Effect of Digital Technology on Environmental Efficiency in Dairy Farms under the Intermediary Role of Land Factor Allocation

This study used the stepwise regression technique to examine the mediating role of land factor allocation in the relationship between digital technology and environmental efficiency. The estimated outcomes of this analysis are presented in Table 6. The results demonstrate a statistically significant positive relationship between digital technologies and the environmental efficiency of dairy farms. In the context of regression analysis, it is seen that the regression coefficients associated with digital technology and land transfer decisions are both statistically significant and positive. This suggests that the land transfer decision acts as an intermediary factor in the relationship between digital technology and environmental efficiency. In the regression analysis conducted in regressions (5) and (6), it was seen that the regression coefficients associated with digital technology and land use rate exhibited a statistically significant positive relationship at a significance level of 1%. This suggests that land utilization rate played an intermediate role in the relationship being examined. Based on the stepwise method test process, the regression analysis reveals that variables a_1 , b_1 , c_1 , and c_2 exhibit statistical significance. Furthermore, the positive relationship between b_1c_2 and c_1 is found to be statistically significant. These findings suggest that the allocation of land factors partially mediates the influence of digital technology on environmental efficiency. Digital technology not only exhibits a direct influence on environmental efficiency but also yields a favorable impact on land utilization rate. Furthermore, it may be argued that this phenomenon also yields an indirect beneficial influence on environmental efficiency through the facilitation of land transfer and enhancement of land usage rates. The coefficients associated with the land transfer decision and the land utilization rate intermediate path are 0.0117 and 0.1109, respectively. Hypothesis 2 has been confirmed.

Table 6. Estimated results of the effect of digital technology on the environmental efficiency of dairy farms under the mediation of land factor allocation.

Variables	Regression (1)	Regression (2)	Regression (3)	Regression (4)	Regression (5)	Regression (6)
	Environmental Efficiency	Land Transfer Decision	Environmental Efficiency	Environmental Efficiency	Land Utilization Rate	Environmental Efficiency
Digital technology	0.1324 *** (0.0117)	0.6472 *** (0.0404)	0.1207 *** (0.0164)	0.1324 *** (0.0117)	0.1762 *** (0.0155)	0.0215 *** (0.0078)
Education attainment	0.0258 *** (0.0055)	0.0803 *** (0.0192)	0.0244 *** (0.0057)	0.0258 *** (0.0055)	0.0346 *** (0.0074)	0.0040 (0.0032)
Age	0.0004 (0.0007)	−0.0028 (0.0025)	0.0005 (0.0007)	0.0004 (0.0007)	0.0023 ** (0.0010)	0.0010 ** (0.0004)
Village Cadre	0.0761 *** (0.0181)	0.0611 (0.0625)	0.0750 *** (0.0181)	0.0761 *** (0.0181)	0.0358 (0.0240)	0.0536 *** (0.0100)
Breeding experience	0.0008 * (0.0005)	0.0021 (0.0016)	0.0008 * (0.0005)	0.0008 * (0.0005)	0.0031 *** (0.0006)	0.0012 *** (0.0003)
Risk perception	−0.0322 *** (0.0075)	−0.0893 *** (0.0261)	−0.0306 *** (0.0077)	−0.0322 *** (0.0075)	0.0014 (0.0100)	−0.0331 *** (0.0041)
Technical training	0.0248 ** (0.0107)	0.1992 *** (0.0370)	0.0212 * (0.0113)	0.0248 ** (0.0107)	0.0548 *** (0.0142)	−0.0097 (0.0060)
Cooperatives	0.0334 ** (0.0130)	0.1452 *** (0.0449)	−0.0308 ** (0.0132)	0.0334 ** (0.0130)	0.0441 ** (0.0172)	−0.0056 (0.0072)
Household registration type	0.0048 (0.0109)	0.0594 (0.0376)	0.0037 (0.0109)	0.0048 (0.0109)	0.0388 *** (0.0144)	0.0196 *** (0.0061)
Composition of income	−0.0004 * (0.0002)	0.0001 (0.0008)	−0.0004 * (0.0002)	−0.0004 * (0.0002)	0.0005 * (0.0003)	−0.0007 *** (0.0001)
Household labor endowment	0.0052 (0.0034)	0.0360 *** (0.0119)	0.0045 (0.0035)	0.0052 (0.0034)	0.0024 (0.0046)	0.0037 * (0.0019)
Land transfer decision			0.0181 ** (0.0077)			
Land utilization rate						0.6295 *** (0.0253)
Constant term	0.3510 *** (0.0835)	−0.3408 (0.2891)	0.3571 *** (0.0838)	0.3510 *** (0.0835)	0.0128 (0.1110)	0.3429 *** (0.0459)
N	278	278	278	278	278	278
R ²	0.6457	0.7524	0.6510	0.6457	0.6163	0.8935
adj. R ²	0.6311	0.7422	0.6352	0.6311	0.6004	0.8887

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. The values in parentheses represent standard deviations.

4.3.2. The Effect of Digital Technology on Environmental Efficiency in Dairy Farms under the Intermediary Role of Labor Factor Allocation

Table 7 displays the projected outcomes pertaining to the effect of digital technology on environmental efficiency, taking into account the intermediate function played by labor factor allocation. The regression results indicate that in regression (8) and regression (11), the regression coefficients associated with digital technology exhibit a statistically significant negative relationship at the 1% level. Conversely, in regression (9) and regression (12), the regression coefficients of digital technology demonstrate a statistically significant positive relationship. Additionally, both b_1c_2 and c_1 exhibit statistically significant positive relationships. This finding suggests that the distribution of labor factors has a mediating role in the relationship between digital technology and environmental efficiency. Digital technology has led to enhanced environmental efficiency through the reduction in labor input in terms of both percentage and time. The labor input ratio coefficient was determined to be 0.1715, while the labor input duration coefficient was found to be 0.1243. Hypothesis 4 has been confirmed.

4.3.3. The Effect of Digital Technology on Environmental Efficiency in Dairy Farms under the Intermediary Role of Capital Factor Allocation

Table 8 displays the projected outcomes pertaining to the effect of digital technology and capital factor allocation on environmental efficiency. The estimated regression coefficient for the effect of digital technology on the short-term productive input of a dairy farm is −0.0363 in regression (14). This coefficient is found to be statistically significant at the 1% level of significance. This suggests that digital technology has the potential to considerably decrease short-term productive input in dairy farms, potentially due to its ability to facilitate precise feeding practices and lower input expenses like as feed and gasoline. In regression (15), the regression coefficients for digital technology and short-term

productive input were determined to be 0.1223 and -0.2806 , respectively. It is worth noting that both coefficients were found to be statistically significant at a significance level of 1%. This suggests that digital technology has the potential to enhance environmental efficiency through the reduction in short-term productive input. In other words, short-term productive input serves as an intermediary factor in the relationship between digital technology and the environmental efficiency of dairy farms. Regression (17) and regression (18) revealed a statistically significant positive relationship between digital technology and long-term productive input. This suggests that digital technology has the potential to enhance environmental efficiency by increasing long-term productive input. To clarify, the long-term productive inputs serve as a mediating factor in the effect of digital technology on environmental efficiency. The coefficients of intermediation for short-term productive input and long-term productive input were 0.0102 and 0.0122, respectively. Hypothesis 6 has been confirmed.

Table 7. Estimated results of the effect of digital technology on the environmental efficiency of dairy farms under the mediation of labor factor allocation.

Variables	Regression (7)	Regression (8)	Regression (9)	Regression (10)	Regression (11)	Regression (12)
	Environmental Efficiency	Labor Input Proportion	Environmental Efficiency	Environmental Efficiency	Labor Input Time	Environmental Efficiency
Digital technology	0.1324 *** (0.0117)	-0.2594 *** (0.0156)	0.0391 *** (0.0078)	0.1324 *** (0.0117)	-0.0270 *** (0.0020)	0.0080 * (0.0043)
Education attainment	0.0258 *** (0.0055)	-0.0311 *** (0.0074)	0.0052 * (0.0027)	0.0258 *** (0.0055)	-0.0084 *** (0.0010)	0.0130 *** (0.0039)
Age	0.0004 (0.0007)	-0.0032 *** (0.0010)	0.0003 (0.0003)	0.0004 (0.0007)	-0.0006 *** (0.0001)	-0.0004 (0.0005)
Village Cadre	0.0761 *** (0.0181)	-0.1131 *** (0.0241)	0.0014 (0.0088)	0.0761 *** (0.0181)	-0.0152 *** (0.0031)	0.0059 (0.0116)
Breeding experience	0.0008 * (0.0005)	-0.0009 (0.0006)	0.0002 (0.0002)	0.0008 * (0.0005)	-0.0000 (0.0001)	0.0007 ** (0.0003)
Risk perception	-0.0322 *** (0.0075)	0.0463 *** (0.0101)	-0.0016 (0.0037)	-0.0322 *** (0.0075)	0.0094 *** (0.0013)	-0.0109 ** (0.0051)
Technical training	0.0248 ** (0.0107)	-0.0061 (0.0143)	0.0208 *** (0.0050)	0.0248 ** (0.0107)	-0.0045 ** (0.0018)	0.0040 (0.0066)
Cooperatives	0.0334 ** (0.0130)	-0.0674 *** (0.0173)	0.0112 * (0.0062)	0.0334 ** (0.0130)	-0.0063 *** (0.0022)	-0.0044 (0.0081)
Household registration type	0.0048 (0.0109)	-0.0204 (0.0145)	0.0087 * (0.0051)	0.0048 (0.0109)	-0.0024 (0.0019)	-0.0060 (0.0067)
Composition of income	-0.0004 * (0.0002)	0.0003 (0.0003)	-0.0002 (0.0001)	-0.0004 * (0.0002)	0.0002 *** (0.0000)	0.0003 ** (0.0001)
Household labor endowment	0.0052 (0.0034)	0.0128 *** (0.0046)	0.0136 *** (0.0016)	0.0052 (0.0034)	0.0013 ** (0.0006)	-0.0008 (0.0021)
Labor input proportion			-0.6611 *** (0.0215)			
Labor input time						-4.6043 *** (0.2198)
Constant term	0.3510 *** (0.0835)	0.8198 *** (0.1117)	0.8930 *** (0.0429)	0.3510 *** (0.0835)	1.5383 *** (0.0143)	7.4339 *** (0.3420)
N	278	278	278	278	278	278
R ²	0.6457	0.7253	0.9226	0.6457	0.7878	0.8666
Adj. R ²	0.6311	0.7140	0.9190	0.6311	0.7790	0.8606

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. The values in parentheses represent standard deviations.

4.4. Robustness Test

4.4.1. Two-Stage Least Squares Test

This study used the two-stage least squares (2SLS) approach to examine the robustness of the effect of digital technology on the allocation of factors in dairy farms. The estimated outcomes are presented in Table 9. Digital technology has been shown to have a favorable influence on land transfer decisions, land utilization rates, and long-term productive input. Conversely, it has been observed to have a notable negative impact on the proportion of labor input, labor input time, and short-term productive input in dairy farms. The projected findings demonstrate a high degree of consistency with the prior research. The result validates Hypothesis 1, 3, and 5 again.

Table 8. Estimated results of the effect of digital technology on the environmental efficiency of dairy farms under the mediation of capital factor allocation.

Variables	Regression (13)	Regression (14)	Regression (15)	Regression (16)	Regression (17)	Regression (18)
	Environmental Efficiency	Short-Term Productive Inputs	Environmental Efficiency	Environmental Efficiency	Long-Term Productive Inputs	Environmental Efficiency
Digital technology	0.1324 *** (0.0117)	−0.0363 *** (0.0066)	0.1223 *** (0.0122)	0.1324 *** (0.0117)	0.9562 *** (0.1206)	0.1202 *** (0.0129)
Education attainment	0.0258 *** (0.0055)	−0.0022 (0.0031)	0.0252 *** (0.0055)	0.0258 *** (0.0055)	0.2806 *** (0.0573)	0.0222 *** (0.0058)
Age	0.0004 (0.0007)	−0.0022 *** (0.0004)	0.0011 (0.0008)	0.0004 (0.0007)	0.0035 (0.0074)	0.0012 (0.0008)
Village Cadre	0.0761 *** (0.0181)	0.0071 (0.0102)	0.0781 *** (0.0179)	0.0761 *** (0.0181)	0.6360 *** (0.1864)	0.0680 *** (0.0183)
Breeding experience	0.0008 * (0.0005)	−0.0001 (0.0003)	0.0008 * (0.0005)	0.0008 * (0.0005)	−0.0200 *** (0.0047)	0.0011 ** (0.0005)
Risk perception	−0.0322 *** (0.0075)	0.0195 *** (0.0042)	−0.0268 *** (0.0077)	−0.0322 *** (0.0075)	0.1556 ** (0.0778)	−0.0342 *** (0.0075)
Technical training	0.0248 ** (0.0107)	−0.0235 *** (0.0060)	0.0182 * (0.0109)	0.0248 ** (0.0107)	0.2297 ** (0.1103)	0.0219 ** (0.0107)
Cooperatives	0.0334 ** (0.0130)	−0.0542 *** (0.0073)	−0.0182 (0.0141)	0.0334 ** (0.0130)	0.4851 *** (0.1338)	0.0396 *** (0.0132)
Household registration type	0.0048 (0.0109)	0.0429 *** (0.0061)	0.0169 (0.0117)	0.0048 (0.0109)	−0.9408 *** (0.1123)	0.0168 (0.0121)
Composition of income	−0.0004 * (0.0002)	0.0007 *** (0.0001)	−0.0002 (0.0002)	−0.0004 * (0.0002)	0.0021 (0.0023)	−0.0004 * (0.0002)
Household labor endowment	0.0052 (0.0034)	0.0071 *** (0.0019)	0.0072 ** (0.0035)	0.0052 (0.0034)	0.1184 *** (0.0356)	0.0037 (0.0035)
Short-term productive input			−0.2806 *** (0.1076)			
Long-term productive input						0.0128 ** (0.0059)
Constant term	0.3510 *** (0.0835)	9.2982 *** (0.0471)	2.9603 *** (1.0035)	0.3510 *** (0.0835)	−4.0327 *** (0.8627)	0.4025 *** (0.0863)
N	278	278	278	278	278	278
R ²	0.6457	0.4892	0.6546	0.6457	0.8032	0.6734
Adj. R ²	0.6311	0.4681	0.6389	0.6311	0.7950	0.6586

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. The values in parentheses represent standard deviations.

4.4.2. Bootstrap Mediation Effect Test

To examine the robustness of the mediating effect of factor allocation, the study employed the Bootstrap technique. This approach was utilized to assess the mediating effect of factor allocation on the effect of digital technology on environmental efficiency. The regression results are presented in Table 10. The 95% confidence interval for the direct effect coefficient of digital technology on environmental efficiency does not include zero. Similarly, the 95% confidence interval for the path coefficients of land factor allocation, labor factor allocation, and capital factor allocation in the indirect effect also does not include zero. These findings suggest that the direct effect of digital technology on environmental efficiency is statistically significant. The significance of the three distinct intermediate effects, namely land factor allocation, labor factor allocation, and capital factor allocation, cannot be understated. In summary, the findings yielded by the Bootstrap intermediary effect test approach align with those obtained by the aforementioned stepwise regression method, further confirming the mediating influence of factor allocation in digital technology on environmental efficiency. Hypotheses 2, 4, and 6 were reconfirmed.

Table 9. Results of two-stage least squares model estimation.

Variables	Land Transfer Decision	Land Utilization Rate	Labor Input Proportion	Labor Input Time	Short-Term Productive Input	Long-Term Productive Input
Digital technology	0.9105 *** (0.0324)	0.1985 *** (0.0110)	−0.2622 *** (0.0163)	−0.0344 *** (0.0015)	−0.0524 *** (0.0065)	0.4484 *** (0.1675)
Education attainment	0.0416 ** (0.0175)	0.0313 *** (0.0057)	−0.0307 *** (0.0054)	−0.0073 *** (0.0009)	0.0002 (0.0035)	0.3553 *** (0.0490)
Age	−0.0001 (0.0013)	0.0025 ** (0.0013)	−0.0033 *** (0.0011)	−0.0007 *** (0.0001)	−0.0024 *** (0.0003)	−0.0483 *** (0.0059)
Village Cadre	0.0475 (0.0347)	0.0347 (0.0228)	−0.1129 *** (0.0253)	−0.0149 *** (0.0023)	0.0079 (0.0076)	0.6623 *** (0.1165)
Breeding experience	0.0016 (0.0018)	0.0031 *** (0.0006)	−0.0009 (0.0006)	−0.0000 (0.0001)	−0.0001 (0.0003)	0.0189 *** (0.0047)
Risk perception	−0.0688 ** (0.0335)	0.0031 (0.0103)	0.0461 *** (0.0115)	0.0088 *** (0.0014)	0.0182 *** (0.0047)	0.1160 (0.0928)
Technical training	0.1913 *** (0.0364)	0.0542 *** (0.0133)	−0.0060 (0.0129)	−0.0043 *** (0.0015)	−0.0230 *** (0.0048)	0.2450 *** (0.0920)
Cooperatives	0.2190 *** (0.0514)	0.0504 *** (0.0149)	−0.0682 *** (0.0134)	−0.0084 *** (0.0021)	−0.0587 *** (0.0069)	0.6274 *** (0.1363)
Household registration type	0.0446 (0.0321)	0.0376 *** (0.0111)	−0.0203 * (0.0106)	−0.0019 (0.0015)	0.0438 *** (0.0051)	0.9121 *** (0.1101)
Composition of income	−0.0003 (0.0005)	0.0005 (0.0003)	0.0004 (0.0002)	0.0002 *** (0.0000)	0.0007 *** (0.0001)	0.0028 * (0.0017)
Household labor endowment	0.0322 *** (0.0101)	0.0021 (0.0038)	0.0128 *** (0.0044)	0.0012 ** (0.0005)	0.0073 *** (0.0018)	0.1256 *** (0.0406)
Constant term	−0.1878 (0.3004)	0.0257 (0.0936)	0.8182 *** (0.0811)	1.5341 *** (0.0129)	9.2889 *** (0.0531)	−4.3277 *** (0.8321)
N	278	278	278	278	278	278
R ²	0.728	0.613	0.725	0.777	0.478	0.669
Adj. R ²	0.717	0.597	0.714	0.768	0.456	0.655

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. The values in parentheses represent standard deviations.

Table 10. Test of mediation effect based on the bootstrap method.

Variables	Type of Effect	Coefficient	Standard Deviation	95% Confidence Interval	
Land factor allocation: land transfer decision	Direct effects	0.0181 *	0.0105	0.0084	0.0446
	Indirect effects	0.0916 ***	0.0119	0.0682	0.1149
Land factor allocation: land utilization rate	Direct effects	0.6295 ***	0.0399	0.5513	0.7076
	Indirect effects	0.0398 *	0.0212	0.0018	0.0815
Labor factor allocation: labor input proportion	Direct effects	−0.6611 ***	0.0307	−0.7213	−0.6010
	Indirect effects	−0.0767 ***	0.0213	−0.1184	−0.0349
Labor factor allocation: labor input time	Direct effects	−4.6043 ***	0.3664	−5.3225	−3.8859
	Indirect effects	−0.1206 **	0.0541	−0.5021	−0.0609
Capital factor allocation: short-term productive input	Direct effects	−0.2806 ***	0.0938	−0.4646	−0.0967
	Indirect effects	−0.3451 ***	0.0815	−0.5048	−0.1853
Capital factor allocation: long-term productive input	Direct effects	0.0128 *	0.0077	0.0022	0.0278
	Indirect effects	0.0240 ***	0.0047	0.0149	0.0332

Note: *, **, *** indicate significant at the 10%, 5%, and 1% levels respectively.

5. Conclusions and Recommendations

5.1. Conclusions

This study utilizes survey data collected from Chinese dairy farms between January and July 2023. It employs several econometric models, including the IV-Probit model, IV-Tobit model, treatment effect model, and two-stage least square technique, to conduct a complete empirical analysis of the effect of digital technology on factor allocation. The study employed the stepwise regression approach and Bootstrap method to develop an intermediate effect model, aiming to examine the mediating function of factor allocation in the relationship between digital technology and environmental efficiency. The primary findings may be summarized as follows: digital technology exerts a substantial influence

on factor allocation. Digital technology has been found to have a statistically significant beneficial influence on land transfer and land use in dairy farms, as determined by a significance threshold of 1%. Digital technology exhibits a noteworthy inverse relationship with the allocation of labor factors, specifically in terms of the proportion of labor input and labor input time. The application of digital technology in the allocation of capital factors can provide dairy farms with the opportunity to reduce short-term production inputs while also facilitating the expansion of long-term production inputs, hence enabling the achievement of economies of scale. Factor allocation plays a vital role in mediating the effect of digital technology on environmental efficiency. Digital technology indirectly contributes to enhancing environmental efficiency through the facilitation of optimal allocation of land, labor, and capital factors. The coefficients associated with the incorporation of land transfer decision and the mediating path of land utilization rate are 0.0117 and 0.1109, respectively. The mediating coefficients for the labor input proportion and labor input time are 0.1715 and 0.1243, respectively. The intermediation coefficients for short-term and long-term productive inputs are 0.0102 and 0.0122, respectively.

5.2. Policy Recommendations

Based on the research findings, this report presents three policy recommendations. First and foremost, it is imperative to place significant emphasis on the advancement of digital technology and facilitate the profound integration of digital technology into dairy farms. In 2020, the European Union implemented the “Farm to Table” strategy, which places a high priority on the application of digital technologies in the agricultural sector. It has already achieved success in the dairy farms. Germany has created digital dairy farming monitoring technology, which can monitor the information of cows’ conception and send the monitoring information to farmers. The Netherlands has developed a computerized feeding management system based on the automatic identification of individual cow numbers, which enables the automatic feeding of cows. The promotion of digital technology should be prioritized by the government as a development strategy in China. This entails a constant reduction in pollution-type factor input within these farms, as well as an enhancement of the factor input structure to its fullest potential. The government may further facilitate the sustainable growth of dairy farms. Furthermore, it is essential to fully use the synergistic potential of digital technology in conjunction with land, labor, and capital within dairy farms, hence facilitating the best allocation of production components in such agricultural settings. Digital technology has the potential to address the resource disparity prevalent in dairy farms, therefore, enhancing the environmental efficacy of such establishments. The agriculture sector must enhance its backing for the use of digital technology inside dairy farms, provide preferential support policies for dairy farms that refrain from utilizing digital technology, and actively encourage the digitalization process within dairy farms. Furthermore, it is imperative to provide specialized training programs focused on the utilization of digital technologies within dairy farming operations. In order to enhance the proficiency and efficacy of dairy farmers in utilizing digital technology, it is proposed to conduct digital technology training, with a specific focus on augmenting the digital skills training of large-scale dairy farms. Additionally, the establishment of digital technology resource-sharing platforms for dairy farms needs to be promoted. This initiative aims to leverage the application of digital technology in dairy farms and facilitate the overall development of the sector.

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Article

Predicting Raw Milk Price Based on Depth Time Series Features for Consumer Behavior Analysis

Zongyu Li ^{1,2}, Anmin Zuo ³ and Cuixia Li ^{1,*}

¹ School of Economics and Management, Northeast Agricultural University, Harbin 150038, China; lizongyu@hljtu.edu.cn

² School of Economics and Management, Heilongjiang Institute of Technology, Harbin 150038, China

³ School of Computer Science, Northwestern Polytechnical University, Xi'an 710060, China

* Correspondence: licuixia.883@163.com

Abstract: The dairy industry has a long supply chain that involves dairy farmers, enterprises, consumers, and the government. The stable growth of consumer groups is the driving force for the sustainable development of the dairy industry. However, in recent years, sustainable development of the dairy industry has faced great challenges due to the constant changes in the global climate environment and the increasing uncertainty of the international economic environment. Therefore, it is essential to systematically monitor and accurately predict the consumption market of dairy products to ensure that the government, dairy enterprises, and dairy farmers can share information in a timely manner and take effective measures to cope with the changes in the dairy consumption market without disturbing the normal pricing mechanism of the dairy market. The purpose of the conducted research is to systematically monitor and accurately predict the dairy product consumption market while consistently delivering dependable forecasts of consumer behavior in the dairy industry. In this paper, we proposed a raw milk price prediction framework (RMP-CPR) to analyze consumer behavior based on the relationship between milk price and dairy consumption. This study concludes that dairy consumption behavior can be predicted accurately by predicting the price of raw milk based on the proposed framework (RMP-CPR). Our research explores a new angle for studying consumer behavior. The results can assist dairy enterprises in developing accurate marketing strategies based on the forecast results of dairy consumption, thereby enhancing their competitiveness in the market. Policymakers can also use the forecast results of the development trend of the dairy consumption market to adjust corresponding policies in a timely manner. This can help to balance the interests among consumers, dairy enterprises, dairy farmers, and other relevant stakeholders and effectively maintain the sustainable and healthy development of the dairy market.

Keywords: raw milk; price prediction; consumer behavior; CNN; contextual-based representation

1. Introduction

Milk is rich in vitamins and protein and is a very common food in the world [1]. Milk and dairy consumption in Asian countries has increased significantly in recent years according to the statistics from the Organization for Economic Cooperation and Development (OECD), and the Food and Agriculture Organization (FAO). Because the development of the dairy consumption market determines the interests of consumers, dairy enterprises, dairy farmers, government departments, and other multi-stakeholders, the development of the dairy consumption market plays an important role in social economic development. Therefore, how to regulate milk prices reasonably and guide consumer behavior for releasing consumption potential in the dairy industry is a great challenge in the development of the market economy. The purpose of the conducted research is to systematically monitor and accurately predict the dairy product consumption market, while consistently delivering dependable forecasts of consumer behavior in the dairy industry. Our accurate prediction

of consumption in the dairy products market can provide reliable information on the change in dairy consumption for the government, dairy enterprises, and dairy farmers, and help them develop reasonable marketing programs and countermeasure mechanisms to cope with the change in the dairy consumption market. It can stimulate the purchase intention of dairy consumers sustainably without disturbing the normal pricing mechanism in the dairy market.

Nowadays, the need for research on the consumption behavior of dairy consumers is becoming more and more topical. Consumer purchasing behavior analysis plays an important role in the development of the market [2] and is approached with the commodity price as a key factor [3]. Price is the monetary expression of the value of goods and an important factor when people choose goods [4]. A high price will increase the cost of consumer input and reduce consumer surplus with the expected income determined. Therefore, regardless of other external conditions, the fluctuation of commodity prices is closely related to sales volume. The hypothesis we propose is that there exists a direct relationship between the consumer behavior of dairy products and dairy prices and that the consumption volume of dairy products can be accurately predicted based on the prices of dairy products.

Price and family cost decreased the probability of products being chosen [5], which affects consumption behavior. There have been studies on the consumption behavior of milk and dairy consumers with key factors: quality, availability, pricing, variety, brand image, and advertisement [6]. Some studies have found that high milk prices have a negative impact on the consumption of fresh milk products [7]. As for the socio-economic characteristics of consumers, age, education, and income revealed positive impacts on willingness to pay [8]. Scholars identify time concerns, high prices, and value for money as the most significant value barriers [9]. Demographic and socioeconomic factors, such as price, availability, awareness, and convenience, could affect dietary behavior [10]. Food curiosity and food price inflation were identified as relevant for both willingness to buy and willingness to pay a price premium [11]. By virtue of low price elasticity, increased prices may negatively affect the household resources available to purchase other key sources of nutrients [12]. As the core raw material of milk production, the price of fresh milk will be transmitted to the downstream milk retail price along the milk industry chain [13]. Many scholars have studied the behavior of dairy consumers from the perspective of influencing factors in product consumer behavior. However, few studies have quantitatively analyzed consumer behavior through a commodity price fluctuation trend. Our research has established a framework which can accurately predict the changes of dairy prices in the short term. Based on this, combined with the price elasticity coefficient of dairy demand monitored at an early stage, the recent consumption of dairy products can be relatively accurately calculated.

As one of the most important factors affecting the price of commercial products, the price fluctuation of raw materials will affect the price of products to a certain extent. As a widely used agricultural product, the price of raw milk also has various fluctuations as do all kinds of products. The forms of product price prediction are various, introducing price into a time series for forecasting is one of the mainstream forms of price forecasting, and there are many mainstream research methods for time series prediction at home and abroad at present. One is the traditional regression method represented by AR, ARIMA, Lasso, Ridge, etc. The autoregressive conditional heteroskedasticity (ARCH) model is a statistical model for time series data that describes the variance of the current error term or innovation as a function of the actual sizes of the previous time periods' error terms [14]. The ARCH model has demonstrated its ability in its wide use [15,16] and shows a certain stability to the volatility series, but its predictive ability in long-term volatility has shown some deficiencies; Ridge Regression [17] and Lasso [18] are very popular in economics topics and prediction tasks [19–21]. The advantage of Ridge Regression is that it has an analytical solution that is easy to calculate. The coefficient related to the least relevant prediction factor is reduced to zero, but it will never be accurate to zero [22]. The

choice of parameters has a great impact on the Lasso model, especially in the model where explanatory variables have very low correlations and there are relatively few effects [23]. ARIMA [24] is applicable to linear time series and is more robust and effective than related models with more complex structures in short-term prediction, but it does not work well for nonlinear time series [25]. To a certain extent, regression methods often have a fast modeling speed. Even in the case of huge amounts of data, these models can run at a fast speed. However, when they are used for nonlinear data such as product prices, the fitting effect is sometimes slightly insufficient.

In recent years, with the rise of artificial intelligence technology, the time series prediction methods represented by the BP neural network, the RNN, LSTM, transformers and the SVM have been widely used. For the nonlinearity and complexity of time series prediction, the deep learning method has the ability to identify the structure and pattern of data [26–28]. The SVM (Support Vector Machine) estimates regression using a set of linear functions that are defined in a high-dimensional space [29]. Researchers used optimized GA-SVM to predict vehicle speed based on a driver–vehicle–road–traffic system [30]. Kaytez et al. [31] applied SVM to electricity consumption forecasting. Though SVM is simple and robust, it is difficult to implement for large-scale training samples and sensitive to parameter selection [32]. The RNN (Recurrent Neural Network) is a class of artificial neural networks which can exhibit temporal dynamic behavior [33] and can be applied to a financial or time series forecast [34]. The RNN is applicable to short-term memory tasks and is also insensitive to data from a long time prior but can be difficult to train. LSTM, improved from the RNN, is widely used in time series prediction [35,36] and has been proven to be superior to the ARIMA algorithm in time series prediction [37]. LSTM has the ability to analyze and exploit the interactions or patterns existing in data through a self-learning process, but the amount of computation will be large and time-consuming when the network is deep. The famous Informer model [38] modified from the transformer shows its strong ability to capture the long-term trend of time series, but it has shown some deficiencies in the ability to capture periodic patterns. In general, the above methods show strong operability and applicability in the research of time series. However, many unsupervised time series research models are similar to those in CV and NLP fields which have strong inductive bias and are not suitable for modeling time series in many cases [39]. The existing methods also rarely capture features of time series from a different granularity, which is important for learning different levels of semantics to improve the generalization ability of the model. At present, these methods still have some limitations in solving the problem of sequence prediction alone.

There are no or very few studies that focus on the quantitative prediction of consumer behavior. In this paper, we propose a framework to accurately predict raw milk price in the coming year after hundreds of experimental comparisons of raw milk price data in mainland China from 2008 to 2022. On this basis, the corresponding consumption of dairy products can be calculated by combining the market price of fresh milk and the price elasticity coefficient of demand. Through the designed framework, policy makers can stimulate consumers through reasonable prices and extensive and effective means of product value publicity, further promote the increase in dairy consumption, and promote the sustainable development of the dairy industry.

2. Materials and Methods

2.1. Workflow

A flowchart of the proposed pipeline for the raw price milk prediction is shown in Figure 1. First, raw milk price data are collected and preprocessed for the milk price analysis. Because raw milk price data are not available with digital documents, we collect the raw milk price data manually and complete missing information through text mining.

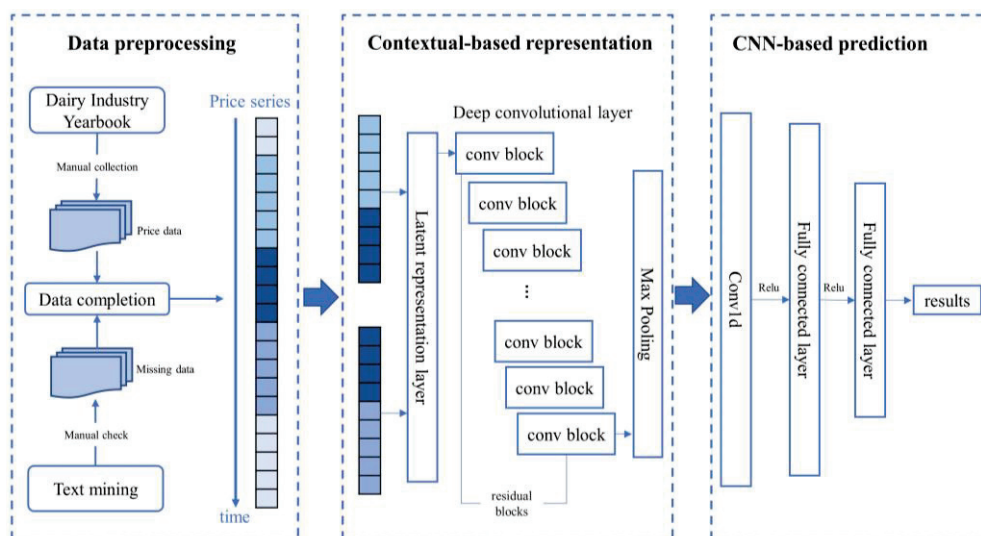


Figure 1. Flowchart of the RMP-CPR workflow. The raw milk price data are manually collected and preprocessed for the milk price analysis. Then, the raw milk price on common segments from two subseries of the price in the contextual-based representation layer is learnt to make contextual semantics consistent. Last, the price of raw milk can be predicted based on the Convolutional Neural Network with the representations of the known price.

Then, the representations of raw milk price are used on the common segments from two subseries of the price in the contextual-based representation to make contextual semantics consistent. Last, the price of raw milk can be predicted based on the Convolutional Neural Network with the features of the known price.

2.2. Data Preprocessing

Because raw milk price data are not available with digital documents, we collected the raw milk price data manually referring to the *China Dairy Industry Yearbook* as shown in Figure 2. We collected 864 items of raw milk price data from 2008 to 2022. However, the weekly data from 2016 to 2022 are missing, which means the *China Dairy Industry Yearbook* does not provide complete data. Therefore, we tried to extract the published data from the website using text mining. First, information from the webpage was analyzed, and extraction rules were made to clarify the target information. Then, we extracted the metadata and manually verified the extracted information. After integrating the information, we completed the missing weekly data and the annual average price data in the raw milk price data.

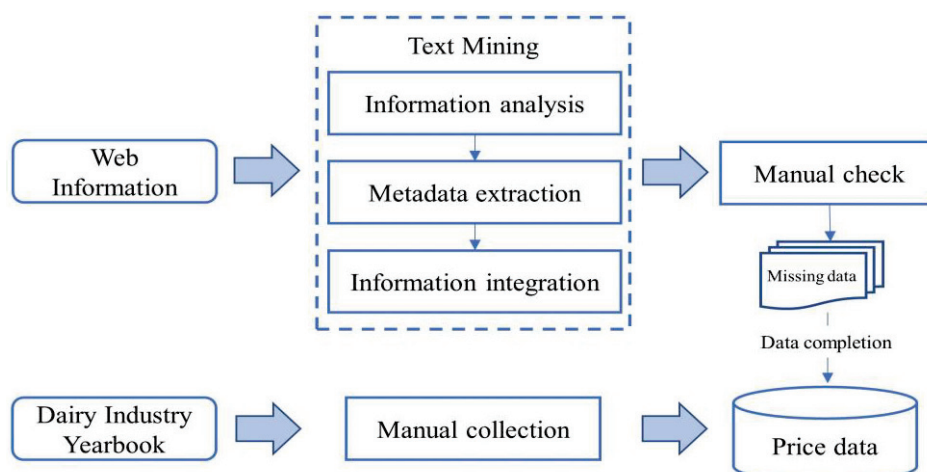


Figure 2. Flowchart of the raw milk price data preprocessing.

2.3. Representation Learning of Raw Milk Price Data

From the perspective of data format and content, raw milk price data can be regarded as time series data. The time series can be defined as $X = \{x_1, x_2, \dots, x_L\}$, where each x_i represents the price at time stamp i , and L is the length of the sequence for the input price. We tried to represent raw milk price with time stamps based on the deep learning network for downstream raw milk price prediction. Therefore, the target is to train a nonlinear embedding function ϕ_θ , and this function can map each x_i to its representation $\gamma_i \in R^{L \times K}$ that can represent its feature. The input time series x_i can have multiple dimensions as F , where F is the feature dimension of the raw milk price data. The representation γ_i has a dimension of K , where K represents the dimension of the representation of raw milk price at a certain time point, and the length of the input and output in the nonlinear embedding function ϕ_θ remains the same.

2.3.1. Latent Representation Layer

The purpose of the latent representation layer is to map the price data to a high-dimensional latent vector. This layer consists of a fully connected layer with a noise mask. First, the time stamps and prices in the raw milk price data were encoded by a fully connected layer. Then, the noise masks were incorporated into the initial representations of raw milk prices in order to prevent the representation learning model overfitting. In the fully connected layer, the linear transformation for the raw milk price can be defined as follows:

$$V = WX + b \quad (1)$$

where V represents the price latent vectors, W is parameters to be learned by the model, and b is the bias parameters of vectors. X represents the initial representations of raw milk prices and $x_{i,t} \in X$ is the input x_i at timestamp t . Because there is a limited amount of sequence data, we sampled the price data in segments by noise mask in order to make the feature integration process more robust. First, in order to relieve overfitting, noise masks were added in the processed price data before training the price data. The price latent vector $v_i = \{v_{i,k}\}$ was masked with a binary mask $mask \in \{0, 1\}^L$ after the price data were projected as input. The noise mask process follows Bernoulli distribution with the probability p set to 0.5. Finally, we obtained the latent representations of the raw milk price data with the noise mask.

2.3.2. Deep Convolutional Layer

The raw milk price is represented through the latent representation layer. In the deep convolutional layer, the CNN will extract the contextual representation at each timestamp, which has multiple residual blocks, and each block contains two 1D convolutional layers with a dilation parameter.

- Sample selection

The available raw milk price data span from 2016 to 2022 and contain 358 items of price data. These data with time stamps can be represented based on the deep learning network. The samples of the raw milk price data have to be effectively selected due to the small amount of data for the representation model training. Therefore, we randomly sampled the series of raw milk price by overlapping any two segments of the original price data inspired by TS2Vec [39]. For time series input $x_i \in R^{L \times F}$, two segments $Seg_m = \{x_m\}$, $Seg_n = \{x_n\}$ with overlapped series will be randomly sampled and satisfied $Seg_m \cap Seg_n \neq \emptyset$. It is found by analyzing the raw milk price data that the factors affecting the fluctuation of raw milk price include seasonal factors and policy factors; a small overlap cannot fully represent the context of the price fluctuations. Therefore, a threshold λ is defined to limit the length of the overlapped series and ensure full contextual information. The sample can be selected as follows:

$$Seg_{target} = Seg_m \cap Seg_n \quad (2)$$

where $|\text{Seg}_m \cap \text{Seg}_n| \geq \lambda$, $|\text{Seg}_m \cap \text{Seg}_n|$ represents the length of the overlapped sequences, and λ indicates the overlapped minimum length. Random sampling by controlling the length of the overlapped portion can fully obtain the contextual representation of the shared part. In the model training, the target is to make the differences between the contextual representations on the overlapped segments reduced and to represent the raw milk price fully.

- Contextual representations

In the deep convolutional layer, the CNN will extract the contextual representation at each timestamp where there are two views for the contextual representation of raw milk price, including temporal comparison and sample comparison.

Samples with shared price sequence fragments were selected through the above process. Then, the latent representations of the raw milk price data were obtained in the representation layer. Therefore, the price data at each time stamp can be seen as a vector with a dimension of K , and the similarity between different representations of raw milk price can be calculated based on cosine similarity. The similarity between Representation γ_1 and Representation γ_2 is defined as follows:

$$\text{coSim}(\gamma_1, \gamma_2) = \frac{\gamma_1 \gamma_2}{|\gamma_1| |\gamma_2|} \quad (3)$$

where $|\gamma|$ represents the length of vector γ . At the same time stamp, the similarity of the representations on overlapping fragments of one sample can be calculated based on Formula (3). Similarly, we can calculate the similarity of representations at different time stamps on the same sample or at the same timestamp on different samples. In other words, we can quantify the differences in the view of the sample and time based on cosine similarity as follows:

$$\text{Sim}(m, n, u, v) = \begin{cases} \text{coSim}(\gamma_{m,u}, \gamma'_{n,v}), m = n \text{ and } u = v \\ \text{coSim}(\gamma_{m,u}, \gamma_{n,v}), m \neq n \text{ or } u \neq v \end{cases} \quad (4)$$

where $\gamma_{m,u}$ is the representation of the index m on a segment of a sample at time u , and $\gamma'_{n,v}$ indicates the representation of the index n on the other overlapped segment of the same sample at time v . Therefore, the loss functions in the two views for the contextual representation of raw milk price can be defined based on Formula (4). Temporal comparison measures the information difference at each time stamp on the overlapped segments of one sample. The loss function for temporal comparison is defined as follows:

$$t\text{Loss}_{(m,u)} = -\log \frac{\exp(\text{Sim}(m, m, u, u))}{\sum_{v \in T} \exp(\text{Sim}(m, m, u, v))} \quad (5)$$

where T represents the time stamp set of the overlapped segments for the sample m . This loss function for temporal comparison is used to calculate the information loss at each time stamp on the overlapped segments of one sample. Similarly, the sample comparison is defined to measure the information difference within and between samples at the same time. The loss function for sample comparison can be defined as follows:

$$s\text{Loss}_{(m,u)} = -\log \frac{\exp(\text{Sim}(m, m, u, u))}{\sum_{n \in S} \exp(\text{Sim}(m, n, u, u))} \quad (6)$$

where S represents the sample set. This loss function for sample comparison is used to calculate the information loss between samples at the same time. Therefore, the loss function of the model can be defined based on the temporal comparison and sample comparison as follows:

$$\text{Loss} = -\frac{1}{|S||L|} \sum_{m \in S} \sum_{u \in L} (t\text{Loss}_{(m,u)} + s\text{Loss}_{(m,u)}) \quad (7)$$

where S represents the sample set, and L is the time stamp set of the sample. $|S|$ and $|L|$ are the number of elements in the collections.

2.4. Predicting Raw Milk Price Based on the CNN

The features of raw milk price can be represented with a contextual-based representation model. Here, we predict the raw milk price based on the Convolutional Neural Network (CNN) with the features of the known price.

The one-dimensional convolution network is applied to process the sequential data of the raw milk price. First, the sequential data are transformed to the three-dimensional tensor by the 2×2 convolution kernel in the convolution layer. Then, the activation function ReLU is used to eliminate the data less than 0 as follows:

$$ReLU = \begin{cases} x, & x > 0 \\ 0, & x \leq 0 \end{cases} \quad (8)$$

We used the fully connected layer to change the three-dimensional tensor into a one-dimensional tensor, and then the final predicted value was obtained through two linear transformations.

3. Results

3.1. Dataset

We manually collected data on dairy consumption, including raw milk prices, corn and soybean meal prices, packaged fresh milk sales prices, and dairy consumption by urban residents in China. As the concentrate feed for dairy cows, corn and soybean meal are the main parts of the production cost of dairy cows, so the price of corn and soybean meal is taken as the factor of the production cost of raw milk. There are 432 items of price data for corn and soybean meal from 2008 to 2022, including the monthly data of corn and soybean meal from 2008 to 2015 and weekly data from 2016 to 2022. At the same time, we collected the price of raw milk in the same period as corn and soybean meal. The monthly data of the above prices were obtained from the 2013 edition and the 2016 edition of the *China Dairy Industry Yearbook*, while the weekly data were manually collated from the monitoring data published on the official website of the Ministry of Agriculture and Rural Affairs of China. The price data of packaged fresh milk in 31 regions of China from 2008 to 2019 were collected from the *China Dairy Industry Yearbook* for a total of 372 items. The national annual average price data were missing and obtained through manual calculation.

3.2. Evaluation Indicator

In order to evaluate the accuracy of the price prediction methods, we applied Mean Absolute Error (MAE) and Mean Squared Error (MSE), which are the most commonly used indicators in predicting sequence data. Mean Absolute Error (MAE) is a measure of errors between paired observations expressing the same phenomenon, which is widely applied in comparisons of predicted versus observed, subsequent time versus initial time, and one measurement technique versus an alternative technique. MAE is defined as follows:

$$MAE = \frac{\sum_{i=1}^n |X_i - Y_i|}{n} \quad (9)$$

where X_i and Y_i are the i -th elements of vector X and Y , respectively, and n is the dimension in the space where the vectors are found. The closer the MSE value is to 0, the better the model is in predicting the future price. Mean Squared Error (MSE) measures how close a regression line is to a set of data points. It is a risk function corresponding to the expected value of the squared error loss. MSE is usually used as the loss function of the regression problem and can also be used to compare prediction results. MSE can be defined as follows:

$$MSE = \frac{1}{n} \sum_{i=1}^n (Y_i - Y'_i)^2 \quad (10)$$

where n is the number of samples, and Y represents the vector for observed values of the variables being predicted, with Y' being the predicted values. Like MAE , the closer to 0, the better the prediction effect of the model.

3.3. Performance of the Framework

Through the above process, we predicted the raw milk price based on the learned representations of the price sequential data. Here, the performance of RMP-CPR is represented based on MSE and MAE. The results show that the MSE and MAE are 1.5971×10^{-4} and 9.8805×10^{-3} , respectively, in predicting the raw milk price, which indicates that the proposed framework RMP-CPR has good performance for predicting the price of raw milk.

To further validate the reliability of RMP-CPR, we conducted five experiments to compare our method with classical price forecasting methods, including long short-term memory (LSTM), Stochastic Gradient Descent (SGD), Ridge Regression, and Lasso Regression. MSE and MAE are taken as the evaluation indicators for these prediction methods. Here, the raw milk price is represented based on the contextual-based representation layer (CRL) and predicted by these above methods. The test results are seen in Table 1. The proposed framework RMP-CPR, which consists of the CRL and CNN, has better performance than the other methods. The prediction methods based on linear regression are all good at predicting the raw milk price with the lower values of MSE and MAE because the features of the price are represented fully in the contextual-based representation layer. LSTM is not as good as the CNN in the downstream method for price predicting because it is more suitable for short sequences. In general, RMP-CPR has higher accuracy in predicting the price of raw milk in the future.

Table 1. Performance comparison of different methods.

Method	MAE	MSE
CRL + LSTM	0.011336167	0.00021248289
CRL + Ridge	0.009256353	0.00017419514
CRL + LASSO	0.010821015	0.00019183145
CRL + SGD	0.013666849	0.0003022581
CRL + CNN	0.009880523	0.00015970702

4. Discussion

4.1. Factors Affecting Raw Milk Price

In this study, the price and time stamp from the integrated data are encoded in the contextual-based representation layer. Then, the encoded information of the raw milk is used to predict the price. In fact, there are other factors affecting the raw milk price, such as corn and soybean meal. As the concentrate feed for dairy cows, corn and soybean meal are the main parts of the production cost of dairy cows, so the price of corn and soybean meal is taken as the factor of the production cost of raw milk. Here, we introduced the price of corn and soybean meal to represent raw milk price at every moment and conduct the experiments using the five methods described above, as shown in Figure 3. It was found that the performance of the models cannot be improved by the representation of raw milk price with corn and soybean meal price encoded. For example, the experimental results of the CRL–Ridge considering the corn and soybean meal price has a 0.002 lower MAE than that of the original method, as shown in Table 2. The CRL–LSTM with the corn and soybean meal price encoded decreased by 0.0003 with MSE as the test indicator.

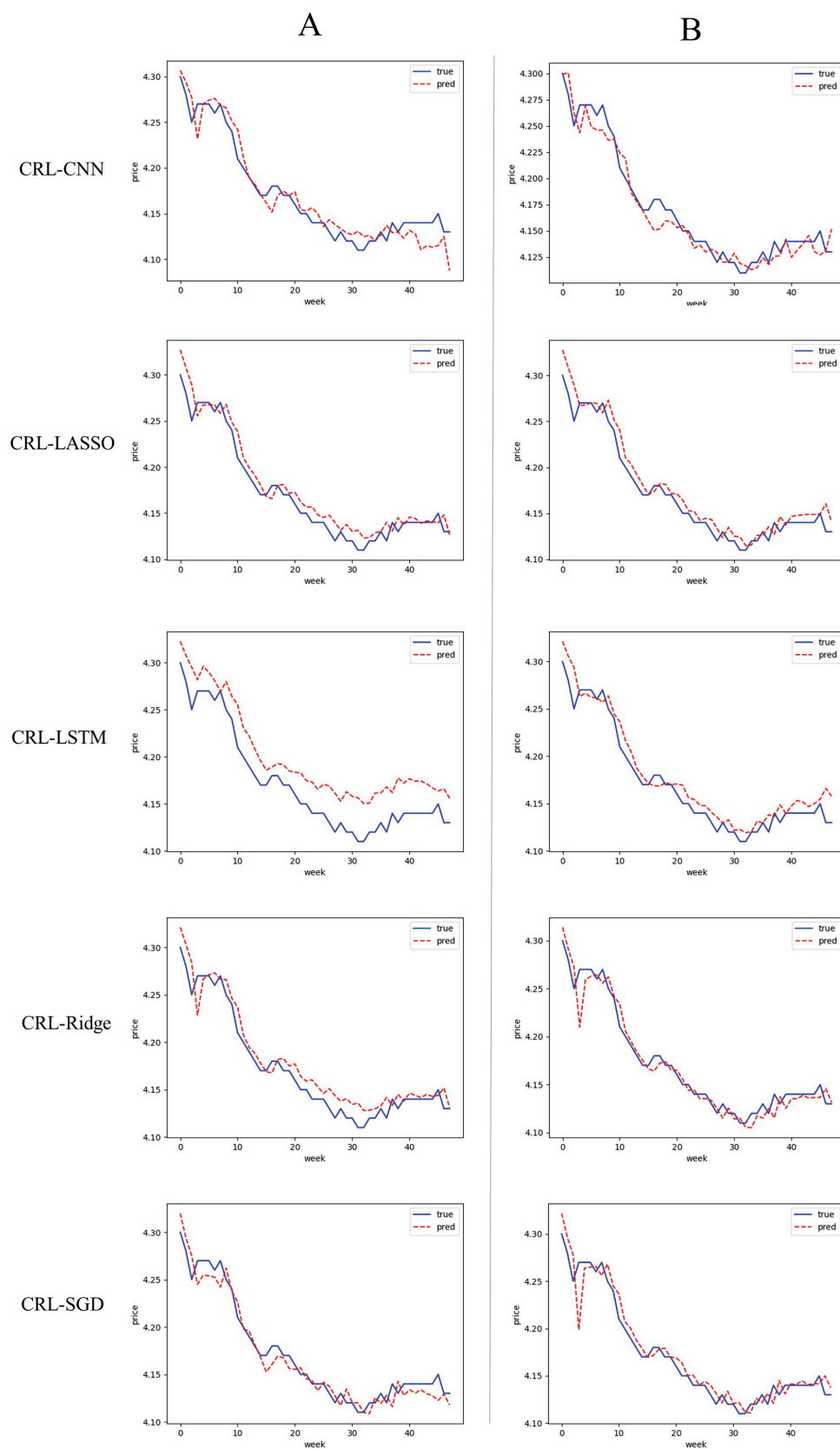
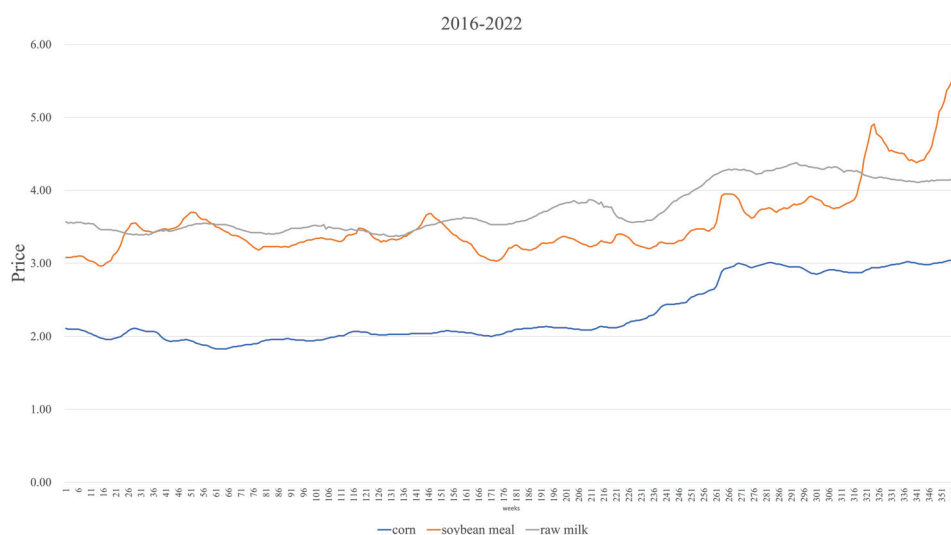


Figure 3. Performance evaluation of the price prediction methods based on different information. In (A), the performance of the methods with corn and soybean meal price is presented. These methods are evaluated in (B) with raw milk price and time stamps.

Table 2. Performance of different methods with corn and soybean meal price.

	LSTM	Ridge	LASSO	SGD	CNN
MAE	0.029185483	0.011006762	0.012051503	0.012768596	0.009396474
MSE	0.000964175	0.000193256	0.000230174	0.000280158	0.000166165

In fact, although corn and soybean meal are the main parts of the production cost of dairy cows, their price is often regulated by the government. As can be seen in Figure 4, the price trend of corn and soybean meal does not completely change with the price of raw milk due to external factors. If there is enough corn and soybean meal price data, the corn and soybean meal price can be used to enhance the prediction for raw milk price with the irregular price data during the regulation period abandoned. We considered that in order to ensure more scientific and rigorous research, we will include more influential factors related to the fluctuation of raw milk price, such as breeding cost and international milk price, into our data analysis in future research.

**Figure 4.** Price trends for raw milk and corn and soybean meal from 2016 to 2022.

4.2. Consumer Purchasing Behavior Analysis Based on Raw Milk Price Fluctuation

Raw milk, which is the natural udder secretions of healthy cows, can be divided into cow milk, goat milk, camel milk, and so on [40]. According to the statistics released by the National Bureau of Statistics, the output of fresh cow milk in China accounted for 97.1% of total raw milk production in 2019. Therefore, raw milk in this paper refers to fresh cow's milk. Raw milk, accounting for more than 70% of milk production cost [41], is the main raw material of milk production. The production of raw milk is located in the middle reaches of the dairy industry chain, and its price fluctuation will extend the transmission of the industrial chain and then affect the prices of downstream milk products [42].

As shown in Figure 5, the price of raw milk has an overall upward trend from 2008 to 2019, while the per capita dairy consumption of urban residents is following a downward trend. However, during certain periods of time, changes in price and dairy consumption cannot follow the pattern of price being a negative factor in consumers' preferences [5]. Through analysis of historical data, it is found that some events and changes in the natural environment have occurred during these periods, affecting the dairy market. For example, the price and consumption of raw milk had a downward trend from 2008 to 2009, when the domestic dairy market fell into a crisis of trust affected by quality problems with dairy products. Dairy market demand was still depressed, even if the price of raw milk was reduced. Because of foot-and-mouth disease in 2013, the high temperature in summer led to a reduction in milk production. Therefore, the price of raw milk rose rapidly with milk

consumption. Due to COVID-19 in 2019, people realized the importance of health, and their awareness of food with high nutritional value, such as milk, has significantly improved. Meanwhile, affected by the epidemic, the production capacity of dairy products was low. Thus, the consumption of dairy products was on the rise with the price of raw milk.

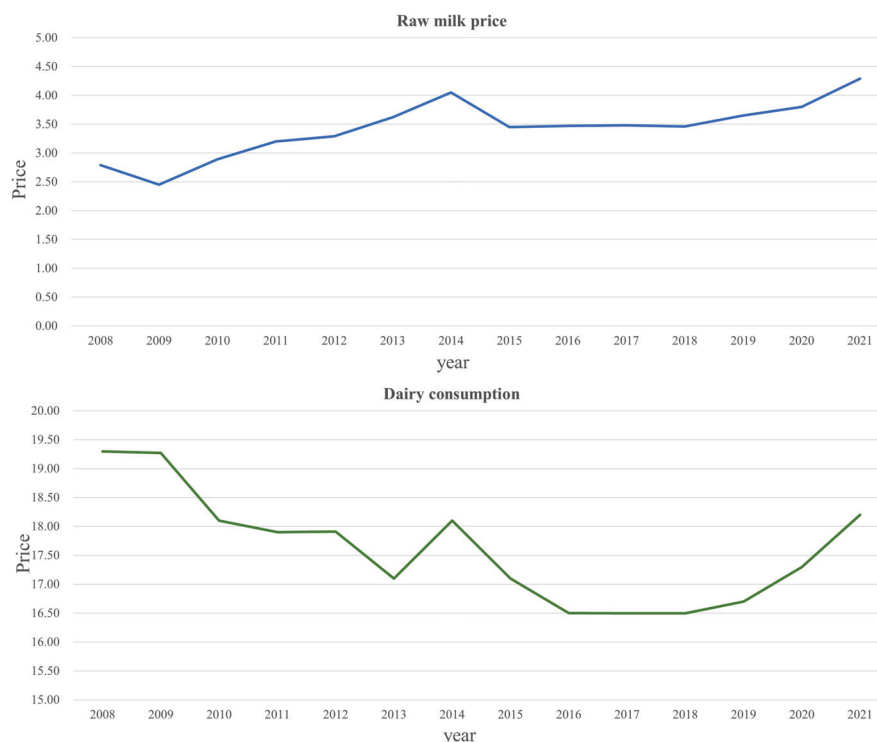


Figure 5. Trend of raw milk price and dairy consumption from 2008 to 2021.

Price had a significant effect on the choice of products. The most common measure of consumers' sensitivity to price is known as price elasticity of demand, which was proposed by Alfred Marshall to reflect the sensitivity of commodity demand to price changes. Price elasticity of demand can be defined as follows:

$$E = \frac{Q_2 - Q_1}{P_2 - P_1} \cdot \frac{P_1 + P_2}{Q_1 + Q_2} \quad (11)$$

where Q_i is the dairy consumption at time i , and P_j is the price of raw milk at time j . Therefore, change in consumption can be reflected according to raw milk price trends based on the demand elasticity coefficient. First, the mean value of the price elasticity of demand is calculated based on the collected annual data of raw milk prices from 2016 to 2022. Then, the predicted price and demand elasticity coefficient are applied to predict the dairy consumption in the future by Formula (11).

We predicted the raw milk price in the next year based on RMP-CPR. As shown in Figure 6, the raw milk price is estimated at 4.14 yuan/kg at the beginning of the year and 4.04 yuan/kg at the end of the year, with a slight increase in the middle of the year. In fact, according to the data provided by the official website of China's Ministry of Agriculture, the average price of raw milk in mainland China in the first week of January 2023 was 4.12 yuan, which is close to the data value we predicted. Overall, the price of raw milk is expected to be stable in the coming year. According to our prediction results of raw milk price, using the elastic coefficient Formula (11), we can estimate that the price of raw milk in 2023 will be 4.18 yuan/kg, and the consumption of urban residents will be 18.45 kg per person. Overall, the price of raw milk in the last three years shows a downward trend, and the per capita consumption of dairy products shows an upward trend with 18.20 kg per person for 2021. Therefore, given the growing willingness to buy foods rich

in high-quality protein and vitamins such as milk, dairy enterprises can improve product structure, develop high-end dairy products and functional dairy products, and employ other means to promote consumer consumption upgrade so as to expand the market share of dairy products to achieve the effect of improving the profitability of dairy enterprises. At the same time, government departments can adopt tax incentives, government subsidies, and other policy means in a timely manner to balance the interest relationship among dairy farmers, dairy enterprises, and consumers.



Figure 6. Trend of raw milk price in 2023.

Consumption is the quantitative value of consumer behavior, and the steady growth of consumption is the goal and driving force of dairy industry development. In this study, by establishing an RMP-CPR prediction model, the price of raw milk can be predicted more accurately, and the consumption behavior of dairy consumers can be predicted accordingly. Predicting dairy consumption through dairy prices has important significances for dairy producers, distributors, and policymakers. By tracking changes in dairy consumption, dairy producers and distributors can anticipate the demand for dairy products and adjust supply to meet it. This information can help businesses make informed decisions about production, distribution, and pricing. Policymakers can use data on dairy prices and consumption to inform decisions about agricultural subsidies, trade policies, and food safety regulations. Overall, dairy producers, distributors, and policymakers can take corresponding measures to respond to market changes in time by the accurate forecasts of dairy prices and dairy consumption to ensure the sustained and healthy development of the dairy market.

5. Conclusions

It is a topical issue to analyze consumer purchasing behavior in the development of the dairy market. In this study, we designed a framework to predict raw milk price, and consumer purchasing behavior analysis was approached with price as a key factor. We first preprocessed the raw milk price data using manual collection and text mining and built the dataset of the raw milk price. The contextual-based representation model was applied to represent raw milk price. Last, the raw milk price was predicted based on the CNN with learned representations of the price. We analyzed the change in dairy consumption according to the raw milk price trend based on the demand elasticity coefficient. Results

showed that our computational framework has good performance in predicting the future trend of raw milk prices, and the consumption behavior was analyzed based on raw milk price. The excellent performance of this framework is mainly reflected in the following aspects: (1) Since integrated digital price data are not available, a complete dataset of raw milk price was constructed to provide data support for accurate price prediction and research on dairy consumption behavior. (2) In order to fully capture features of the price data, we performed a pipeline to fully represent the price data from different views and accurately predict the price trend of raw milk. (3) With the representations of raw milk price, we analyzed the impact of raw milk price on consumer behavior based on the demand elasticity coefficient, providing guidance for dairy market research.

Our experiment effectively validated the hypothesis that we proposed. Through the RMP-CPR framework, we predicted that the price of raw milk in mainland China at the beginning of 2023 would be 4.14 yuan/kg. In fact, the actual value of raw milk in mainland China at the beginning of 2023 was 4.12 yuan/kg, and our prediction accuracy exceeded 95%. Furthermore, we calculated that the per capita consumption of dairy products in urban areas of mainland China in 2023 would be 18.45 kg per person, representing a 6.6% increase compared to the actual dairy product consumption in 2020. Our estimation indicates that the consumption of dairy products in mainland China has been steadily increasing over the past three years, which aligns with the actual development trend of dairy product consumption in mainland China. Our research has important practical significance to guide the sustainable and stable development of the dairy industry. For market analysis, by examining dairy prices, analysts can gain insights into consumer demand and market supply. This information can help businesses make informed decisions on production and pricing strategies, leading to better financial outcomes. By predicting dairy consumption through dairy prices, businesses can anticipate changes in consumer behavior and adjust their marketing strategies accordingly. For policymakers, predicting dairy consumption through dairy prices can also be useful for governments when making policy decisions related to the dairy industry. For example, if dairy prices are expected to rise, the government may need to consider implementing policies to help mitigate the impact of higher prices on consumers, such as subsidies or price controls. For public health professionals, if dairy prices increase, consumers may switch to alternative protein sources, which may have different nutritional profiles. Public health professionals can better understand how dietary patterns may shift and how they may affect public health through predicting changes in dairy consumption. In summary, on the premise of not disturbing the normal market pricing mechanism, all stakeholders of the dairy industry can take corresponding measures in a timely manner according to the systematic monitoring of the price and consumption of dairy products to maintain the sustainable development of the dairy industry.

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Article

Tasmanian Dairy Farmers' Attitudes towards Using E-Extension Methods; Strengthening the Dairy Extension System for a Sustainable Dairy Industry in Tasmania, Australia

Adeel Afzal ^{1,*}, Sue Kilpatrick ¹ and Lydia R. Turner ²

¹ Faculty of Education, University of Tasmania, Launceston 7250, Australia

² Tasmanian Institute of Agriculture, University of Tasmania, Burnie 7320, Australia

* Correspondence: adeel.afzal@utas.edu.au

Abstract: The Tasmanian dairy industry is one of the major contributors to the Tasmanian economy and Australia's export portfolio. The Tasmanian Government funding plan (2018–2023) for RD&E focuses on sustainable dairy farm production with an impact pathway incorporating provisions for extension services. Considering the need for an effective extension system, the continued adaptation of extension services is required to ensure that there is a collaborative and learning mechanism between extension experts and farmers that supports relationship building and innovation. E-extension methods can increase dairy farmers' access to timely information while addressing time and cost challenges by reducing personal visits and establishing frequent communications between farmers and extension workers. This study uses the Technology Acceptance Model (TAM) to understand the attitudes of dairy farmers toward using E-extension methods. It was revealed that dairy farmers who are young, educated, and managing dairy farms with large herd sizes hold positive attitudes toward E-extension. These farmers regularly seek online dairy-related guidance as well as regularly participate in different extension activities. This study concludes that establishing a hybrid framework incorporating E-extension methods with complementary face-to-face extension activities will help maintain a profitable and sustainable dairy industry in Tasmania.

Keywords: dairy industry; dairy farmers; dairy extension; E-extension; technology acceptance model; sustainability

1. Introduction

Tasmania's temperate weather conditions support premium perennial pasture growth and result in high-quality dairy products. Tasmanian dairy cows are exposed to one of the cleanest environments in the world while grazing outside all year round [1]. The dairy industry is one of the most important sectors of Tasmania's agricultural industry and the greatest contributor to the Tasmanian economy, contributing more than \$1 billion to the state economy every year. It offers several investment opportunities, including large-scale milk production, cheese manufacturing, and commercial-scale dairy processing [2]. As Tasmania recovers from the global COVID-19 restrictions, upward pressure on major inputs like fertilizer, seed, fuel, and chemicals, and a competitive employment market are expected to continue. In addition, labor shortages and increasing land and commodity prices in other sectors are expected to influence on-farm decisions in the coming years [3].

The Tasmanian Government, industry, and the Tasmanian Institute of Agriculture (TIA) manage research and development projects collaboratively. These projects aim to increase agricultural productivity, food production, and address natural resource management challenges. The TIA is home to the Livestock Production Centre, which provides dairy research, development, and extension services of international standards [1]. Increasing farmers' awareness and knowledge related to farm management practices has been a core focus point of extension services in the Tasmanian dairy industry [4]. According

to Agricultural Research, Extension Principles, and Investment Strategy (2018–2023), a considerable amount of Tasmanian Government funding for Research, Development, and Extension activities (RD&E) will focus on sustainable farm production. That is further articulated with the help of a clear impact pathway incorporating a credible connection from RD&E investment to dairy farms, including facilitating extension and advisory services [5]. Furthermore, Dairy Australia's strategic plan (2022–2027) for the Tasmanian dairy industry emphasizes an effective extension system in its priority action list, specifically highlighting the need for increased participation of dairy farmers engaged with activities and programs incorporating new engagement methods [3].

Dairy extension helps capacity building and facilitates innovation so that dairy farmers can adopt sustainable, profitable, and better farming practices [6]. It enables researchers and entrepreneurial farmers to facilitate dairy growth. The corporate and industrial establishments utilize the benefits of the latest research with the dairy stakeholders at large, including farmers. It also contributes to the communication of scientific developments in the dairy industry to the stakeholders, assessment and upgradation of dairy extension methodologies, exploring the reasons for non-adoption of new technology, and keeping extension activities up-to-date with changing levels of technology [7]. The current dairy research and extension system is transitioning from a focus on technology transfer to including more participatory approaches. The contemporary scenario requires behavioral changes through education which needs to be addressed with the help of using different extension methods [7]. This reflects the need for incorporating participatory approaches to the extension system, which recognizes the active contribution of farmers as well as other dairy actors. However, the concept of participation is complex and resource intensive, as farmers cannot act alone but need to act collectively with other farmers and RD&E stakeholders. It needs to be built upon a communication network established on the basis of mutual understanding with reliability, time, and cost-effectiveness [8].

As this translates into an extension system that transforms from a knowledge transfer process to a knowledge exchange mechanism [9], with facilitation delivered in a learning process [10], convergence to a range of online platforms and information communication tools (ICTs) to support interactions that co-produce knowledge and build networks of innovative people, institutions, and systems is required [11]. A collaboration and learning mechanism between extension personnel, entrepreneurs, and dairy farmers that creates new space for building relationships and innovation makes it a complete package [12]. Further classifying and merging it into extension services using a combination of different online tools, platforms, and the latest ICTs, which support networking, online interaction, and knowledge exchange, are termed E-extension [13,14]. E-extension methods can profoundly enhance ease of access, real-time information delivery, instant feedback, the ability to reach geographically scattered audiences, and decreased travel by audiences or presenters [15]. Recent developments in ICTs and innovations have opened many new opportunities to improve veterinary practices [16], timeliness, the accuracy of data collection, reporting for disease surveillance, and animal health monitoring [17]. Information communication tools, in combination with different online platforms, can increase dairy farmers' access to timely information while addressing time and cost challenges by reducing personal visits and establishing frequent communications between farmers and extension workers [11,18].

A theoretical framework incorporating perceived ease of use (EoU) and perceived usefulness (U) of existing ICTs and online platforms informing dairy farmers' attitudes towards E-extension was utilized [19]. There are several different theoretical approaches based on the Innovation Diffusion Theory [20], which helps identify different attributes of a technology influencing users' adoption. However, in this study, we wanted to identify characteristics of certain behaviors within the individuals rather than the technology. The Theory of Reasoned Action (TRA) [21] identifies how an individual's beliefs, perceptions, and attitudes are related to their desire to perform and act. According to TRA, attitude related to a behavior is controlled by how an individual responds to the repercussions of a behavior and the evaluation of those repercussions by that individual. Beliefs are

described as an individual's understanding that performing a given behavior will result in a specific consequence [21]. This constitutes an information processing mechanism of attitude development and change, which argues that external factors influence attitudes only through changes in the individual's belief structure [22]. Thus, the TRA provides a complete justification for the transition of a person's perception toward a system to attitudes about its usefulness and perceived benefits and ultimately to actual usage behavior [21].

For this study, TRA is further enhanced into the Technology Acceptance Model (TAM), which forecasts an individual's acceptance built upon the influence of two factors: perceived usefulness and perceived ease of use of a system (Figure 1) [19]. TAM argues that an individual's perception of usefulness and ease of use determines their attitudes towards adopting and using the system. Taking into consideration the TRA concept, behavioral intentions to use are controlled by attitudes toward using the system. According to this concept, behavioral intentions to use in return determine actual system use. Also, a relationship between perceived usefulness and behavioral intentions by individuals towards a system is also proposed by TAM. Perceived usefulness (U) is the level to which an individual thinks that using the system will increase his/her performance. Perceived ease of use (EoU) is the level to which an individual thinks that using the system will need effort. Both factors are modeled as having a significant impact on their attitude toward using a system. Behavioral intentions (BI) to use are the resulting functions of U and EoU. The actual use of a system is then determined by BI. Research has demonstrated that BI is the strongest predictor of the actual use of a system [19,23]. According to Davis [19], EoU directly influences U. It was revealed that while comparing two systems offering the same functionality, the easier-to-use system was considered more useful by its user. Davis [19] argues that because some of the individuals' work requirements include the use of a computer system, if an individual becomes more productive by using a new system, then he or she should become more productive overall. He further states that constructing a system that is easier to use, with all other factors kept constant, should result in a more useful system.

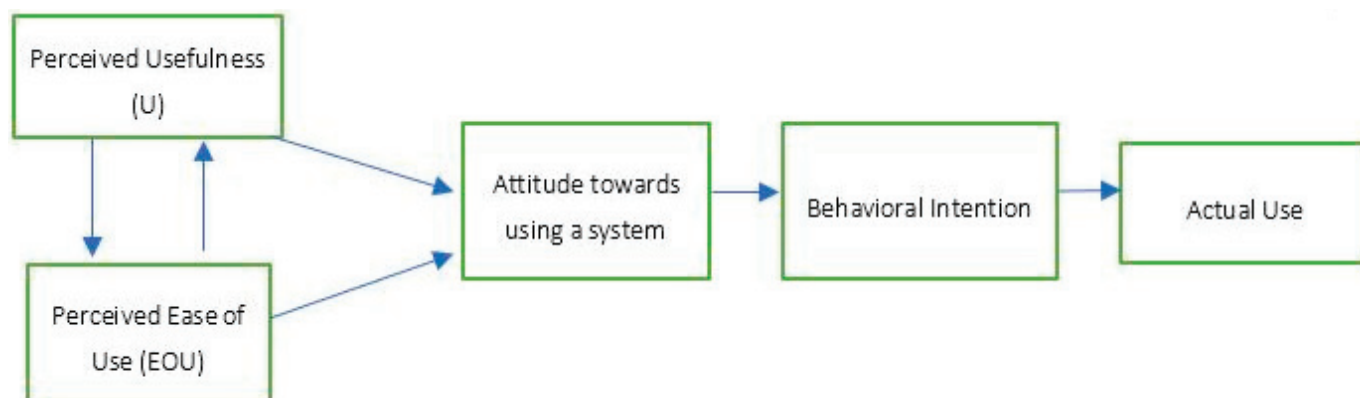


Figure 1. Technology Acceptance Model [19].

There are no or very few studies that focus on the use of a combination of different online tools, platforms, and the latest ICTs in the dairy industry. This is the first time that attitudes towards the use of E-extension methods have been studied in the Tasmanian dairy industry. This research aimed to explore the current attitudes of dairy farmers toward the use of E-extension methods in Tasmania, Australia. The focus is identifying what demographic factors and other characteristics of dairy farmers influence their attitudes toward using E-extension methods.

2. Methods

The selection of dairy farmers for this study was based on whether they could provide sufficient information. The participants were expected to be: (1) actively involved and engaged in dairy farming and dairy extension-related activities to have the necessary

knowledge and experience of the phenomenon under study, and (2) show a willingness to participate in the study. Participants who met the above criteria were surveyed. The research was conducted in line with the University of Tasmania's ethical guidelines and obtained ethical approval from the University of Tasmania Human Research Ethics Committee (H0021920).

Surveys were pretested and validated through piloting with Tasmanian dairy farmers [24]. According to the data available from the Dairy Australia report for Tasmania, there are 387 estimated dairy farms operating on a commercial scale in Tasmania [25]. In 2021, a paper-based survey was distributed through the post to all 220 Tasmanian dairy farms using their contact details which were registered with TIA. The survey was mailed out to each dairy farm once with a reply envelope included. The response rate was 74 (33.6%). As the survey was sent to the dairy farms individually, one response per dairy farm was expected with a limitation of the data representing the respondent's attitude and characteristics only.

The survey intended to collect information on dairy farmers' demographics, dairy farm information, participation in extension activities, current use of ICTs, and how decisions were made to adopt E-extension methods. Some questions in the survey had multiple-choice options for responses to get a better insight into the respondent's situation. To enable further analysis, numerical coding was done for the responses which could not be grouped into 'yes' or 'no' options. The survey comprised two sections, the first section with demographic characteristics and characteristics reflecting ICT usage. The second section comprised a Likert scale instrument with 22 statements representing attitudes towards using E-extension methods. These statements were designed to reflect the ease of use and usefulness of E-extension methods [23,26]. The simplicity and uniformity of the Likert scale makes it the most frequently used research instrument for the measurement of attitudes. As measuring the statements that constitute these attitudes directly is challenging, it is common to develop the variables that represent these statements by adding or averaging the valuations obtained from the items used to measure them [27,28].

Statistical Package for the Social Sciences (SPSS 28) was used to analyze the data. Results are reported using descriptive and summary statistics with correlations produced. Spearman correlation was used to determine the effect of dairy farmers' age, education, milking area, and herd size on their attitudes towards using E-extension methods [29,30]. To understand how dairy farmers' genders, formal agricultural/dairy qualifications, extension activities involvement, online dairy-related interactions, and associated interaction frequencies can influence their attitudes towards E-extension, non-parametric Mann-Whitney and Kruskal-Wallis tests were used, respectively. The participants marked their response to attitude statements through a five-point Likert-type scale: 1 = strongly disagree to 5 = strongly agree, with 3 = neutral. The mean value of the overall attitude (summed across the 22 statements) of the dairy farmers towards the use of E-extension was calculated to help identify the relationship between dairy farmers' characteristics and their overall attitude [31–33]. Further post-hoc tests were performed to identify relationships between specific characteristic groups and attitudes towards E-extension [29,34,35].

3. Results and Discussion

Dairy farmers' demographics and other characteristics related to dairy extension engagement are presented in Table 1. Most of the participants of the study (81%) were farm owners. Forty-six percent of the respondents were between 46–60 years of age. Only 11% of them were females, with the majority (89%) being males. Slightly less than one-third (31%) of the respondents held university degrees. About 16% of the respondents had a diploma or other educational certificate, with the rest of the respondents declaring their highest education (28%, 24%) up to 'year 11/12' and 'year ten or below,' respectively. Fifty percent of the respondents had a formal agricultural/dairy-related qualification. Milking areas ranging from 100–200 ha were declared by more than one-third (38%) of the respondents, while 34% of the respondents had larger than 300 ha of milking area at their dairy farms.

The average milking area in Tasmania of 357 ha was reported in a study conducted by Dairy Australia; however, that study was based on the feedback provided by 30 dairy farms [3]. Slightly more than half (51%) of the respondents in that study were managing a herd size ranging from 200–500 cows, with around one-third (33%) from the rest found managing herd sizes larger than 500 cows. This finding is comparable to the average herd size in Tasmania of 450 cows [36], suggesting that the survey population represents the broader Tasmanian dairy farm population. When asked about involvement in extension activities, 77% of the respondents were engaged in face-to-face interactions, with ‘field days’ (49%) and ‘regional on-farm discussions’ (49%) as the most attended activities. About 37% of the respondents reported that they attended 3–5 extension activities in the last year. While exploring dairy farmers’ online interactions and their frequency, it was revealed that 89% of the respondents were seeking dairy-related information and guidance online, and 45% of them consulted online resources every week.

3.1. Dairy Farmers’ Attitudes towards E-Extension

The mean value of the overall attitude (summated across the 22 statements) of the dairy farmers towards the use of E-extension was 3.43; SD = 0.42 (Table 2). This overall mean value suggests that dairy farmers generally had a positive attitude towards the use of E-extension methods [31]. Similar findings emerged in different studies focusing on dairy farmers’ attitudes toward using ICTs [33,37,38].

Respondents who agreed with the statement, ‘Online dairy farming-related information and support is useful.’ were 76% of the total sample with the highest mean value of 3.90; (SD = 0.70), and 77% of the respondents with the second highest mean value of 3.87; (SD = 0.70) agreed with the statement, ‘Smartphones help in getting latest market and weather information.’ ‘Smartphones and tablets are playing an important role in strengthening dairy research and industry linkages’ was agreed by 72% of the respondents with a mean value of 3.83; (SD = 0.70). It can be assumed that the usefulness of online resources and associated tools helped develop positive attitudes in dairy farmers toward E-extension methods. Using smartphones and online resources to increase production and effective farm management specifically, innovation adoption is seen as a crucial factor in different studies [39,40].

Innovation is a concept that an individual perceives as a new way to find solutions [41]. Today, technological innovation is a key driver for increasing growth and productivity [42] and has assisted in meeting the increasing demand of consumers, which is also greatly driven by the enhancements in consumption technologies and commercial operations [43]. The ability to innovate is a strategic instrument for those industries which want to remain competitive in the global market [44,45].

It is precisely here where the concept of E-extension emerges, which is the modernization of the extension and advisory services. E-extension strengthens extension services through harnessing innovations in the field of ICTs: new communication systems and tools, online data standards, and mobile and smart communication devices with advanced accessibility [46,47]. In terms of the innovative capabilities offered by ICTs, as demonstrated by Guo [48] in their research conducted in Beijing, or in other studies like those performed by Young in Igloolik (Canada) [49], it is exhibited that innovations in online interaction and ICTs are increasing the human capacity of storing information and communication, which means that people have more opportunities to process, communicate, and use digital media as never before.

Table 1. Demographics, farm characteristics, use of extension methods, and usage frequency of survey participants ($n = 74$).

Variable	Survey Sample
Farm Role %	
Farm owner	81.1
Farm manager	4.1
Share farmer	14.9
Age %	
18–30	2.7
31–45	33.8
46–60	45.9
Above 60	17.6
Gender %	
Male	89.2
Female	10.8
Education level %	
Year 10 or below	24.3
Year 11/12	28.4
Diploma/Other	16.2
University	31.1
Agricultural/Dairy qualification %	
Yes	50
No	50
Milking area %	
<100 ha	8.1
100–200 ha	37.8
201–300 ha	20.3
>300 ha	33.8
Herd size %	
<200	13.5
200–500	51.4
501–1000	32.4
>1000	2.7
Attend face-to-face extension activities %	
Yes	77
No	23
Frequency of attending extension activities in last year %	
None	28.4
1–2	28.4
3–5	36.5
6–8	6.8
Seek online dairy-related guidance %	
Yes	89.2
No	10.8
Frequency of seeking online content %	
None	8.1
Weekly or more often	44.6
Fortnightly	13.5
Monthly	20.3
Less often than monthly	13.5

Table 2. Distribution of the respondents according to their responses regarding different statements about E-extension ($n = 74$).

Statements	Mean	SD
Online dairy farming-related information and support is useful.	3.90	0.70
Smartphones help in getting the latest market and weather information.	3.87	0.70
Smartphones and tablets are playing an important role in strengthening dairy research and industry linkages.	3.83	0.70
I am comfortable using devices and online sources to access information.	3.78	0.88
Online discussion groups provide access to dairy experts who could not attend regional discussion groups.	3.75	0.59
Online dairy farming-related information and support is reliable.	3.71	0.56
Dairy extension personnel are actively participating in online discussion forums.	3.64	0.60
Online discussion with dairy experts on dairy farm management is a cost and time-effective way of communication.	3.62	0.65
I have access to a reliable internet connection that allows me to participate in webinars, zoom sessions, and online activities.	3.59	1.00
Dairy social media groups help in connecting with dairy extension workers.	3.50	0.70
Social media groups help in connecting and sharing ideas with fellow farmers.	3.48	0.72
I am comfortable interacting in an online discussion group/workshop (e.g., asking questions, making comments)	3.43	1.00
Online communication is a useful tool to access dairy experts.	3.43	0.75
Expert opinions and success stories on video sharing platforms help in solving farm management issues.	3.39	0.67
Webinars on farm management provide sufficient and useful information.	3.37	0.67
Social media chat applications, e.g., (WhatsApp, Facebook, Skype, Signal) could serve as an effective tool to communicate with extension workers and fellow farmers.	3.36	0.73
Dairy social media groups provide sufficient help and support.	3.18	0.71
DairyTas and other dairy-related organizations' Twitter accounts are providing useful information.	3.14	0.80
Online learning platform "Enlight" by DairyTas is a useful program to promote and strengthen the dairy farming business.	3.14	0.51
Dairy extension could be more effective by increasing the online proportion of extension activities.	2.98	0.73
Video chat and Zoom sessions could be a better alternative to face-to-face and in-person meetings.	2.70	0.93
I get as much value from attending an online training session as I do in-person training sessions.	2.66	0.84

Note: 1 = strongly disagree to 5 = strongly agree, with 3 = neutral.

The lowest mean value of 2.66; (SD = 0.84) was attained by the statement, 'I get as much value from attending an online training session as I do in-person training sessions'. and was agreed with by only 14% of the respondents. Similarly, only 21% of the respondents were of the view that 'Video chat and Zoom sessions could be a better alternative to face-to-face and in-person meetings,' with the second lowest mean value of 2.77; (SD = 0.93). It can be assumed from the results that dairy farmers do acknowledge the importance and effectiveness of using ICTs but oppose completely replacing face-to-face interactions. Perhaps, a tailored combination of both methods reinforcing each other could be a preferable package. It is observed in similar studies that when it comes to specific and detailed advice on farming issues, there is still a strong preference for the more traditional interpersonal communication methods that are face-to-face, i.e., farm visits, field days, and discussion groups [50–52].

The impact of Tasmanian dairy farm attributes and dairy farmers' characteristics on ICT adoption is also evident in a study by Watson [53]. Young and educated dairy farmers with large herd sizes were found to be more comfortable with using ICTs [53]. With increasing emphasis on the organizational efficiency of extension services, frequent visits to farms by extension workers are expected to be curtailed [50]. Considering these

factors, ICT usage will have to be increased by extension personnel and dairy farmers at a pace suited to both being conscious of the digital divide that can occur through various levels of adoption. Farmers' uptake and usage of technology will be driven by personal requirements, characteristics, and ease of use. Consequently, the extension system must continue managing and offering field days, farm visits, office consultations, and face-to-face communications while ensuring that these are used to maximum efficiency and not for just the transfer of information that can easily be accessed through online resources.

3.2. Factors Affecting Attitudes towards E-Extension

The findings presented in Table 3 show a highly significant relationship at the 0.001 level between age and overall dairy farmers' attitudes towards E-extension ($p = 0.001$; $r_s = -0.393$). The negative value indicates that, as the age of the respondents' increases, their attitude towards E-extension becomes negative, conversely indicating a positive attitude from young respondents. Older adults adopt new technologies and innovations slowly compared to younger adults [54] but will adopt if they find those technologies valuable and useful, for example, in improving their quality of life [55]. To make technologies more age-friendly, it is important to understand how older people perceive their advantages and disadvantages [56]. To facilitate E-extension adoption, especially for older dairy farmers, it is suggested that E-extension methods be promoted from a benefits-based perspective, focusing on its positive attributes and the creation of a peer support network to assist with the learning of new systems and technologies.

Table 3. Relationship between age, education, milking area, herd size, and the attitudes towards E-extension.

Factor	r_s	p
Age	−0.393	0.001 **
Education	0.307	0.008 **
Milking Area	0.113	0.340
Herd size	0.264	0.023 *

* Significant at 0.05 (2-tailed); ** Significant at 0.01 (2-tailed).

Dairy farmers' education also showed a highly significant relationship with their attitudes towards E-extension ($p = 0.008$; $r_s = 0.307$). It was observed that as the dairy farmers' level of education increased, their attitude towards E-extension became more positive. However, dairy farmers' milking areas were found to have no significant relationship with their attitudes towards E-extension. A study by Kilpatrick [57] found that most innovative, efficient, and progressive farmers in Australia tended to be younger, had higher levels of education, were open to new ideas and ways of implementing them, were better at planning and management in general and were more likely to participate in learning groups. Several other studies with a focus on the impact of education on ICT's adoptability found similar results [58–60]. It was observed that education helps increase human exposure and knowledge spectrum, which results in enhanced decision-making and adaptability. This could be the reason that individuals with higher education found ICTs easy to use and developed a positive attitude toward E-extension.

It was observed that farmers with larger herd sizes had a relatively more positive attitude towards E-extension ($p = 0.023$; $r_s = 0.264$). Managing a large herd size comes with a few challenges which need to be addressed to maintain profitability and sustainability. An increase in the average herd size on dairy farms also increases the labor and herd management pressure on farmers, thus potentially encouraging the adoption of innovative and resource-efficient methods [61]. In this case, dairy farmers realized the usefulness of online platforms and ICTs to face challenges associated with large herd sizes, which led them to have positive attitudes toward E-extension. Information communication tools have been found to increase resource efficiency and productivity in food systems in different studies [62,63]. In an earlier study on Tasmanian dairy farmers, it was revealed that

herd management software was being used by farmers irrespective of their herd size, but automation was adopted by farmers with larger herd sizes to manage tasks requiring costly human resources [53].

Dairy farmers who revealed that they do seek online guidance ($U = 93.5$; $p = 0.003$; Mean rank: Yes = 40, No = 16) for their dairy-related issues found this practice more useful compared to non-users (Table 4). Realizing the usefulness of online resources leads them to develop a specific behavioral intention resulting in a positive attitude toward E-extension [19,23].

Table 4. Relationship between role at farm, gender, formal qualification, types of extension activities, frequency of interaction, and the attitudes towards E-extension.

Factor	Test	Value
	MW (U)	<i>p</i>
Gender	226.5	0.513
Agricultural/dairy qualification	585.5	0.284
Attend face-to-face extension activities	335	0.054
Seek online guidance	93.5	0.003 **
	KW (H)	<i>p</i>
Role at farm	1.636	0.441
Frequency of attending face-to-face extension activities	9.696	0.021 *
Frequency of seeking online guidance	8.251	0.083

* Significant at 0.05 (2-tailed); ** Significant at 0.01 (2-tailed). MW = Mann-Whitney test, KW = Kruskal-Wallis test.

The frequency of attending face-to-face extension activities was also found to be a significantly related factor influencing the attitudes of dairy farmers towards E-extension ($H = 9.69$; $p = 0.021$). Further post-hoc tests revealed that the dairy farmers who attended 3–5 face-to-face extension activities (Average rank = 45.46) in the last year held a more positive attitude ($p < 0.05$) towards E-extension compared to those who had not been involved in any type of extension activities (Average rank = 27.95). Dairy farmers' gender, role at farm, agricultural/dairy qualification, face-to-face interaction, and frequency of seeking online guidance were found to have no significant relationship with their attitudes towards using E-extension methods.

It can be concluded from the results that the dairy farmers attending 3–5 extension activities annually wanted to remain connected with extension personnel and available advisory services as well as utilize E-extension opportunities. Hall [64] revealed a positive relationship between the level of extension engagement and farmer adoption of best-practice pasture management tools. The farmers regularly engaging with extension services were optimizing learning opportunities and actively developing new knowledge and skills. At the time of the current study, Tasmanian dairy extension activities had to be adapted to COVID-19 social distancing restrictions [65]. Due to these restrictions, dairy farmers were mostly left with E-extension methods for seeking assistance and guidance, and this helped them to experience their ease of use and usefulness in terms of accessibility. The Dairy extension team from the TIA played an important role at that time by remaining engaged and providing due support through their dairy twitter handle, online webinars, discussion groups and online dairy literature [65,66]. Understanding these factors, it could be assumed that using E-extension methods are not only important to strengthen already available extension services, but they can also help all dairy stakeholders remain engaged under unforeseen circumstances.

It is observed from the results that dairy farmers' age, education, herd size, online interaction, and frequency of face-to-face interaction directly influence their perceived ease of use (EoU) and perceived usefulness (U) of E-extension methods. Ease of use affects U and vice versa; the easier a technology or system is to use for an individual, the higher the perceived usefulness by that same individual. Similarly, it also becomes easy for the individual to adopt an innovative system or technology if it is found useful [19]. A study

by Borchers and Bewley [67] informs that dairy farmers who do not know how to use precision farming and are less familiar with its benefits are less likely to be adopters.

Thus, if dairy farmers think implementing and using E-extension methods is easy, they will have a higher intention to use such methods. According to the results, it can be concluded that dairy farmers who were young, educated, and were already engaged in seeking online dairy-related information found E-extension methods easy to use. Dairy farmers handling large herd sizes and who attended relatively more extension activities found E-extension methods more useful. Both factors lead dairy farmers with the aforementioned attributes and characteristics to develop a behavioral intention to use online platforms and ICTs, ultimately developing a positive attitude toward E-extension.

4. Conclusions

Considering the factors that emerged from the results of this study, it is understood that E-extension deployment induces far-reaching changes that impact individuals, societies, and the environment. Community interaction dynamics change significantly with the multiplication of devices and their increased connectivity. Dairy farmers who are young, educated, handling a relatively big dairy business, and are more engaged with extension activities are more inclined towards using new ways of interaction. After realizing the usefulness and possible ease of use, they developed a behavioral intention to use online platforms and ICTs, leading to a positive attitude towards using E-extension methods. However, the results also indicate that holding a positive attitude does not mean that dairy farmers want a complete replacement for face-to-face activities. E-extension methods should complement the already established extension system in a hybrid framework to assist and support dairy farmers in varying conditions and circumstances, leading the way to a comprehensive and seamless extension and advisory system for a sustainable dairy industry in Tasmania.

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Article

Influence of Functional Feed Supplements on the Milk Production Efficiency, Feed Utilization, Blood Metabolites, and Health of Holstein Cows during Mid-Lactation

Shaker B. AlSuwaiegh ^{1,*}, Abdulrahman M. Almotham ¹, Yousef Mohammad Alyousef ¹, Abdallah Tageldein Mansour ^{1,2} and Adham A. Al-Sagheer ^{3,*}

¹ Department of Animal and Fish Production, King Faisal University, P.O. Box 402, Al-Ahsa 31982, Saudi Arabia; aalmotham@kfu.edu.sa (A.M.A.); yyousef@kfu.edu.sa (Y.M.A.); amansour@kfu.edu.sa (A.T.M.)

² Fish and Animal Production Department, Faculty of Agriculture (Saba Basha), Alexandria University, Alexandria 21531, Egypt

³ Department of Animal Production, Faculty of Agriculture, Zagazig University, Zagazig 44511, Egypt

* Correspondence: shaker@kfu.edu.sa (S.B.A.); adham_alsagt@zu.edu.eg (A.A.A.-S.)

Abstract: A 70-day feeding trial was performed to assess the effect of feeding a mixture of functional feed supplements (FFS; contains encapsulated cinnamaldehyde, condensed tannins, capsaicin, piperine, and curcumin) during mid-lactation on the milk production and composition, feed intake, and blood profile of multiparous dairy cows. Sixty Holstein dairy cows (116.1 ± 17.1 days in milk, 606 ± 9.3 kg BW, and 45.73 ± 6.7 kg/d milk production) were distributed into two trial groups: control (CON: $n = 30$), which received a basal diet; and FFS ($n = 30$) treatment, which received a basal diet fortified with the FFS at a rate of 35 g/day/head. The results revealed that daily milk production ($p = 0.01$) and solids-not-fat yield ($p = 0.05$) were significantly higher in dairy cows that had received FFS compared with the control group. In addition, the 3.5% fat-corrected milk, energy-corrected milk, lactose and protein yields, and milk energy output tended to be higher ($p \leq 0.10$) in dairy cattle that consumed FFS during the experimental period. Significant treatment $\times$ period interactions were identified ($p \leq 0.02$) with respect to feed efficiency and somatic cell count. Dry matter intake tended to be greater ($p = 0.064$) in dairy cattle that consumed FFS during weeks 0–2 and 2–4 of the trial period. Most serum biochemical parameters were not changed ($p \geq 0.114$) between FFS and control cows. However, a greater concentration of serum albumin ($p = 0.007$) was observed in cows fed diets supplemented with FFS. In summary, supplementing FFS to lactating Holstein cows during mid-lactation was associated with enhanced lactation performance, feed efficiency, and a tendency to increase feed intake, with no obvious adverse effects.

Keywords: dairy cattle; milk production; blood; phytogetic feed additives; Actifor[®] Pro

1. Introduction

The global demand for an adequate and reliable supply of milk is predicted to increase by 35% by 2030, owing primarily to increased demand in Asia [1,2]. As a result, in recent decades, various countries—including Saudi Arabia—have encouraged the expansion and development of dairy production in order to fulfil increasing consumer demand [3,4]. However, various socioeconomic and environmental issues confront milk production strategies, including the risks linked with the use of growth promoters and antibiotics in livestock [5,6]. Such difficulties have inspired a worldwide search for natural feed supplements that can improve cow milk yields [7–9].

Condensed tannins, for example, have demonstrated a range of antimicrobial properties in ruminants, as well as a great potential to affect the rumen environment, with the specific consequence of enhancing milk efficiency and nitrogen use in lactating dairy

cows [10]. Moreover, some earlier reported studies highlighted the capacity of condensed tannin to mitigate methane emissions from cattle [11,12]. Essential oils, such as cinnamaldehyde with its potent antimicrobial activity, have been shown to favorably modify dairy cow performance and rumen fermentation [13,14]. Additionally, various beneficial effects have been reported for plant-based bioactive compounds such as curcumin, such as boosting immune status and protecting against infectious disease in dairy cows [15] and dairy sheep [16]. Additionally, capsaicin—an active phenolic compound in *Capsicum* spp.—has been established to be an antibacterial agent that improves rumen fermentation [17], a regulator of glucose homeostasis through an insulin secretion mechanism, and a stimulant of digestive enzyme secretion [18]. Furthermore, other bioactive plant secondary components such as piperine have been reported to improve rumen fermentation and boost animal production efficiency and health [19,20].

Based on the information provided, it was hypothesized that feeding a blend of encapsulated cinnamaldehyde, condensed tannins, and plant-based bioactive compounds could improve lactation performance and dairy cow health. Hence, this study evaluated the effects of using Actifor[®] Pro as a functional feed supplement (FFS) containing the above-mentioned ingredients on the milk production efficiency and composition of multiparous Holstein cows during mid-lactation. Additionally, blood biochemical indicators of liver and kidney function as well as the cows' electrolyte balance and protein profiles were also studied to evaluate the safety of this product.

2. Materials and Methods

2.1. Animals, Diets, Investigational Design, and Housing

The experiment was conducted between September and November 2020 at the National Agricultural Development Company (NADEC) in Haradh, Kingdom of Saudi Arabia. All procedures and treatments in the current study were approved by the Research Ethics Committee at the King Faisal University. The present study included sixty Holstein multiparous (mean $\pm$ SD: 3.71 $\pm$ 0.8 lactations) dairy cows. The experimental animals were on average (mean $\pm$ SD) 116.1 $\pm$ 17.1 days in milk, 606 $\pm$ 9.3 kg body weight, and producing 45.73 $\pm$ 6.7 kg/d milk yield. Cows were grouped by parity and daily milk yield and then randomly allocated to the experimental groups in a completely randomized block design. Animals were randomly assigned to the control group (CON: n = 30), which received a total mixed ration (TMR) diet; or the FFS (n = 30) treatment group, which received TMR fortified with a mixture of functional feed supplements at a rate of 35 g/cow/day. The amount of supplement (Actifor[®] Pro, Delacon company, Engerwitzdorf, Austria) used in this study followed the recommendation of the production company. Actifor[®] Pro is a patented formulation that contains encapsulated cinnamaldehyde, curcumin, condensed tannins, capsaicin, and piperine. The experiment was continued for 70 days in total.

Daily feed intake was measured throughout the experiment by subtracting the offered feed from the uneaten feed. All cows were subjected to a 14-day ration adaptation period before being put on their assigned diet for a 70-day supplementation period (experimental period). All cows were kept in tie-stalls in a mechanically ventilated barn, with free access to TMR and freshwater. At the start and during the trial, the dairy cows' health status was checked and recorded. The TMR consisted of concentrates and forages at a ratio of 53.6:46.4, respectively (DM basis). A description of the formulation and proximate composition of the TMR is presented in Table 1. Throughout the experiment, TMR samples were taken fortnightly and kept at -20°C until further analysis.

2.2. Ration Chemical Analysis

By the end of the study, composite samples of the TMR were dried at 60°C for 48 h in a forced-air oven and ground in a Wiley mill (Arthur H. Thomas, Philadelphia, PA, USA) to pass through a 1 mm screen. The chemical composition of the TMR was determined using AOAC [21] procedures. The content of dry matter (procedure 934.01) and organic matter (procedure 942.05) was estimated in all samples. Crude protein ($\text{N} \times 6.25$) content

estimation was performed using the Kjeldahl method (procedure 990.03). Ether extract (procedure 2003.06) content was estimated using petroleum ether in a Soxhlet extractor (Sigma-Aldrich, St. Louis, MO, USA). Acid detergent fiber (ADF) and neutral detergent fiber (NDF) levels were measured following the methods of the AOAC [21] (Method 973.18) and Van Soest, et al. [22], respectively. All chemical analyses were calculated on a dry-matter basis (DM).

Table 1. Ingredients and chemical composition (on a DM basis) of the basal diet ¹ fed to the lactating dairy cows during the experimental period.

Ingredients	[g/kg Feed]	Nutrient Levels	[g/kg Feed]
Corn grain	295.6	Chemical analysis ³	
Wheat bran	17.7	Organic matter	921.6
Soybean meal	31.9	Crude protein (N × 6.25)	158.6
Corn silage	49.6	Ether extract	40.4
Uncorticated cottonseed meal	85.0	Neutral detergent fiber	304.0
Alfalfa hay	343.4	Acid detergent fiber	194.4
Wheat straw	70.8	NFC ⁴	418.6
Limestone	12.3	Calculated values ⁵	
Sodium bicarbonate	7.3	Digestible crude protein	669.1
Canola meal oil-free	70.7	Metabolizable energy, Mcal/kg	2.19
Palm oil hydrogenated	7.8	Net energy for lactation, Mcal/kg	1.38
Calcium salt palm oil	5.9	NDICP	18.4
Premix ²	1.2	ADICP	12.4
Distiller yeast	0.4		
Mycotoxin binder	0.4		

Note: NDICP, neutral detergent insoluble protein; ADICP, acid detergent insoluble protein. ¹ The basal diet based on a concentrate feed mixture and forages at a ratio of 53.6:46.4, respectively. ² Premix contents per kg: 141 g Ca, 87 g P, 45 g Mg, 14 g S, 120 g Na, 6 g K, 944 mg Fe, 7613 mg Zn, 484 mg Cu, 748 mg Mn, 58 mg I, 81 mg Co, 13 mg Se, 248 000 IU vitamin A, 74 000 IU vitamin D3, 1656 IU vitamin E. ³ According to the AOAC [21]. ⁴ Non-fibrous carbohydrates calculated by difference [1000 – (NDF + CP + EE + ash)] [23]. ⁵ Calculated according to tables of ingredients [23] N = nitrogen.

2.3. Milk Yield and Composition

Milk was sampled on days 1, 14, 28, 42, 56, and 70. Cows were machine-milked daily at 4.00, 12.00, and 20.00 h, and composite samples (20 g/kg milk production) were taken at each milking time to determine the milk composition. An equal proportion from each milking was composited for each cow and sent immediately to NADEC laboratories for analysis. Milk samples were evaluated for protein, lactose, fat, ash, and total solids using mid-infrared (FTIR) spectrophotometry (MilkoScan™ FT1, SCANCO, San José, Costa Rica). The total somatic cell count in the milk samples was measured using a Fossomatic™ device 7 (FOSS, Hilleroed, Denmark).

The data for the energy-corrected milk (ECM), fat-corrected milk (3.5% FCM), gross energy content of the milk, and the milk energy output were calculated as follows [24–26]:

$$\text{ECM (kg/day)} = \text{daily milk yield (kg)} \times [20.7 + \text{protein (g/kg)} \times 24.2 + \text{fat (g/kg)} \times 38.3 + \text{lactose (g/kg)} \times 16.54] / 3140 \quad (1)$$

$$3.5\% \text{ FCM} = (\text{fat yield (kg)} \times 16.216) + (\text{milk yield (kg)} \times 0.4324) \quad (2)$$

$$\text{Milk energy content (MJ/kg)} = 4.184 \times [(\text{protein (g/kg)} \times 24.13 + \text{fat (g/kg)} \times 41.63 + \text{lactose (g/kg)} \times 21.60 - 117.2) / 10000] \times 2.204 \quad (3)$$

$$\text{Milk energy output (MJ/d)} = \text{daily milk yield (kg/d)} \times \text{milk energy content (MJ/kg)}. \quad (4)$$

2.4. Serum Biochemistry

Blood samples (10 cows per treatment) were collected before the morning feed on days 1, 14, 28, 42, 56, and 70 of the experiment. The blood was taken from the tail vein (vena coccygeal) into a sterile tube without anticoagulants. After clotting, serum samples

were separated by centrifuging at $2000\times g$ and $4\text{ }^{\circ}\text{C}$ for 10 min. Then, the resulting serum was transferred to 2 mL labeled plastic tubes and stored at $-80\text{ }^{\circ}\text{C}$ until analysis. Serum biochemical parameters were analyzed using a fully automatic biochemical analyzer (VetScan VS2, Abaxis, Inc., Union City, CA, USA). Serum biochemical measurements were conducted to determine the serum levels of total protein (TP), albumin (ALB), gamma glutamyl transferase (GGT), creatine kinase (CK), alkaline phosphatase (ALP), blood urea nitrogen (BUN), alanine aminotransferase (AST), magnesium (Mg), inorganic phosphorus (PHOS), and calcium (Ca). The globulin content (GLO) was computed by subtracting the ALB from the TP.

2.5. Statistical Analysis

All quantitative data (dry-matter intake, milk yield, and composition and blood profile) were analyzed with the period (week) as a repeated measure using the PROC MIXED method of SAS [27] and individual cows as the trial unit. The statistical model included the effects of supplementation, period, and their interaction (supplementation $\times$ period). To achieve normality, somatic cell count values were log-transformed (base-10 log) before analysis. Continuous parameter values at the end of the 14-day adaptation period were included as covariates in each of the respective data analyses. The significance level was set at a p -value of less than 0.05 ($p \leq 0.05$), and a tendency was accepted when $p \leq 0.10$ and >0.05 . In case of the existence of significant effects, means were compared using the least squares means probability of difference.

3. Results

3.1. Lactation Performance, Feed Intake, and Feed Efficiency

Figure 1 illustrates the daily milk yield of lactating Friesian cows fed with the experimental diets (control vs. FFS) over ten weeks. Despite the higher values observed in the daily milk yield in the FFS group compared to the control group during all weeks of the experiment (Figure 1), the treatment $\times$ period interaction was not significant. Daily milk production ($p = 0.01$) and solids-not-fat yield ($p = 0.05$) were significantly higher in cows that had received FFS compared to the control group (Table 2). In addition, 3.5% FCM, ECM, lactose and protein yields, and milk energy output tended to be greater ($p \leq 0.10$) in dairy cows that consumed FFS during the experimental period. No interaction effect between the treatment and period was noted for milk yield and composition (Table 2).

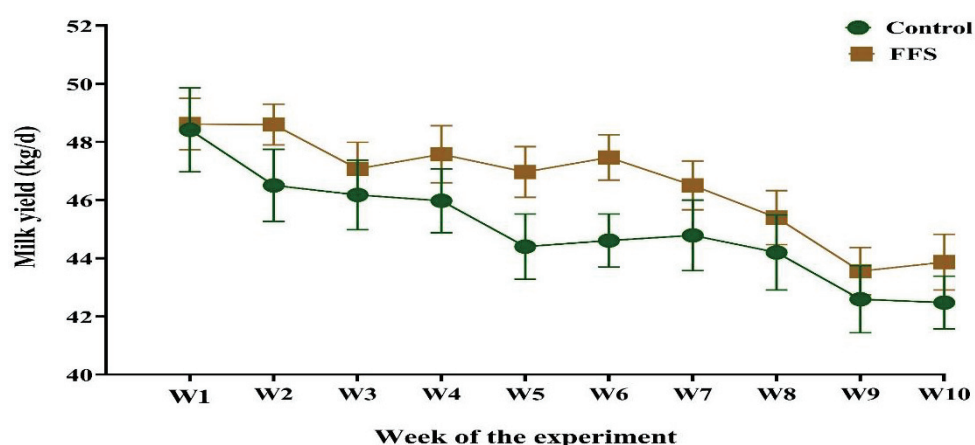


Figure 1. Milk yield of the lactating Friesian cows assigned to receive 35 g/cow/d of a functional supplement mixture (FFS group; $n = 30$), or not (Control group; $n = 30$), for 10 weeks. The supplement contained condensed tannins, essential oils, and pungent compounds (Actifor Pro; Delacon Biotechnik GmbH; Steyregg, Austria). The values shown are the means $\pm$ SE.

Table 2. Intake, milk yield, and composition of lactating Friesian cows fed a basal diet supplemented with a functional feed supplement mixture.

	Treatment		SEM	<i>p</i> -Value		
	Control	FFS		Treatment	Period	Treatment × Period
Number of cows	30	30	-	-	-	-
Production (kg/d)						
Milk	45.01	46.59	0.320	0.010	<0.001	0.918
Fat corrected milk 3.5%	34.77	36.43	0.743	0.100	<0.001	0.206
Energy corrected milk (ECM)	34.74	36.15	0.436	0.093	0.001	0.329
Total solids	4.98	5.04	0.057	0.512	<0.001	0.564
Solids-not-fat	4.03	4.14	0.030	0.050	0.091	0.946
Fat	0.93	0.99	0.029	0.285	0.001	0.184
Protein	1.50	1.55	0.011	0.051	0.030	0.943
Lactose	2.12	2.25	0.016	0.051	0.078	0.948
Ash	0.38	0.36	0.016	0.412	0.053	0.626
Milk energy output (MJ/d)	107.86	112.21	1.367	0.098	0.001	0.333
Milk composition (g/kg)						
Total solids	110.62	108.15	0.897	0.169	0.099	0.525
Solids-not-fat	89.48	87.46	0.311	0.349	<0.001	0.860
Fat	21.14	20.69	0.584	0.692	0.032	0.225
Protein	33.42	33.22	0.123	0.348	<0.001	0.869
Lactose	48.70	48.42	0.165	0.356	<0.001	0.859
Ash	8.42	7.60	0.317	0.200	0.206	0.715
Somatic cell count ($\times 10^5$)	3.68	2.85	0.55	0.452	0.395	0.049
Milk energy content (MJ/kg)	2.40	2.41	0.024	0.872	0.136	0.366
Dry matter intake (kg/d)	25.40	25.76	0.733	0.536	0.279	0.064
Feed efficiency						
Kg milk/kg DM intake	1.78	1.81	0.014	0.187	<0.001	0.011
Kg ECM/kg DM intake	1.37	1.40	0.018	0.361	<0.001	0.046

SEM: standard error of the mean. The basal diet based on 536 g of concentrates feed mixture/kg DM and 464 g forages/kg DM with no additive (Control group), or with the addition of 35 g/cow/d of functional supplement mixture (FFS group).

A significant treatment × period interaction was identified ($p \leq 0.02$) with respect to the milk efficiency and somatic cell count. Cows receiving FFS had a lower ($p = 0.049$) somatic cell count on weeks 6–8 of the experiment compared with those on the control diet (Figure 2A). In addition, the dry-matter intake tended to be higher ($p = 0.064$) in animals that consumed FFS during weeks 0–2 and 2–4 of the trial period (Figure 2B). FFS supplementation significantly increased the feed efficiency, expressed as ECM /DM intake ($p = 0.046$), and milk yield/DM intake ($p = 0.011$) on weeks 4–6 and 6–8 of the experiment (Figure 2C,D).

3.2. Blood Measurements

Most serum biochemical parameters were not changed ($p \geq 0.114$) between the FFS and control cows, including TP, GLO, BUN, CK, ALP, AST, GGT, Ca, PHOS, and Mg (Table 3). However, a greater concentration of serum ALB ($p = 0.007$) was detected in cows supplemented with FFS. There were no significant treatment × time interactions for the serum biochemical parameters. Interactions between treatment and time with respect to the concentrations of serum hepatic enzymes (ALP, AST, and GGT) were not detected ($p > 0.05$; Figure 3). In addition, the serum protein parameters BUN and CK were not significantly affected by interactions between treatment and time (Figures 4 and 5). The treatment × day interaction was also not significant for the major serum minerals measured (Figure 6).

Table 3. Blood biochemistry of lactating Friesian cows fed a basal diet supplemented with a functional feed supplement mixture.

	Treatment		SEM	<i>p</i> -Value		
	Control	FFS		Treatment	Period	Treatment × Period
Total protein, g/dL	8.05	8.21	0.060	0.154	0.004	0.578
Albumin, g/dL	3.65	3.80	0.024	0.007	0.039	0.599
Globulin, g/dL	4.41	4.42	0.053	0.813	0.081	0.803
Urea nitrogen, mg/dL	15.35	14.93	0.255	0.424	0.001	0.927
Creatine kinase, U/L	221.23	273.23	26.123	0.326	0.659	0.988
Alkaline phosphatase, U/L	40.06	38.66	1.158	0.628	0.568	0.956
Alanine aminotransferase, U/L	70.55	74.66	1.515	0.114	<0.001	0.566
Gamma glutamyl transferase, U/L	27.68	29.26	0.919	0.221	0.774	0.999
Calcium, mg/dL	9.42	9.34	0.042	0.417	0.530	0.928
Phosphorus, mg/dL	7.06	7.13	0.109	0.642	0.030	0.656
Magnesium, mg/dL	2.31	2.37	0.019	0.148	0.009	0.959

SEM: standard error of the mean. The basal diet based on 536 g of concentrates feed mixture/kg DM and 464 g forages/kg DM with no additive (Control group) or with the addition of 35 g/cow/d of a functional supplement mixture (FFS group).

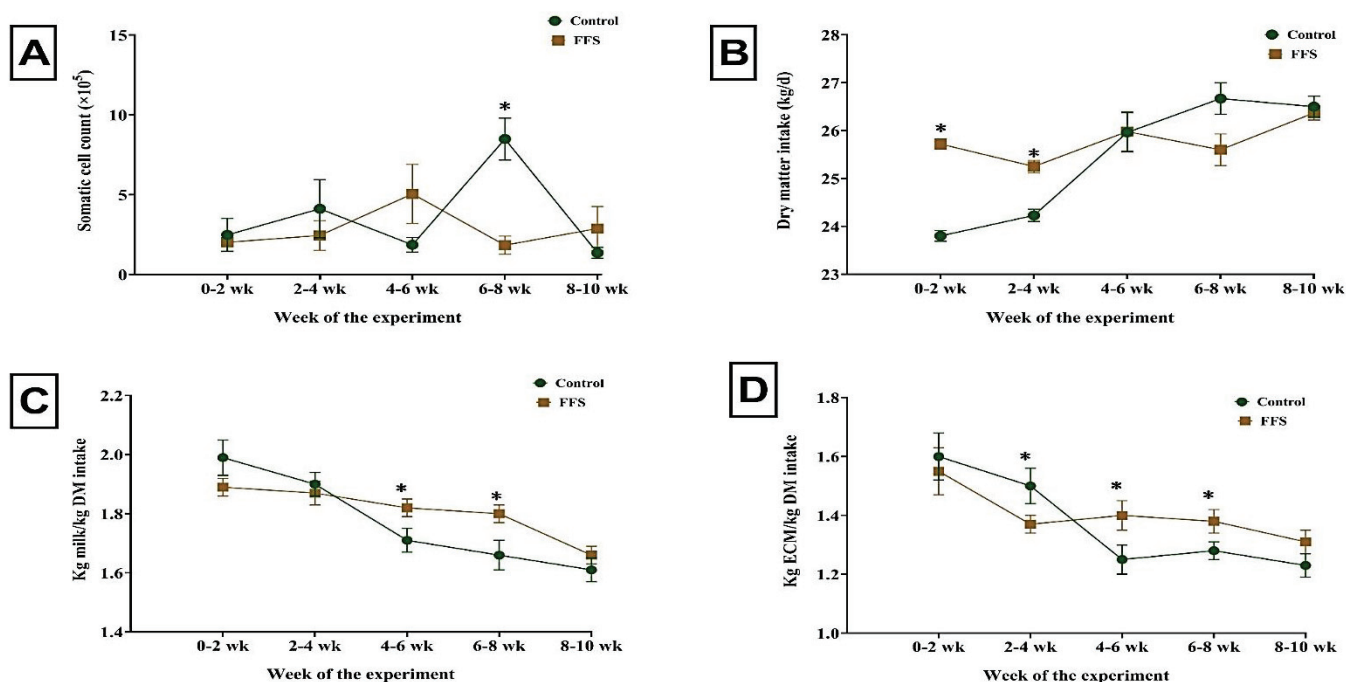


Figure 2. Somatic cell count (A), dry-matter intake (B), and feed efficiency (C,D) of lactating Friesian cows assigned to receive 35 g/cow/d of functional supplement mixture (FFS group; $n = 30$), or not (Control group; $n = 30$), for 10 weeks. The supplement contained condensed tannins, essential oils, and pungent compounds (Actifor Pro; Delacon Biotechnik GmbH; Steyregg, Austria). The values shown are the means $\pm$ SE. Treatment comparison within weeks; * $p \leq 0.05$.

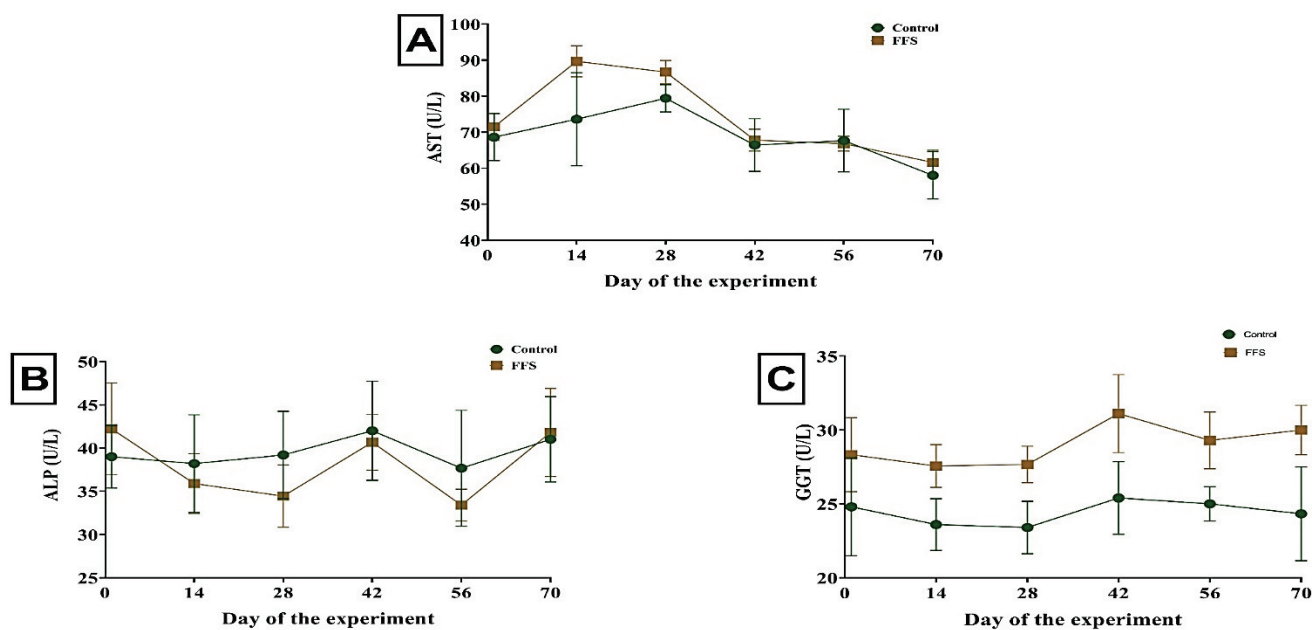


Figure 3. Changes in the activity of alanine aminotransferase (AST; (A)), alkaline phosphatase (ALP; (B)), and gamma glutamyl transferase (GGT; (C)) in the blood serum of lactating Friesian cows assigned to receive 35 g/cow/d of a functional supplement mixture (FFS group; $n = 10$), or not (Control group; $n = 10$), for 70 days.

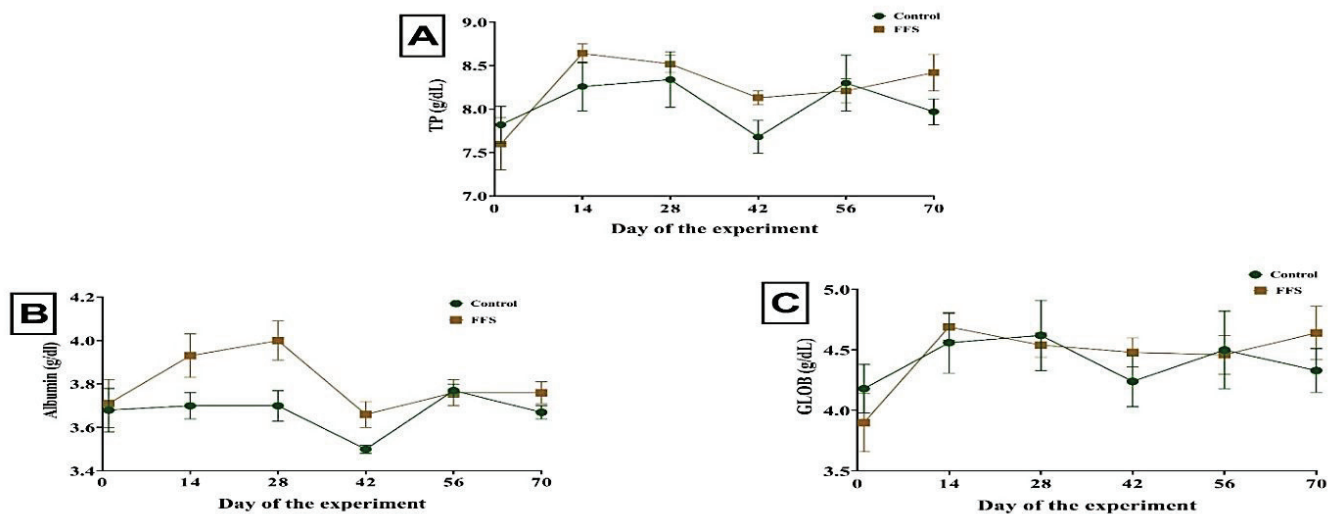


Figure 4. Changes in the concentrations of total protein (TP; (A)), albumin (B), and globulin (GLOB; (C)) in the blood serum of lactating Friesian cows assigned to receive 35 g/cow/d of a functional supplement mixture (FFS group; $n = 10$), or not (Control group; $n = 10$), for 70 days.

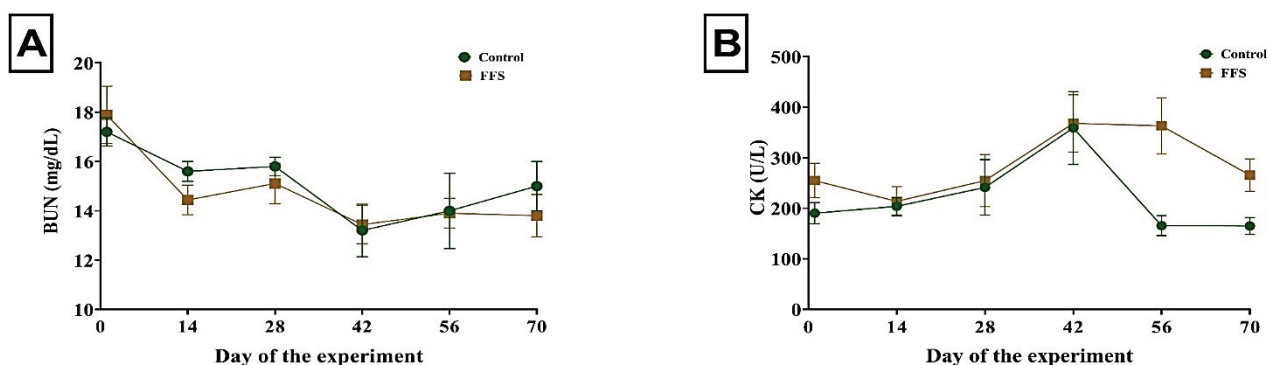


Figure 5. Changes in the blood urea nitrogen (BUN; (A)) concentration and creatine kinase (CK; (B)) activity of lactating Friesian cows assigned to receive 35 g/cow/d of a functional supplement mixture (FFS group; $n = 10$), or not (Control group; $n = 10$), for 70 days.

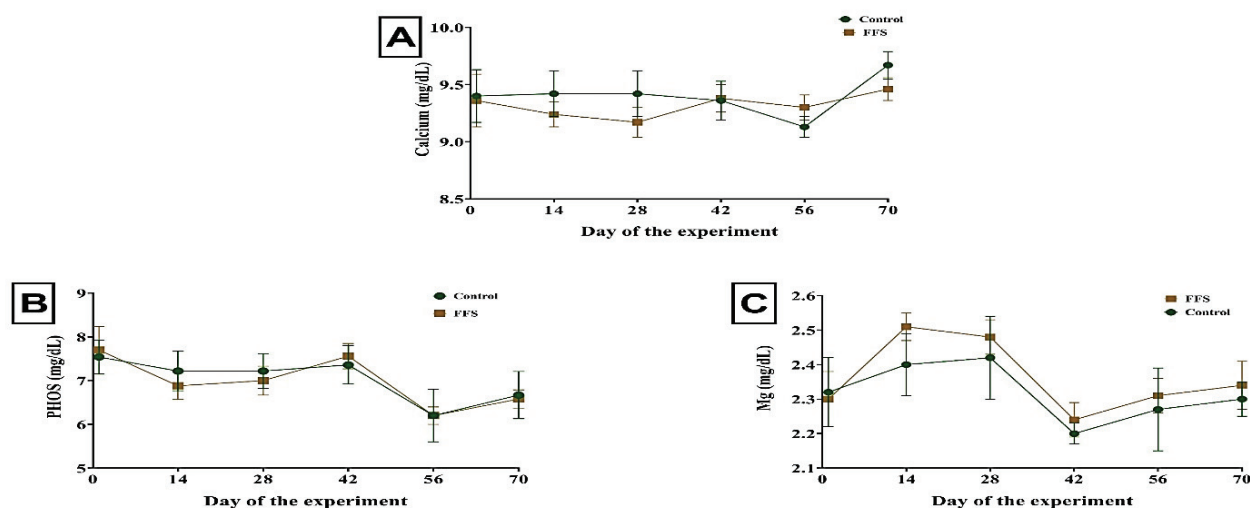


Figure 6. Changes in the concentrations of Calcium (Ca; (A)), Phosphorus (PHOS; (B)), and Magnesium (Mg; (C)) in the blood serum of lactating Friesian cows assigned to receive 35 g/cow/d of a functional supplement mixture (FFS group; $n = 10$), or not (Control group; $n = 10$), for 70 days.

4. Discussion

In the current experiment, lactating Holstein cows fed FFS-fortified diets had significantly greater milk production compared to those fed with control diets. The FFS-associated boost in milk production could be highly related to the biological activities of its ingredients. In this regard, the addition of 100 mg curcumin/kg diet for 15 days has a beneficial impact on the milk yield of lactating ewes [16]. Additionally, an obvious increase in milk production was recorded for cows fed diets fortified with an herb mixture comprising *Curcuma longa* [28]. Additionally, earlier studies found that adding an essential oil blend containing cinnamaldehyde to lactating cows enhanced milk yield [29,30]. The favorable impact of cinnamaldehyde in improving the rumen fermentation efficiency could be responsible for optimizing milk yield [31,32]. Additionally, in a recent study by Abulaiti et al. [33], capsaicin supplementation in Chinese Holstein dairy cows maintained milk production and composition. Furthermore, the increasing tendency in the dry-matter intake of lactating Holstein cows fed with FFS-fortified diets could also contribute to the enhancement of milk production [34].

Of note, in the current study, changes in not only the milk yield were observed by the addition of FFS to the lactating Friesian cows' feed, but also in the milk's composition. A significant increase in the solids-not-fat yield and an increasing tendency in the lactose and protein yields were recorded in Holstein cows fed FFS-fortified feeds compared with cows in the control group. However, a significant decrease in the somatic cell count was recorded

in the milk of cows of the FFS groups compared to control group. Similarly, supplementing lactating dairy cows with a blend of cinnamaldehyde, thymol, and orange peel increased the protein content of their milk [35]. Additionally, supplementing dairy ewes with a 100 mg curcumin/kg diet decreased the somatic cell count in their milk [16]. The anti-inflammatory and antioxidant actions of curcumin could act both in the mammary gland and systemically, controlling inflammatory responses and reducing inflammatory cells in milk [36,37]. Importantly, the presence of piperine in the formulation could potentiate the biological activities of curcumin [38]. Additionally, when capsaicinoids are injected postruminally, they trigger significant changes in the physiological responses linked to inflammation and milk yield in lactating cows [39]. Moreover, several research works have suggested that low somatic cell count values are correlated with increased milk production [40,41]—a finding observed in the current investigation.

Feed additives must be safe for the health and wellbeing of a cow to support her milk production and milk quality [42]. In the present study, several blood biochemical indicators were estimated to determine the safety of FFS as a feed supplement for dairy cows. Measurements of the serum activities of the hepatic enzymes AST, GGT, and ALP are considered as a reliable indicator of liver function in dairy cows [43–45]. Additionally, CK has been used as a screening parameter in the diagnosis of endometritis muscular damage or hypocalcemia in dairy cows [46]. The present data on serum AST, GGT, ALP, and CK show that no significant alterations exist in Holstein cows fed FFS-fortified diets compared to those fed control diets. Hence, the provision of FFS efficiently enhanced the cows' performance without affecting their liver function or muscle condition.

Serum levels of TP, GLO, and BUN have been extensively used in dairy animals to determine the amount of protein required for milk production [47]. The normal ranges that have been recorded demonstrate the optimal conditions for milk production. BUN levels may increase during water deprivation [48], thirst, diarrhea, urinary diseases [49], pregnancy toxemia [50], and acidosis [51], none of which were the case in the current study. Cows fed FFS showed higher serum ALB levels ($p = 0.007$) than those fed with the CON diet. This could be because cows fed with FFA have a tendency to increase their dry-matter intake, as observed in the current experiment—or, it could be due to an increase in the amino acid availability of cows fed with FFA. Waghorn, et al. [52] observed a significant increase in post-ruminal amino acid flux and intestinal amino acid availability as a result of feeding with condensed tannins.

Major blood mineral concentrations provide an indication of the health status of dairy animals. The role of macro minerals such as Ca, Phos, and Mg are more important than other minerals, and their balance in the body improves animal health, reproduction, and production performance [47]. Hypomagnesaemia or hypocalcemia in high-producing dairy cows increases the risk of some disorders such as milk fever [53]. Hypocalcemia reduces milk production and increases diarrhea and vagus indigestion due to the inhibition of feed intake [54]. Herein, serum mineral concentrations within the normal range reflect that animal diets contain an adequate amount of minerals [47].

5. Conclusions

Overall, the results showed that the dietary application of Actifor® Pro as a functional supplement mixture including encapsulated cinnamaldehyde, condensed tannins, capsaicin, piperine, and curcumin to Holstein lactating cows at 35 g/cow/day enhanced milk production and feed efficiency. Moreover, the functional supplement mixture increased blood albumin levels and had no negative effect on other blood measurements or milk composition. Further studies are recommended to evaluate the effects of functional supplement mixtures on the physiological and metabolic aspects of high-producing cows during the transition period.

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Article

A Qualitative Study of Irish Dairy Farmer Values Relating to Sustainable Grass-Based Production Practices Using the Concept of ‘Good Farming’

Orla Kathleen Shortall

James Hutton Institute, Aberdeen AB15 8QH, UK; orla.shortall@hutton.ac.uk

Abstract: Ireland’s grass-based dairy system is relatively unique in industrialised countries in its focus on producing milk from grazed grass rather than increasing yields through non-forage feed. The environmental benefits of a grass-based dairy system have been promoted within Ireland and abroad. However, the means by which grass is produced is important. There have been environmental concerns about water pollution from nutrient leaching and increasing greenhouse gas emissions from the increased number of cows and higher fertiliser application in the Irish dairy sector. This paper uses qualitative interviews with Irish dairy farmers to assess: (1) how can we understand Irish farmer attitudes towards the grass-based system within a ‘good farmer’ theoretical framework? (2) How do concepts of extensive and intensive production fit with good farming norms within the grass-based system? (3) How could cultivation of multispecies swards, including legumes, fit with existing notions of good farming? The research finds that there had been a concerted efforts by researchers, advisory bodies and other actors to foster a definition of good farming to mean good grass management. This definition of good farming excluded the use of feed inputs over a certain level to increase yields but included the use of fertiliser to maximise grass production. There is scope to change the definition of good farming within the industry to include minimal use of fertiliser, for instance through the cultivation of multispecies swards including legumes and the skills and knowledge this involves. In terms of policy implications, the paper identified three strategies for government and industry to facilitate a definition of good farming which involves low fertiliser use: emphasising the cost-saving aspect of reducing fertiliser; identifying visible symbols of ‘good farming’ using multispecies swards; and co-producing the definition of good farming with a diverse range of stakeholders including farmers.

Keywords: dairy; Ireland; grass; grazing; qualitative; greenhouse gas emissions; nutrient pollution; good farming

1. Introduction

The role of grass and grazing has decreased in importance in dairy sectors in many industrialised countries, with cows fed concentrate and grain and spending more time indoors to increase yields [1]. Ireland is something of an exception to this trend with 95–100% of dairy farms grazing [1]. Some 90% of Irish farms calve in spring, meaning milk can be produced from seasonal grass growth, and 90% of Irish dairy produce is exported in processed form which requires a high fat and protein content; this circumstance is suited to a grass-based system.

Researchers have argued that there is a need for better understanding of farmer attitudes towards grazing and measures that facilitate the uptake of grazing practices because of the environmental benefits of grazing [1]. Previous research has used surveys to explore attitudes towards grazing with farmers in Germany [2] and Denmark [3] and the adoption by Irish farmers of particular grass management technologies such as grass measurement [4,5], paddock grazing [6], grass budgeting [7] and the use of a spring

rotational planner [8]. This paper uses a theoretical framework grounded in research on ‘good farming’ [9] to add further depth to research on farmer attitudes toward grass-based systems. In addition, how grassland is managed affects nutrient cycling and environmental footprint [10,11]. This paper also explores farmer views of ‘extensive’ and ‘intensive’ grass management and how a potential lower-input grass-based practice of using multispecies swards fits with existing good farming ideals, where ‘intensive’ is taken to broadly mean agricultural production that uses more inputs and ‘extensive’ broadly involves fewer inputs [12].

As the next section describes in more detail, the Irish government and industry promote the environmental sustainability of the Irish dairy sector because it is grass based [13], but the recent expansion of the sector following the removal of EU milk quotas in 2015 has resulted in negative environmental outcomes [14]. Successfully reducing greenhouse gas emissions and nutrient leaching from the dairy sector will involve changes in practices by dairy farmers. This paper focuses on farmer attitudes and practices relating to the current grass-based system in Ireland and grass-management practices that have the potential to reduce greenhouse gas emissions and nutrient pollution, in particular the use of multispecies swards. A multispecies sward is one that includes herb and legume species as well as grasses. Legumes such as clover and sainfoin have the ability to fix nitrogen in the soil and thereby reduce the amount of fertiliser required, which reduces the resulting nitrous oxide emissions [15], and herbs such as chicory and plantain have deep roots to access minerals deeper in the soil and are more resistant to drought [16,17]. The use of perennial rye grass dominates the Irish dairy sector, making up 95% of grass seed sales [18]. In the 20th century, research and development focused on perennial rye grass because of its early spring growth, high digestibility and palatability for cattle, high dry matter content and ability to regrow after defoliation [19]. Fertiliser use to enhance the growth of perennial rye grass was incentivised by government subsidies beginning in the 1950s [18]. Fertiliser use led to a reduction in grassland diversity as most native grass species and herbs cannot compete with perennial rye grass when fertiliser is applied [18].

Social sciences researchers have examined how cultural factors influence the behaviour of land managers [20]. The concept of the ‘good farmer’ was developed to analyse the kinds of practices, identities and skills that are valued in different farming communities [9]. There are two main theoretical underpinnings to the good farmer concept: Pierre Bourdieu’s theory about economic, social and cultural capital and a symbolic interactionist perspective which looks at how people create and maintain meaning and identity within the social world [9]. According to Bourdieu’s conceptualisation, capital is accumulated labour in material or embodied form [21]. Economic capital is material assets which can be readily converted into money; cultural capital consists of embodied dispositions such as skills, cultural material goods and institutionalised goods such as qualifications; and social capital is the potential or actual resources that can be accessed through networks and ‘connections’ [21]. Being a good farmer means accumulating different kinds of capital within common ‘rules of the game’ [22]. This paper will use this framework of good farming as striving for different kinds of capital, which will be referred to in the results section. It is also worth noting that terminology used in the good farming literature varies: terminology of identities and different types of capital is widely used. This paper will also use the term ‘norm’, which is taken to mean an internalised value that is socially reinforced [23].

The early good farming literature consistently found that high production is a sign of good farming [24–26]. The good farming concept originally showed how valuing productivity meant that farmers were resistant to change towards environmental initiatives which might have reduced production [24,26]. Good farming symbols such as tidy fields [27] or healthy looking livestock [28] and identities are shaped by economic conditions [22,26]; technological development [9]; the influence of advisers [9,28,29]; and government policy [30–32] and are reinforced through ‘roadside farming’ where farmers look at their neighbours’ fields for symbols of good farming [24].

Policies incentivising production increases and technological innovation led to substantial changes in production methods in 20th-century livestock production, including breeding for higher yields, greater stocking density, more housing of animals to allow for greater control and increased use of purchased feed rather than grazing [33,34]. Productivist agricultural policy was replaced to some extent in the EU, or at least augmented since the 1990s, by the policy trajectory of multifunctionality or post-productivism [35]. This involves encouraging and supporting farmers to produce goods on farms other than commodities, such as diversification and environmental schemes, and supporting rural development [35] as a way around the ills caused by productivist ‘monofunctional’ agriculture [36,37].

Recent good farming literature has demonstrated how norms can and do change in response to changing market and policy landscapes and has shown a move away from productivist good farming identities. Because of reductions in production subsidies, farmers have in some cases responded to a difficult economic environment by reducing inputs and yields to reduce costs [22,38,39]. Environmental stewardship has also been documented as a good farming norm [30–32,38–41], although there may be a ceiling on farmers’ endorsement of environmental measures where they conflict with profitability [22, 31,39]. Productivist norms are still relevant as farmers are juggling different identities in the face of changing rules of the game [27,40,42]. While there is a wider debate within research on agriculture about the economic and environmental benefits of grazing [1], the good farming literature has not considered the role of grazing in livestock production systems. This paper addresses this gap within the Irish context by asking to what extent grass-based dairy farming is defined by farmer interviewees as good farming. The paper aims to contribute to debates within Ireland and in the literature on grazing more widely about how best to meet environmental objectives in dairy farming by analysing whether intensive or extensive grass production methods are considered to be good farming.

This paper uses qualitative interviews with Irish dairy farmers to assess (1) how can we understand Irish farmer attitudes towards the grass-based system within a ‘good farmer’ theoretical framework? (2) How do concepts of extensive and intensive production fit with good farming norms within the grass-based system? (3) How could cultivation of multispecies swards fit with existing notions of good farming? The analysis relates to the Irish dairy sector but is relevant to other contexts. The first question is in line with calls for more understanding of why farmers graze, in order to facilitate uptake of grazing practices, which are declining in many countries [1]. The last two questions consider the challenge of promoting sustainable grazing practices, which are relevant in contexts where the dairy industry is predominantly grass-based or where grass is used in addition to significant amounts of non-forage feeds.

2. Background

This section provides background on the Irish dairy sector to help the reader understand the origins of the farmer interviewees’ views on good farming presented in the results section. It explains why the Irish dairy sector has a unique focus on grass and the current environmental challenges the sector faces. The Irish dairy sector has recently undergone a period of significant expansion within the grass-based system following the removal of European Union milk quotas in 2015 [43]. Milk quotas stalled farm expansion and kept Irish dairy farms smaller than was considered economically optimal [44]. In the lead up to the removal of milk quotas, the Irish government set an ambitious target for the sector to increase milk production by 50% by 2020 [13]. This expansion was intended to happen through a continuation of the grass-based system: an increase in grass production and cow numbers [13]. Researchers at the Irish national food and research authority Teagasc argued that a system based on maximising milk from forage is the more economically rational [45,46]. A report written by two dairy industry stakeholders in 2015 cautioned that Irish farmers should keep to the grass-based system after milk quotas were removed and not increase yields through increasing purchased feed: ‘The greatest danger to realising this [grass-based] potential is that farmers will drift away from grazed grass as the

foundation for low-cost, profitable milk production and sustainable, profitable farm family incomes'. [45] (p. 7).

Ireland has a unique extension landscape with a single body, Teagasc, carrying out research, education and extension, alongside a number of private agricultural advisors [47,48], compared with the rest of Europe, where farm advisory services are characterized by increasing diversity and privatization [49]. Research and extensive at Teagasc have for decades promoted the merits of the grass-based system [50]. Teagasc developed a dairy manual which set out the principles of the grass-based system [51]. The software Pasture-Base Ireland was developed to facilitate farmers' grass management decisions, allowing them to benchmark themselves in a national database of grass production [52]. A Dairy Efficiency Programme run by Teagasc from 2010 to 2012 encouraged adoption of best practices in cow breeding, grass management and profitability [53]. Teagasc has an extensive knowledge exchange network of discussion groups used as means of sharing knowledge among farmers [54]. Despite these measures, researchers state that grass production varies widely across dairy farms and that further increases in production are needed, with many dairy farming only achieving 50–60% of what they could produce [46].

Targets for increasing milk production by 50% in 5 years were largely achieved with a 40% increase in milk production between 2014 and 2019 [45]. There were concerns from environmental groups when expansion targets were proposed that an expansion of the national dairy herd would conflict with environmental targets in relation to greenhouse gas emission, biodiversity, ammonia emissions and water quality [55]. The 2010 government Food Harvest 2020 report [13] and its successor, FoodWise 2025 [56], both set out commitments to economic and environmental sustainability. Food Harvest 2020 described Ireland's grass-based livestock production system as inherently environmentally friendly: 'Ireland's extensive, low-input grass-based production systems are the foundation of its green credentials [...] [2] (p. 5).

The Irish dairy system is seen as having lower greenhouse gas emissions per unit of produce than other countries: a European report showed Irish milk to have the lowest greenhouse gas (GHG) emission footprint in the EU [57]. Dairy farming is a source of a number of greenhouse gases: methane from enteric fermentation produced by the cow; carbon dioxide for embedded fossil fuels in feed, machinery use and loss of carbon from soils; and nitrous oxide from fertiliser and manure [58]. The carbon sequestered in grassland soils is seen as a factor making the Irish system more environmentally friendly than systems which buy in non-forage feeds, where soils tend to store less carbon or to emit carbon [57], although the topic of grassland carbon cycles is very complex, with claims that grassland may not sequester or may emit carbon depending on management [10].

Indeed, after continued dairy expansion, the Environmental Protection Agency made a bleak assessment of the environmental situation in 2019 in a response to a consultation for the agri-food strategy 2030. A report stated that the FoodWise 2025 strategy brought about intensification in production but not environmental protection. Evidence suggests that the intensification of farming has resulted directly in a deterioration in water quality, greenhouse gas emissions, biodiversity loss and ammonia emissions [14].

A report by the Department of Agriculture Food and Marine states that though emissions per unit of output decreased between 2015 and 2017, total greenhouse gas emissions from agriculture have increased, primarily because of the expansion of the dairy sector [59]. Ireland did not meet statutory 2020 climate change targets [60]. In relation to the expansion of the dairy herd, increased emissions have come from an expansion in cow numbers and use of inputs. Ireland has a derogation from the EU requirements for a maximum of 170 kg of livestock manure nitrogen per hectare to allow some farms 250 kg of livestock manure nitrogen per hectare. The number of farmers availing themselves of this derogation increased by 34% between 2014 and 2018 [59]. Fertiliser sales increased in 2017 and 2018, over 50% of which is used in the dairy sector [59]. Nitrogen fertiliser sales are projected to increase between 2020 and 2030 [59].

The Department of Agriculture, Food and the Marine set a target reduction of 50% of nitrous oxide emissions from fertiliser use by 2030 and a reduction of fertiliser use in Irish agriculture from its peak of 408,000 tonnes in 2018 to 350,000 tonnes by 2025 [61]. The Food Vision 2030 report commissioned by the Department for Agriculture, Food and the Marine set out a target of a climate-neutral agricultural system by 2050 with verifiable progress by 2030 [62]. The Ag Climatise strategy sets out grass management measures intended to reduce nitrous oxide emissions and water quality problems from the dairy sector including a requirement for clover in all grass reseeding by 2022 and a consideration of the use of legume crops [61]. There is also a government scheme that helps farmers with the costs of establishing multispecies swards [63]. A draft of the 2021 agri-food strategy received criticism for not being ambitious enough and for being a continuation of a model of agricultural intensification. The representative of the environmental group Environmental Pillar withdrew from the Strategy Committee prior to publication [64].

The research questions in this paper focus on the potential to meet environmental objectives for the Irish dairy sector through different grass management practices.

3. Materials and Methods

The research is based on qualitative interviews with dairy farmers in Ireland. Interviews, a qualitative research method, involves asking someone in-depth questions about what they do and what they believe [65]. The aim is to obtain detailed information on the interviewee's experiences and views on a particular topic. Qualitative interviewing involves carefully selecting a relatively small number of participants whose experiences are relevant to the research questions. The aim is not to generalise to a larger group of people, e.g., 'all dairy farmers think or do x', but to look in detail at the reasons why people do what they do and draw conclusions based on their circumstances [66]. Qualitative interviews were chosen because they were considered most appropriate for answering the wider project research questions about structural and cultural factors hindering or fostering change towards meeting policy objectives in the Irish dairy sector.

Ethical approval for interviews was obtained from the [removed for peer review] research ethics committee. Farmer interviewees were recruited through participation in a survey which was also carried out as part of the research project and which was disseminated between August 2018 and February 2019. In the survey, participants were asked if they were willing to take part in a follow-up interview. Out of 396 respondents to the survey, 92 indicated they were willing to be interviewed. Purposive sampling was used to interview people in a range of locations with different production systems and views [67]. The interviews were carried out in December 2019 and January 2020. All but one interview were carried out in person, so the aim of interviewing farmers in different locations was balanced with the logistical constraints of travelling to interviews within a given time frame. In total, 20 farmers were interviewed: 4 in the northeast, 2 in the midlands and 14 in the southwest of Ireland. The southwest was chosen as the location of the majority of interviews because this area has the highest concentration of dairy farmers in the country [68]. The number of interviews carried out was influenced by data saturation: the point at which no new information is being generated from additional interviews [69]. Notes were made after each interview to record the main findings to assess data saturation. The figure of 20 interviews is in keeping with the number of interviews normally carried out within qualitative research: for instance, McDonald et al. [7] carried out 8 narrative interviews with new entrants in addition to a survey; Regan et al. [4] carried out 21 interviews with farmers exploring their decisions whether or not to measure grass; and Kessler et al. [42] carried out 17 interviews with beef farmers in Canada on good farming values. All but one interviewee were male, as there were few female respondents to the survey. While the farmers interviewed are interested, motivated, engaged farmers because those are the people who are likely to fill in a survey and agree to be interviewed, their views speak to the wider culture in the industry as a whole. The interviews were semi-structured; there was an interview guide which was applied in a flexible way as farmers were asked

follow-up questions to elaborate on particular points. Farmer interviewees were asked to describe their farms, their views on the expansion of the dairy industry, challenges facing the dairy industry, views on grass-based and higher-feed-input systems and specifically about multispecies swards. Interviews lasted an average of 69 min, with the shortest being 36 min and the longest 124 min. Interviews were recorded and stored in a secure folder that was only accessible to the researcher. Interviews were sent to a third party for transcription. More details of the farmer interviewees' demographic details are shown in Table 1. The amount of concentrate farmers fed to cows is included because it indicates the extent to which they follow mainstream industry advice, from, for instance, the advisory body Teagasc, within the low-cost grass-based system to minimise concentrate use and maximise milk production from forage. The question was asked in terms of 'average' concentrate use over several years rather than in a given year. Some farmers answered in terms of concentrate given to cows per day at different times of the year, so different metrics are used in the table. Interview data were anonymised by giving the interviewees a number.

Table 1. Interviewee demographic information.

Farmer Pseudonym	Location	Cow Numbers	Amount of Concentrate Fed per Cow	Position on Farm	Gender	Relationship to Other Interviewees
F1	Northeast	460	1500 kg/year	Owner	Male	n/a
F2	Northeast	200	1000 kg/year	Owner	Male	n/a
F3	Midlands	180	7 kg/day in winter, 2–5 kg/day in spring/summer	Owner	Male	n/a
F4	Midlands	130	500 kg/year	Owner	Male	n/a
F5	Northeast	400	600–700 kg/year	Owner	Male	n/a
F6	Northeast	260	1200 kg/year	Owner	Male	n/a
F7	Southwest	200	800 kg/year	Manager	Male	n/a
F8	Southwest	80	No data	Owner	Male	n/a
F9	Southwest	170	650–700 kg/year	Owner	Male	n/a
F10	Southwest	200	800 kg/year	Owner	Male	n/a
F11	Southwest	250	2000 kg/year	Manager	Male	n/a
F12	Southwest	50	6 kg/day	Owner	Male	n/a
F13	Southwest	110	700 kg/year	Owner	Male	n/a
F14	Southwest	100	250–300 kg/year	Owner	Male	n/a
F15	Southwest	80	1700 kg/year	Owner	Male	n/a
F16	Southwest	80	>1500 kg/year	Owner	Male	n/a
F17	Southwest	75	700 kg/year	Owner	Female	Partner of F20
F18	Southwest	180	3 kg/year in summer	Owner	Male	n/a
F19	Southwest	130	500 kg/year	Owner	Male	n/a
F20	Southwest	75	700 kg/year	Owner	Male	Partner of F17

In the results section, the terms 'grass-based' or 'low-cost grass-based' are used to describe the system promoted by research and advisory bodies in Ireland of focusing on grass production as the engine of profitability and minimising concentrate use. The term 'higher-feed-input' describes a system where there is not a belief that concentrate use needs to be minimised. Initial analysis was carried out of the notes taken after each interview. These notes were used to assess when data saturation was reached: when no substantially new content is generated from subsequent interviews [69].

Interviews were transcribed and analysed using Nvivo 12 software. Thematic analysis was carried out [70]. Thematic analysis involves reading each transcript and coding parts of the text into themes. These themes are then read for patterns that emerge within and across them. The analysis was part of a project looking at the role of grazing and year-round housing in dairy sectors in the UK and Ireland. The coding covered themes beyond those reported in this paper relating to structural and cultural factors hindering or fostering change towards meeting policy objectives in the Irish dairy sector. The research questions for this paper and the results presented were identified through an iterative inductive and deductive process consulting good farming literature on environmental norms and literature about grazing in the dairy sector presented in the introduction.

4. Results

4.1. Grass Production and Management as Good Farming

The messaging coming from research and advisory services in Ireland that maximising the grazed grass in the cows' diet is a way to ensure profitability and operate a relatively simple system was described in the introduction. The introduction showed some of the work that has been done to communicate this philosophy to farmers: Teagasc's dairy manual, farmer discussion groups and the development of grass management software. This section asks whether and how messaging about the value of grass production and management has been converted into good farming norms and identities.

The farmers interviewed described the skills, knowledge and facilities associated with grass management and the grass-based system as 'good farming':

F7: 'Some farmers fall into high-input systems, because maybe they can't manage grass. With a low-input system, you need to have very high-quality grass. Some farmers are I suppose, refuse to be educated in grass measuring and that, that they just feed a lot of meal, and graze heavy covers during the summer, and cows milking well and they're happy. But it's non-profitable, it's not profitable.'

Here we see that in terms of the good farming theories of capital: 'high-quality grass', grass measurement and management skills and profitability are types of good farming cultural capital. A farmer would be judged by F7 as a 'good farmer' if they possess this type of cultural capital. According to this farmer, the issue is not that the practice of feeding more meal involves different types of cultural capital which belong to a different production system; rather, there is a deficit of cultural capital, which effectively makes a high-feed-input system unprofitable. Feeding more meal comes about because of a lack of investment by the farmer in the types of cultural capital associated with the grass-based system.

The use of grass was linked to profitability: several interviewees cited grass as a low-cost feedstuff:

F4: 'Grass is the cheapest possible input, we'll say that you can have for cows. So, therefore it should be used to its max.'

This point about reducing costs as part of good farming is further explored in Section 5.1 below. An interviewee described how the grass-based system came to Ireland from New Zealand and changed the way farmers related to grass: it was treated as important feedstuff that needed to be carefully measured and managed rather than something that was taken for granted.

Interviewees spoke about how their grass management practices have changed as a result over time.

F2: 'We measure grass. All the young farmers measure grass. I now know how to measure grass, you know, [laughs] we never did that before. [...] But now, the way they do it is so much better. Able to budget in front of them, knowing what you have in front of you for twenty-one days, whatever the cycle you're currently grazing in, and how to manage that. That's brilliant stuff.'

This farmer clearly values the grass management skills he and his team have acquired on their farm. Similarly, another farmer states that the principles of the grass-based system have been taught to farmers in the last 10–15 years:

F4: 'And in Ireland, that rhetoric of trying to get cows out for longer, to grass and everything's going on for ten or fifteen year, and there's some people only changing now.'

This farmer's comment that 'there's some people only changing now' shows that he thinks these people are late adopters, behind the curve of good farming. Farmers defined their system in terms of a focus on grass:

F5: 'It's pretty simple, we focus on growing grass as much if not more than actually on the cow itself.'

Interestingly, the farmers interviewed who identified as operating a higher-feed-input system emphasised the importance of grass and were not involved in separate social and information networks of farmers in the dominant grass-based system. A liquid milk producer states that he is not replacing grass with meal—he is supplementing it:

Interviewer: ‘And what made ye go down what you call the high-input sort of route in the Irish context, you know that’s high input for Ireland?’

F11: ‘I suppose traditionally going back to the earlier discussion about the milk, we were always in winter or liquid milk, so we always had a high yielding cow; we always fed the cow well and looked after the cow as a priority. That’s mainly it. Now I wouldn’t feed excessively either to the extent that you’re trying to replace forage with meal; you have to as I say back to profitability too, there’s no point in feeding a cow out there and she walking out in the field and lying on lovely grass, either. So there has to be a balance.’

A farmer made the point that the metrics used in the grass-based system, low concentrate use and a long growing season, can be detached from the aim of profitability and become aims in their own right because they bestow status on farmers:

F1: ‘So, once you’re performing and you’re farming for profit not for milk, or for ego in the grass system, the ego, what I’m saying is having cows out on the first of February, [laughter] feeding them no meal, and having them out on Christmas Day; there’s ego that way just as much as there’s ego in the high-input system, to have ten or twelve thousand litre cows.’

This farmer’s comments are wry, and he aims to point out the folly of farming for ‘ego’: aiming to build status according to the culture of the day rather than for profitability. The ‘good farming’ concept describes a similar mechanism at play: farmers aim to build status and succeed within the rules of their peer group. The research suggested that the principles of ‘good grass farming’ have successfully been established as the dominant culture of good farming among Irish dairy farmers because skills, knowledge and resources associated with the grass-based system are valued forms of cultural capital which bestow status on farmers.

4.2. *Intensive Grass Management as Good Farming*

The introduction showed a quotation from the Irish Government’s ‘Food Harvest 2020 report’ which described Irish grazing systems as ‘extensive’: ‘Ireland’s extensive, low-input grass-based production systems are the foundation of its green credentials [...]’ [13] (p. 5). In the quotation, extensive production is associated with environmental sustainability, but the research showed that ‘extensive’ grass management, taken to mean minimising inputs and not aiming to maximise grass production per hectare, is not considered ‘good farming’ in the Irish dairy sector. Rather, the interviewees suggested that a more intensive, productivist system of using inputs to maximise grass production per hectare within certain parameters was considered good farming. In addition to skills and knowledge about *how* to manage grass in dairy farming, the volume of grass produced was also considered part of ‘good farming’. Interviewees described their aim of producing more grass to produce more milk from the cows, which increases profits.

A farmer describes the change in norms that took place when Ireland entered into a grass-based system:

F8: ‘So now even, it’s still going back to yield because people are still . . . I won’t say blowing, but about their yields of grass. So, it’s gone from yields of milk or yields of beef or whatever, to yields of grass. And people make plenty noise about how much grass they’re growing now.’

Telling others about the volume of grass you produce is a way to displaying cultural capital and winning status. The rules of the game still create ‘productivist’ values but now focusing on volumes of grass rather than milk. According to this account, it is not the case

that a grass-based dairy system can be considered ‘extensive’ and higher-feed-input one ‘intensive’; rather, but both systems have the aim of maximising production, of grass or milk, respectively:

Interviewer: ‘And in your view what’s a good dairy farmer?’

F10: ‘[...] you can say performance wise, they must be hitting so many cows per hectare or so much milk solids per hectare, you know. But like look, they obviously have to be hitting within certain norms.’

Intensive, highly stocked dairy farms require fertiliser inputs to produce grass and in turn produce high volumes of manure per unit of land, both of which contribute to greenhouse gas emissions, ammonia emissions and water quality problems. A farmer who had some criticisms of Ireland’s grass-based system on environmental grounds states that not maximising grass production using inputs was considered a ‘low achievement’:

F8: ‘Now, we’ve all gone, conventional agriculture has gone completely natural to an automatic high-input system for forage structure. It’s not considered on a low-input basis because it’s seen as a waste of resources or as low achievement.’

By an ‘automatic high-input system’, the interviewee means using fertiliser to promote forage growth. This links use of inputs to good farming: not using inputs to maximise grass production from the land is not good farming. Interestingly, while the dominant story told in Ireland that a higher-feed-input system is expensive, inefficient and dependent on inputs which increased farmer’s running costs and capital costs, an intensive grass-based system using fertiliser to produce more grass was considered efficient ‘good farming’. A system involving maximising fertiliser inputs within legal parameters is seen by many interviewees as ‘good farming’, but it is also criticised on environmental grounds [64]. Government targets to reduce nutrient pollution and nitrous oxide emissions that involve a reduction in fertiliser use could conflict with current ‘good farming’ practice in the Irish dairy sector.

4.3. Potential for Low-Input Grass Management as Good Farming

This section will look at how the use of multispecies swards fits with current conceptions of ‘good farming’. Farmer interviewees were asked about their views on the potential of multispecies swards including clover to lower the fertiliser requirement of grass production on Irish dairy farms. The majority of dairy farmer respondents stated that they were interested in trying mixed swards, or a few had tried them, because they knew mixed swards could lower fertiliser use. A few interviewees also expressed misgivings about the amount of fertiliser that was currently used to drive grass production:

F19: ‘I can see huge potential for it [clover], huge potential for it. Obviously, the clover, it pulls the nitrogen from the atmosphere into the soil, and if it stops you spreading artificial fertiliser, sure there’s a huge benefit in it.’

F11: ‘We need to do a bit more reseeding and maybe incorporating clover or the mixed herbal leys or something; just try and get more with less fertiliser. Even just outside of that [the cost of fertiliser] like environmental as well like you know. There’s more organic ways of hopefully growing grass than having to be pumping a load of chemicals in too like.’

As well as the environmental benefits of reducing fertiliser use, farmer interviewees spoke about the production benefits of clover and mixed swards: milk production can be maintained or even increased with less fertiliser application. Farmers’ desires to farm in more environmentally friendly ways can be built on in policy and advisory initiatives, as expanded on below in Section 5.3.

Multispecies swards were described by interviewees as more challenging to manage than perennial rye grass, and interviewees felt that they currently lacked skills and knowledge. The management challenges were seen to stem from different grass species being suited to different types of ground, the potential of clover to cause bloat in cattle and

different growth rates of clover and perennial rye grass at different times of year. Farmers describe the complications of managing clover on their farm:

F7: 'There's three different types of ground, I suppose, in the one block; further down it's a very wet land, I suppose, clover mightn't survive in it. Here on the dairy block, it's dry; clover will survive. And then over in the middle there's both. So, I suppose the one thing we can't have is three different types of grazing mixes, because it's harder to manage. If there's cows going from just grass only to clover, you have problems with bloat, because cows will gorge on clover. You'd have to start putting up twelve-hour wires, and it's just harder management.'

The interviews suggested there was appetite for more environmentally friendly grass production practices, but there was a need for help developing skills and knowledge to make management possible. If there is a desire to promote grass management practices that involve less fertiliser use, the skills and knowledge needed to manage multispecies swards could in time be a higher value form of cultural capital than the skills and knowledge needed to produce perennial rye grass using fertiliser inputs to drive production. This point is expanded on below in Section 5.2. An environmentally conscious farmer reframes the use of fertiliser from a vital part of the grass-based system to a disruptive addition to natural nutrient cycling processes:

F8: 'And now obviously without getting into the microbiology, in any system if you add something in biology, something else goes ... if you add too much sugar to your diet it affects your insulin system, and you eventually can become diabetic because your body has stopped producing. Similarly, if you add a lot of nitrous to the cycle, the nitrogen cycle in the soil is interrupted and maybe made a bit redundant and diminished and whatever. So, there is an actual inhibiting quality to the nitrogen to the output, or to the functionality of the diversity of the multispecies forms.'

Here, he frames the use of fertiliser as not part of good farming because it diminishes the potential of the soil to cycle nitrogen naturally. Just as farmer 7 describes a higher-feed-input system as a system that a farmer might fall into it because of a lack of skills and knowledge to manage grass, here also, the use of nitrogen fertiliser is reframed from an essential part of the grass-based system to a disrupting and inhibiting input. He identified interest in multispecies swards as 'good farming':

F8: 'And the now most progressive ... I won't say, progressive is the wrong word, but the most aware or engaged dairy farmers are aware of multispecies swards by, I would say, an inordinate magnitude than they were twelve months ago.'

This farmer describes 'good farming' as engagement with multispecies swards, which shows a desire for change is in his definition of good farming.

5. Discussion

The results showed that the grass-based system in Ireland of maximizing milk from grass and minimising the use of bought in feed had successfully become identified with 'good farming', according to the farmers interviewed in this study. The skills and knowledge in grass management associated with the grass-based system were valuable forms of cultural capital. In relation to the environmental impacts of the grass-based system, while it was framed in a government report as 'extensive', these results suggest that 'extensive' production within the grass-based system would mean minimizing fertiliser use and having a low stocking rate, and these practices were not part of the dominant definition of good farming. The dominant definition of good grass-based farming was productivist and intensive: aiming to maximise grass and milk production from the land using fertiliser inputs, within legal parameters. Producing high volumes of grass could be taken as a demonstration of skill. Given that producing a high grass yield is dependent on using high volumes of fertiliser, government targets to reduce fertiliser use could conflict with

current productivist, intensive good farming norms in the dairy sector. This paper analysed views on the potential for the uptake of multispecies swards in grass management which could reduce fertiliser use. The results showed some appetite from farmers for reducing the environmental footprint of current grass management practices but perceptions of a deficit in skills and knowledge in how to implement multispecies swards.

The discussion will explore three areas in more detail: firstly, the potential to frame low fertiliser usage as good farming because it is cost saving; secondly, the potential for the skills needed to manage multispecies swards to be understood as good farming; and thirdly, the mechanisms by which these changes could come about.

5.1. Good Farming as Practices That Lower Costs

As described in Section 2, good farming ideals develop around production methods that are profitable in a given context [38]. The price of agricultural commodities and inputs, and the availability of agricultural subsidies, can influence whether ‘good farming’ means maximizing yields or reducing inputs and yields [9,22,30]. In the face of economic pressures, farmers may define ‘good farming’ as increasing production to achieve economies of scale or, alternatively, reducing inputs and lowering costs [38]. Research has shown that productivism is still important to farmers as a good farming ideal [40]. New-entrant Irish dairy farmer respondents to a survey rated maximizing production as the fifth-most important farming objective after objectives relating to profitability and quality produce [7]. According to farmer 8 quoted in Section 4.2, there had been a change in productivist values in the Irish dairy sector: yields of milk were replaced with yields of grass as a valued form of cultural capital in the grass-based system.

The development of the grass-based system is linked to profitability. Using feed inputs to increase milk yields is framed by research bodies in Ireland as high cost and uneconomical, whereas under current prices, increasing grass yields through application of fertiliser is seen as economical [43,46]. Running a profitable farm has been shown in other research to be part of a definition of ‘good farming’ [22,31,32]. The results here showed that interviewees linked good grass-based farming with profitability.

Messaging about the cost of inputs has been shown in other studies to trump productivist good farming ideals. Huttunen and Peltomaa [71] showed how policies aimed at encouraging Finnish farmers to use less fertiliser and optimize the timing and method of fertiliser application did succeed in creating good farming ideals around these practices. The policies inspired farmer to invest in knowledge and facilities need for reduced fertiliser application: ‘The changes in the policy have affected the fertilisation practices in ways that have helped in internalising the objectives behind the reductions.’ (p. 222). The government has set out a target to lower fertiliser use on Irish farms [61]. In order to achieve this policy target, advisory services could frame the economics of using fertiliser not only in terms of the current price of fertiliser but with respect to locking in to a system dependent on inputs with fluctuating prices, and the externalized costs of production, even if it means producing less. Given that the Russia-Ukraine conflict has resulted in an increase in fertiliser prices internationally [72], this finding is relevant to dairy sectors in other countries which are also highly dependent on fertiliser inputs.

5.2. Good Farming Skills and Knowledge

This research explored whether the philosophy of the grass-based system of minimizing concentrate feed and focusing on milk production from grass was translated into a commonly held definition of good farming among Irish dairy farmers. Skills and knowledge are forms of embodied cultural capital [73]. Given that managing multispecies swards requires new types of knowledge and skill sets compared with current best practice grass management, there is potential for these practices which lower fertiliser use to be identified as ‘good farming’ in the Irish dairy sector. Burton et al. (2008) state that there are three conditions for a practice to become identified as ‘good farming’: the practice must be

culturally relevant to farmers; there must be observable, visible results from the practice; and these results must be accessible to other members of the farming community.

In relation to the first criterion of cultural relevance, there is also research showing that environmental sustainability in and of itself is now a culturally relevant norm to many farmers, particularly if they have taken part in environmental schemes or changed to environmentally friendly forms of production [22,30,32]. Farmers in England recognized the skills needed to produce grass using less fertiliser as a valuable form of cultural capital on environmental grounds [30]. This was echoed by several interviewees' comments in Section 4.3 that they wanted to adopt grass management practices that involved less fertiliser use for environmental reasons. This adds to the body of international examples of farmers being aware of and concerned about their environmental impacts.

In addition practices which link production and environmental sustainability such as conservation tillage practices can be considered culturally relevant because they are still production focused but have the potential to bring about environmentally sustainable outcomes [74]. The same could be true of multispecies swards, which need not involve a reduction in grass production, but involve a reduction in the use of environmentally detrimental inputs.

The last two of Burton et al. (2008) criteria for a practice to be established as good farming are a visible demonstration of skill and that they must be accessible to other farmers, which can also be called 'roadside farming' [9]. A description of 'roadside farming' can be seen in the quote in Section 4.1 from farmer 1 that within the grass-based system farmers will try to have their cows out on Christmas day or the first day of February to farm for 'ego', i.e., gain status within the grass-focused 'rules of the game' when other farmers see this practice. Research has shown that certain practices lend themselves to visible demonstration better than others. For instance it could be difficult to include management of waterways in a definition of good farming because water course management may not produce visible symbols of good farming [39]. In contrast, conservation areas on farm can be valued by the farmer for the wildlife they produce [22,30,31] and displayed to visitors as indications of the farmers' commitment to sustainability [30,32] and taken as a sign of skill that a farmer can cultivate wildlife while producing food [32]. The Irish government has set out policy to increase the uptake of multispecies swards [61]. In order to meet this policy objective, visible symbols associated with successful cultivation of multispecies swards could be identified and used in knowledge exchange. Just as some interviewees saw practices associated with feeding more concentrate as reflecting a deficit in skills and knowledge, compared to the skills and knowledge needed in the grass-based system, the same could become true of practices of using multispecies swards which lower fertiliser use. While, as described in the background section, Ireland has a unique advisory landscape that allows for efficient exchange of consistent messaging, this finding about the value of cultural relevance and visible symbols of mixed sward cultivation are also relevant to international contexts with more diverse knowledge exchange landscapes [49].

5.3. Translation of Good Farming Ideals into Practice

The way in which a definition of good farming came to be understood as good grass management in the Irish dairy sector accords with literature on how good farming symbols and identities are produced.

As we saw in Section 2 good farming can be shaped by the development of technology [9]. Different technologies are integral to the operation of the grass-based system which are required for grass growth, grass measurement, grass budgeting, etc. [75]. Good farming ideals around the use of certain technologies do not always translate into practice however [31,42]. For instance McDonald et al. (2016) found that 80% of new entrant dairy farmers surveyed recognized grass budgeting as important to their farming needs, but 51% implemented it. Other factors can mean that practices which are understood to be beneficial are not implemented, such as time commitment and need to develop new skills [5]. Thus, in relation to multispecies swards, as the interviewees described, the ease of use and

management influence their decisions about whether or not to use them, in addition to how multispecies swards fit with good farming identities and ideals. The government industry report Food Vision 2030 called for more research on ‘Grass, herbs and fodder varieties that deliver required sward yields and longevity at lower levels of nitrogen application.’ [61] (p. 59). This could include research on farmer priorities in the usability of multispecies swards.

In relation to the influence of advisors and policy, as described in Section 1, there are a number of policy documents and initiatives aimed at bringing about sustainable dairy production practices [61,62,76]. Peer-to-peer deliberation and translation of extension advice are valuable ways to ensure that information becomes culturally relevant and understood in the context of farmers’ individual circumstances [75]. A study on new-entrant dairy farmers concluded that the more equal power dynamics are in a knowledge exchange relationship, the more potential there is for actors to meaningfully influence each other [77]. The good farmer concept is underpinned by questions about power: who has the power to define what a ‘good farmer’ is and for what purpose. ‘Good farming’ can be understood as prescriptions about how agriculture should be carried out by experts, or as a form of cultural resistance to change by farmers [9]. This could be borne in mind in the context of the future development of grass-based good farming ideals in allowing farmers to co-determine what ‘good farming’ is in the Irish context in tandem with scientists, industry stakeholders and farm advisers. The comments by farmer interviewees in Section 4.3 that they would like to see lower-input grass-management practices adopted could be a basis for shaping future grass-based good farming ideals. In terms of co-producing outcomes, the Irish government carried out public dialogue events ahead of the publication of the agri-food strategy 2030 [78], and the Signpost Programme involves a number of dairy demonstration farms to facilitate peer-to-peer learning on the environment [76]. Another option to include different perspectives in policy making is to commission a farmers’ group to carry out work on how to achieve environmental targets, similar to an initiative in Scotland [79]. These results have relevance to an international context because they provide greater understanding of farmer involvement in a grass-based system, as called for in previous research [1].

Qualitative interviews are a valuable method for gaining in-depth understanding of the factors that shape farmer decision making [20]. There are limitations to this method, however, as the in-depth nature of qualitative research limits the number of participants involved in the study. Purposive sampling was used to access interviewees with a range of perspectives from different areas, ages, production systems and values. Women were under-represented because participants were recruited from a survey which received the majority of responses from male farmers. The gendered aspects of farming are another area which has not yet been explored in depth using the good farming concept [9]. The majority of interviews took place in the southwest of Ireland. Including more female interviewees and interviewees in other areas of Ireland may have yielded different or additional insights to the ones identified in this paper. However, these results can be taken to indicate the prevailing attitudes towards good farming norms in Ireland and as providing insights for fostering sustainable production practices in other contexts.

6. Conclusions

Today, the environmental benefits of different ruminant production systems are debated, with claims about the environmental benefits of grass-based production over higher-feed-input systems [1,57]. This paper adds nuance to the discussion about environmental impacts by drawing attention to different production practices within the grass-based system. As the result of concerted industry and advisory effort, good farming norms in Ireland moved away from productivism focused on output of milk to productivism focused on outputs of grass. The research showed some appetite among farmers to reduce fertiliser use in grass production which could be built on to meet environmental policy aims. The paper identified three strategies for facilitating a definition of good farming which involves low

fertiliser use: emphasising the cost-saving aspect of reducing fertiliser; identifying visible symbols of ‘good farming’ using multispecies swards; and co-producing the definition of good farming with a diverse range of stakeholders including farmers. These results could be extended to other countries where there is an aspiration to foster a transition to more sustainable grass-based livestock production systems.

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Grosspeteranlage 5
4052 Basel
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