

Article

Environmental Impacts of Rice Intensification Using High-Yielding Varieties: Evidence from Mazandaran, Iran

Oriana Gava ^{1,*} , Zahra Ardakani ^{2,3,*} , Adela Delalic ⁴  and Stefano Monaco ⁵

¹ Research Centre Policies and Bioeconomy, Council for Agricultural Research and Economics, 50127 Florence, Italy

² Department of Agricultural Economics, Islamic Azad University, Qaemshahr Branch, Qaemshahr 4765161964, Iran

³ Department of Agricultural and Food Science, University of Bologna, 40126 Bologna, Italy

⁴ Department for Quantitative Economics, School of Economics and Business, University of Sarajevo, 71000 Sarajevo, Bosnia and Herzegovina; adela.delalic@efsa.unsa.ba

⁵ Research Centre for Engineering and Agro-Food Processing, Council for Agricultural Research and Economics, 10135 Turin, Italy; stefano.monaco@crea.gov.it

* Correspondence: oriana.gava@crea.gov.it (O.G.); ardakani.z@qaemiau.ac.ir or zahra.ardakani@unibo.it (Z.A.)

Abstract: This article aims to show the potential contribution of high-yielding rice varieties to achieve sustainable intensification in paddy farming, by focusing on a developing country. A comparative life cycle assessment of traditional vs. high-yielding varieties is carried out by comparing the area-based and yield-based results. Primary data are collected through a farm survey (49 farms in the Mazandaran province, Iran; spring 2018). The results highlight that high-yielding varieties can reduce the yield-scaled impacts. However, area-scaled impacts are subject to increase for most impact categories. Statistically significant trade-offs involve global warming potential (+13% per ha and −28% per t in high-yielding varieties) and fossil resource depletion (+15% per ha and −26% per t in high-yielding varieties). Pesticide management is the most alarming practice. High-yielding varieties increase pesticide consumption and related toxicity impacts both per t and per ha. This study is a new contribution to the literature by improving and broadening the mainstream productivity perspective of current life cycle assessment research about crop varieties. The lessons learnt from this study suggest that the trade-offs between yield-scaled and area-scaled impacts should be carefully considered by decision-makers and policymakers, especially in developing countries that, like Iran, are affected by the overexploitation of natural resources. Targeted policy and the development of farmer education and advisory services are needed to create the enabling conditions for farm management changes, including conscious use of production inputs while avoiding heuristics.

Keywords: life cycle assessment; hotspot analysis; functional unit; normalization; pesticides; toxicity



Citation: Gava, O.; Ardakani, Z.; Delalic, A.; Monaco, S. Environmental Impacts of Rice Intensification Using High-Yielding Varieties: Evidence from Mazandaran, Iran. *Sustainability* **2024**, *16*, 2563. <https://doi.org/10.3390/su16062563>

Academic Editors: Jacopo Bacenetti and Daniele Duca

Received: 1 December 2023

Revised: 1 March 2024

Accepted: 18 March 2024

Published: 20 March 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Understanding how to improve the sustainability and food security outcomes of staple crop production within planetary boundaries is paramount [1,2]. This is a global challenge especially in hotspot regions severely affected by climate change and the overexploitation of natural resources, and in developing countries characterized by high population growth rates [3]. The urgency of addressing these challenges is reflected by the United Nations' Sustainable Development Goals, i.e., goals 2 (zero hunger), 3 (good health and well-being), 6 (clean water and sanitation), 12 (responsible production and consumption), 13 (climate action), 14 (life below water), and 15 (life on land) [4].

Rice is one of the most important staple foods worldwide. Paddy farming systems are widespread in more than 100 countries and are a vital source of human livelihood, especially in developing countries in Asia [5,6]. While global rice production is requested to increase in the coming years to meet the world's population growth, the sustainability of paddy

systems is questioned, including their contribution to food security and farmers' income, due to their health and environmental impacts (e.g., water consumption for flooding, water and soil pollution, greenhouse gas emissions, toxicity) and vulnerability to climate change [7,8].

In developing countries, rice intensification through the use of high-yielding varieties has raised growing research interest, given its ability to reach the objectives of narrowing the yield gap while reducing the yield-scaled impacts of farming [9–12]. However, the substitution of traditional (TRV) with high-yielding (HRV) rice cultivars may increase the demand for production inputs (e.g., machinery, fertilizers) to achieve a higher expected yield [13–15]. More evidence from real-world farms is needed about the comparative environmental impacts of variety substitution (e.g., TRV vs. HRV), based on the evaluation of all production inputs and outputs over the life cycle, to highlight potential achievements and trade-offs between food security and overall sustainability outcomes [16–19].

Against that background, this study aims to compare the life cycle environmental impacts of the cultivation of TRV vs. HRV on a per yield and per area basis, by providing evidence from real-world paddy farming in Iran. The research method is life cycle assessment (LCA; ISO 14040:2006 [20], 14044:2006 [21]). Primary data were collected on a sample of farms that cultivate TRV or HRV in the province of Mazandaran (Qaemshahr district). Statistical analysis is used to support the delineation of an environmental profile for TRV and HRV and to highlight the trade-offs associated with variety selection and with the evaluation of area-based and yield-based impacts.

Different sustainability assessment methods embrace a life cycle approach (e.g., cost-benefit analysis, material flow analysis, environmentally extended input–output analysis, and life cycle assessment). Method selection depends on the aims and scope of the study (e.g., material flow analysis does not include an impact assessment, environmentally extended input–output analysis is an economy-wide assessment that is not suitable for micro-level assessments) [22–24]. This study uses LCA as it enables the generation of evidence about cause–effect relationships between field management and environmental impacts [25], which is of utmost importance for designing an environmentally friendly policy to boost the sustainability of rice supply [26,27].

Paddy farming in Mazandaran is a relevant case study for multiple reasons. It is the major rice-producing region in Iran [28]; therefore, improving the sustainability of paddy production would deliver beneficial outcomes at the local and country level [29,30]. In Iran, rice is the second most consumed cereal, after wheat, with 100 g white rice/person/day [31]. The domestic production (about 2 million t unpolished rice per year) is insufficient to meet the current demand (over 4 million t unpolished rice per year) [28,32]. Increasing domestic rice production is essential for national food security, while the country's population is projected to grow from 80 to 94–112 million by 2050 [33]. Reducing the difference between current and potential farm yields (i.e., closing the yield gap) while minimizing the negative environmental impacts is a significant challenge for developing countries to achieve food self-sufficiency and sustainability, especially in the driest geographical areas [34–36]. Iran is one of the countries where the sustainability of paddy rice is a matter of great concern, also due to its pressures on natural resources that are exacerbated by climate change [35]. Several critical environmental issues are affecting the country's agricultural sector: (i) it contributes greatly to and is heavily affected by climate change [37,38]; (ii) there is limited availability of land and water resources for agriculture [39,40]; agricultural land in major rice-producing regions is affected by heavy metals contamination, with increased cancer risk for the local population [41,42]; and (iii) the production and consumption of fossil fuels, chemical fertilizers, and pesticides contributes dramatically to the environmental burden of crop production [43]. Moreover, trade isolation due to international sanctions and self-sufficiency policies set serious limitations to food imports and exports [39].

The LCA method has been extensively applied worldwide to assess and compare multiple aspects of paddy rice production [44–48]. However, the LCA research about rice variety selection is not well developed. Especially, in Iran, the literature has concentrated on

the level of farm technology [49–51], the cultivation method [30,49], and the socioeconomic characteristics of farmers [52], to date. There are just very few studies about variety comparison: [53–55] carry out the assessment under experimental conditions, thereby failing to provide evidence about the real-world production context; and [56] focus on cover–crop–rice rotations, thereby failing to provide evidence on the baseline cultivation method in the area, i.e., rice monoculture [29]. Likewise, in other countries, LCAs of rice varieties are not widespread and show research gaps: [57] deliver a scenario-based assessment in Bangladesh based on official statistics, simulating different adoption levels of TRV and HRV, but fail to show the comparative impacts of the two variety groups; and [58] assess the life cycle greenhouse gas emissions of 14 commonly produced rice varieties (conventional, hybrid, genetically modified) in the USA, based on test plot data from across Arkansas, thereby failing to provide a comparative impact assessment, considering real-world farming conditions.

Most articles adopt a productivity perspective, showing just the yield-scaled impacts to indicate how different varieties alleviate the environmental impacts per unit of food produced. This approach is relevant to meeting the food security challenge; however, it fails to provide evidence about the overall environmental impacts of rice cultivation in a specific area and the trade-offs between yield-scaled and area-scaled impacts. While yield-scaled assessments can provide comprehensive overviews of the efficiency of alternative production choices (environmental impacts per unit supplied food), especially across space and time, area-scaled assessments deliver necessary and complementary evidence that could be used as a baseline against which to compare changes over time from potential rice intensification policies [29,58].

This study adds to the existing knowledge by bridging the identified knowledge gaps as follows:

- (i) Showing improved evidence from real-world conditions, by carrying out data collection and assessment at the farm level;
- (ii) Delivering a comprehensive impact assessment across the environment, ecosystems, and human health;
- (iii) Broadening the current research perspective to evaluate the trade-offs between area-scaled and yield-scaled impacts;
- (iv) Highlighting hotspots to improve the delivery of practice and policy recommendations.

The implications of the presented research are relevant not only to researchers but also to entrepreneurs and policymakers dealing with sustainable rice intensification in Iran and other developing countries, especially those severely affected by climate change and the overexploitation of natural resources [27,59,60]. The research findings feed into the science–policy–practice dialogue to foster the diffusion of sustainable intensification, by supporting the creation of synergies between scientific evidence, the design of targeted policy instruments, and the conscious adoption of farming practices on the ground [61]. This would contribute to the creation of the socioeconomic conditions for enabling crop management changes at the territorial level, towards agricultural resilience and the local population’s wellbeing [3,59].

The next section describes the case study area and details the methodological approach of the study and data sources. The Results section presents the empirical findings. In the following section, the findings are discussed by highlighting how the study achieved its stated objective and the related implications for future research and policy-making. The Conclusions provide a summary of the research findings and highlight the study limitations.

2. Materials and Methods

2.1. Case Study

This study was conducted in the Qaemshahr County (Mazandaran Province), on the Caspian coast (Figure 1).



Figure 1. Location of the case study area. Source: Authors' own elaboration.

Mazandaran is an important agricultural region, generating over 10% of the value added from agriculture at the national level [62]. Mazandaran is the core of Iran's rice farming, with 37% rice land area (about 150,000 ha utilized agricultural area), over 36% producers (about 150,000 farm holdings), and 38% produced quantity (about 750,000 t/year) at the national level [28]. Rice is cultivated mainly by smallholder farms, with traditional methods and low levels of mechanization, in paddy fields located in lowlands relatively close to the Caspian Sea [63–65], which has a climate-moderating role. Rice-producing areas have a humid Caspian climate, with hot summers and mild winters [14,66]. In Qaemshahr (location between 36° 21' N to 36° 38' N and 52° 43' E to 53° 3' E; elevation: 51 m a.s.l.; total area: 458.50 km²), the temperature ranges between −6 °C (few frost days) and 42.5 °C, with an average annual temperature of 16.2 °C. The average precipitation is 749 mm/year (mean relative humidity: 79%), ranging between 20 mm month^{−1} in July and over 130 mm month^{−1} in November [14].

In the case study area, farms cultivate traditional and high-yielding rice varieties in paddy fields, without rotations, with traditional varieties being the most widespread. HRV can deliver a 30% greater yield than TRV [67]. Therefore, recently, the adoption of HRV has been growing, especially to maintain farm profits as a response to yield losses due to climate change [68,69]. Tarom rice is the most widespread among traditional varieties [67,68,70]. Tarom is a group of locally adapted aromatic rice varieties, highly appreciated by local consumers, and benefiting from higher producer prices than high-yielding varieties. However, Tarom is subject to lodging and blast disease. Shiroodi and Neda are common high-yielding varieties. The main aim of the introduction of these varieties in Mazandaran was to meet the increased domestic demand to feed the growing population, while keeping quality features. Traits for tolerance to lodging and blast disease were introduced as well.

Paddy irrigation requires a large volume of water, i.e., 4 billion m³/year (about 26,000 m³/ha) in Mazandaran [28,71], to enable field flooding and to meet crop demand (about 5000 m³/ha consumed through evapotranspiration during the production cycle of rice in Qaemshahr) [72]. Water is supplied by a surface water network made of a system of traditional artificial ponds (*Ab-Bandans*) and dams (western and downstream part of the Tajan river basin), springs, and wells [71,73]. In Mazandaran, surface water is a significant source for paddy irrigation (about 33% of total water supply), which is primarily used (almost 70%) in upstream areas of the Tajan basin, then in downstream areas, a large

share of irrigation water for paddy fields is pumped from public and private wells (about 9000–11,000 m³/ha for the most widespread rice varieties) [71,74].

Rice cultivation practices do not usually differ between TRV and HRV. The case study area is vulnerable to salinity, so rice cultivation is enabled through a hardpan at about 30 cm depth to prevent upward salt transport [75,76]. Field preparation occurs between winter and early spring, and involves three rounds of mechanical plowing and harrowing, to break up the muddy soil. Then, fields are manured, and chemical fertilizers are applied. At the beginning of the spring, seeds are germinated in nest trays on a farm before transplanting (Figure 2).



Figure 2. Rice farming in Qaemshahr, Mazandaran (Iran). (a) Nest trays for seedling production; (b) transplanting; (c) rice plots; (d) harvesting. Source: Agricultural Jihad of Mazandaran, Qaemshahr branch.

Seedlings are manually transplanted at the 3–4-leaf stage on flooded fields. The use of chemical pest (insecticides, fungicides) and weed (herbicides) control is widespread. Especially, herbicides usually replace mechanical weeding for cost saving. Rice is harvested using combine harvesters. No post-harvest operations are carried out on farms, with paddy rice being sold in the local market.

2.2. Methods

LCA (ISO 14040: 2006, 14044: 2006) is a widespread environmental management tool utilized in the agri-food sector for the estimation of a series of impact indicators covering pollution and human and ecosystem health via a four-phase approach (i.e., goal and scope definition, life cycle inventory analysis, life cycle impact assessment, interpretation) [77]. This paragraph describes the empirical application of the LCA method to the present work. The software used for the analysis is SimaPro 9.3 (PRé Sustainability B.V., Amersfoort, The Netherlands).

2.2.1. Goal and Scope Definition

The goal of this LCA is to assess the cradle-to-farm gate environmental impacts of TRV vs. HRV cultivation in Qaemshahr (Mazandaran, Iran). Two functional units (FUs) are used as follows: (i) the occupation of 1 ha of paddy field for one year, to highlight the overall impacts of farming; (ii) the supply of 1 t paddy rice, to relate the environmental impacts to farm productivity. No allocation is needed as rice is the only product of the system. Figure 3 shows the system under study.

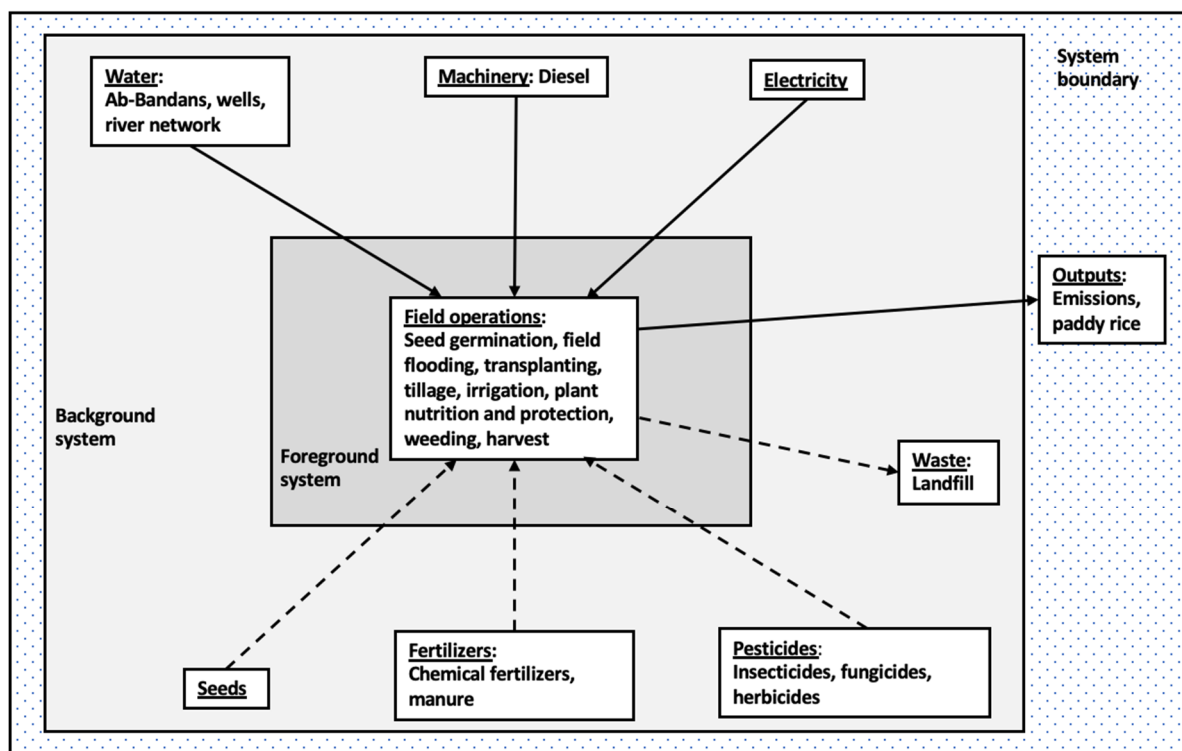


Figure 3. System boundaries of cradle-to-gate paddy rice production. Dashed lines: transportation. Source: Authors' elaboration.

The background system includes producing, manufacturing, and disposing of all the materials, resources, and energy used throughout the life cycle. The environmental burden of machinery production was not considered, as agricultural machinery is rented in the sampled farms. The foreground system is defined as using agricultural inputs for the set-up and management of the paddy field and the crop by farm labor, including ordinary tillage, seedling transplanting, distribution of fertilizers and pesticides, and harvesting. Transportation connects the seeds, fertilizers, pesticides, and waste stages to the foreground system. The outputs are emissions to the environment and paddy rice at the farm gate.

2.2.2. Life Cycle Inventory Analysis

This phase models the system under study by quantifying the production inputs and the outputs generated through their use to achieve the system's functions. A farm-level inventory was created by integrating primary data about foreground processes with background processes from the Ecoinvent 3.5 database, a cut-off approach [78].

(1) Data collection:

A farm survey was carried out in the spring of 2018 in collaboration with the Qaemshahr agricultural extension office (Agricultural Jihad). The research team set up a schematic questionnaire to collect quantitative data about the production inputs (i.e., area of paddy fields, cultivated variety and quantity of seed, duration of the cropping period, machin-

ery, energy, water, fertilizers, pesticides, purchase locations of production inputs, waste management) and outputs (i.e., gross and marketable rice yield).

The survey involved three stages, i.e., questionnaire design by the research team, face-to-face questionnaire administration, and review. Agricultural Jihad's officers were involved in the survey by taking care of questionnaire administration and supporting their review. The theoretical sample size was identified through the Morgan table [79]. The questionnaires were administered to 150 rice farm households in 4 districts (Khadamat, Koohsaran, Nowkandehkah, Aliabad-e-Tajan) of Qaemshahr. The response rate was 45% (68 farm households). Review meetings with respondents were then organized to cover information gaps and to correct mistakes. Just about 70% respondents participated in the review round, which led to a final set of 49 complete questionnaires for analysis, with an overall response rate of 33% (Table 1).

Table 1. Overview of the farm sample (49 observations). Summary statistics of yearly data. Source: Authors' elaboration.

Materials/Resources	Mean	Min	Max	Notes
Area (ha/farm/year)	1.35	0.2	10	Utilized agricultural area for paddy production
Seed (kg/farm/year)	71.7	13	400	Traditional rice variety = 37 farms High-yielding rice varieties = 12 farms
Water (m ³ /farm/year)	16,895	2500	150,000	Pumped water
Electricity (kWh/farm/year)	4416	654	39,205	
Machinery operation (h/farm/year)	20.2	2	200	
Diesel (L/farm/year)	287	30	1750	Diesel mass per unit volume = 0.84 kg/L
Nitrogen fertilizers, chemical (kg/farm/year)	159	9.22	1383	
Phosphorous fertilizers, chemical (kg/farm/year)	33.9	0	315	Urea, Ammonium Sulphate, 15-15-15 NPK, Simple Super Phosphate, Potassium Sulphate
Potassium fertilizers, chemical (kg/farm/year)	75.9	0	826	
Poultry manure (kg/farm/year)	9.80	0	200	
Polyethylene (kg/farm/year)	1.86	0	17	Packaging (seed, fertilizers, and pesticides); manufacturing: extrusion (bags), injection molding (bottles)
Transport distance (km/farm/year)	37.90	13	171	
Insecticides, active ingredients (kg/farm/year)	4.8	0	40	Diazinon 78%, Carboxin 25%, Thiram 25%, Fipronil 6%, Fenitrothion 17%
Fungicides, active ingredients (kg/farm/year)	3.37	0	9.3	Tricyclazole 35%, Propiconazole 31%, Tebuconazole 31%, Trifloxystrobin 31%, Iprodione 9%
Herbicides, active ingredients (kg/farm/year)	0.32	0	1.9	Butachlor 77%, Benzofuran methyl 64%, Oxadiazon 11%, Pretilachlor 7%, 2,4-DB 7%
Paddy rice, marketable (t/farm/year)	7.53	0.686	78.4	Production loss: 2.14%
Producer price (US\$/farm/year)	1517	191	14,833	1US\$ = 185,000 Iranian rial (2018)

The TRV is Tarom Hashemi (average cultivation period = 125 days; average harvest index = 35%); 37 farms adopt the variety. The HRVs are Shiroodi and Neda (average

cultivation period = 132 days; average harvest index = 42%) and are adopted by 12 farms. All three varieties are common in the case study area [64,80]; all farms use the same production inputs, regardless of the adopted rice variety.

The average area of the paddy fields is about 1 ha, as in similar research [49,50]. Purchased seeds are germinated on farms to obtain seedlings for transplanting. Rice (one cropping cycle/year) is produced using the alternate wetting and drying system [81]. Water supply is ensured by the *Ab-Bandans* system and by private and public wells. Through the *Ab-Bandans* system, water for field flooding circulates with no energy use. Collected data about water inputs refer to water pumped from private and public sources (electric pumps; 0.261 kWh/m³ on average). Farm household labor carries out most field operations, especially rice transplanting and applying fertilizers and pesticides. Agricultural machinery for field operations (e.g., land preparation, harvesting) is rented. Agricultural machinery has an average nominal power of 82 kW, with a mean power during fieldwork of 40 kW. Chemical fertilizers ensure crop nutrition: nitrogen (urea: 279 kg/year on average; ammonium sulfate: 29.6 kg/year on average), phosphorus (simple superphosphate: 160 kg/year on average), and potassium (potassium sulfate: 138 kg/year on average) fertilizers; one farm uses a triple fertilizer (NPK 15:15:15; 125 kg/year). Only three farms apply poultry manure (60% dry matter; 160 kg/farm/year on average). Almost all farms (43 out of 49) use herbicides, while insecticides and fungicides are used by a smaller number of farms, 33 and 23, respectively. Rice straw is not harvested and is incorporated into soil through tillage while preparing the land for the next cropping cycle. The harvested product is sold by farmers in local markets, with no intermediaries. Production inputs are purchased by farmers in Qaemshahr city and transported on farms using private pick-ups (gasoline fueled). Poultry manure is self-produced; therefore, no transport is considered. Waste includes plastic packaging of production inputs and is disposed of in the local landfill through a dedicated lorry (public service).

(2) Direct emissions:

Direct emissions from the foreground system are calculated for paddy fields, machinery, fertilizers, and pesticides (Table 2).

Table 2. Calculation of direct emissions to air, water, and soil. Source: Authors' elaboration.

Emission	Formula	Description	Reference	
Rice fields (to air)				
CH ₄ (kg/ha/yr)	= EF × t _{TRV,IRV}	EF (kgCH ₄ /ha/day) = daily emission factor t _{TRV,IRV} (days/yr) = cultivation period of each rice variety; TRV: traditional rice variety; IRV: improved rice variety	[82]	
		EF (kgCH ₄ /ha/day) = EF _b × SF _w × SF _f × SF _p × SF _s		
		EF _b = 1.3 kgCH ₄ /ha/day = baseline daily emission factor SF _w = 0.52 = scaling factor for water regime SF _p = 1 = SF for non-flooded season before the cultivation period SF _f = 0.68 = SF for field management before harvest SF _s = SF for the management of rice straw		
		SF _s = (1 + SQ × CF) ^{0.59}		
		SQ = straw quantity (t/year) CF = conversion factor for application (>30 days before cultivation) = 0.29		
		Machinery (to air)		
		CO, HC, NO _x		= ER _{CO,HC,NO_x} × ot
CO ₂	= DC × EF _{CO₂}	DC = diesel consumption (kg) EF _{CO₂} = emission factor for CO ₂ = 3120 g/kg _{diesel}		
PM _{2.5}	= EF _{PM_{2.5}} × 0.854 × MP × ot	EF _{PM_{2.5}} = emission factor for PM _{2.5} (g/kg _{diesel}) MP = mean power during fieldwork ot = total operation time (h)		
		EF _{PM_{2.5}} = 7.25 – 3.62 × nominal power ^{0.1}		
Fertilizers (to air)				
N ₂ O	= 0.01 × N _{fc} + 0.02 × N _m + 0.003 × (N _f + N _m)	N _f = total N applied with fertilizers N _{fc} = N applied with chemical fertilizers N _m = N applied with manure N _u = N applied with urea	[82]	
NH ₃	= 0.08 × N _f		[84]	
NO _x	= 0.21 × emissions of N ₂ O		[83]	
CO ₂	= 0.2 × N _u		[82]	

Table 2. Cont.

Emission	Formula	Description	Reference
Fertilizers (to water)			
NO ₃ ground water	= 0.3 × N _f	N _f = total N applied with fertilizers	[85]
P surface water	= 0.07 × P _f	P _f = total P applied with fertilizers	
P ground water	= P _{er} × (CF _{cf} + CF _m)	P _{er} = phosphorus loss via erosion = 0.175 kgP/ha/yr	[83]
		CF _{cf} = correction factor for P, as a quantity of P ₂ O ₅ applied with chemical fertilizers	
		CF _m = correction factor for P, as a quantity of P ₂ O ₅ applied with manure	
		CF _{cf} = 0.2/80 × P ₂ O ₅	
		CF _m = 0.4/80 × P ₂ O ₅	
Pesticides			
to air	= 10% active ingredient		[86,87]
to water	= 8.5% active ingredient		
to soil	= 76.5% active ingredient		

In paddy fields, methane (CH₄) is released into the atmosphere due to the anaerobic decomposition of organic material during flooding. CH₄ emissions to air are calculated based on the IPCC method, Tier 1 [82]. Emissions to air from diesel consumption by machinery during field operations are calculated based on [83]. Significant emissions are considered as follows: carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), carbon dioxide (CO₂), particulate matter (PM_{2.5}) [52,88]. The use of chemical fertilizers and manure generates emissions mainly due to nitrogen and phosphorous nutrition, as follows: emissions to air are CO₂ from urea application, dinitrogen oxide (N₂O), ammonia (NH₃), NO_x; emissions to water are nitrates (NO₃) to groundwater and phosphorous (P) to surface and groundwater. Estimating emissions from pesticide application relies on the assumption that most active ingredients are emitted into the soil [86,87].

2.2.3. Life Cycle Impact Assessment

This phase includes classifying emissions and resource consumption into impact categories and characterizing impacts using specific characterization factors. Characterization factors (CF_{*i,j*}) represent the potential contribution of emissions (E_{*j*}) or resource consumption (R_{*j*}) to the impact categories (IC_{*i*}) they are classified to as follows:

$$IC_i = \sum_j (E_j \text{ or } R_j) \times CF_{i,j}$$

Characterization factors are calculated via quantitative models at the midpoint or endpoint level, for individual impact categories. Characterization factors are dimensionless numbers expressing the strength of certain amounts of specific substances relative to 1 kg reference substance to one specific environmental compartment, for all impact categories except LU, for which it is the area and time integrated for one type of land use [89]. Life cycle impact assessment methods collect characterization models for multiple impact categories [90]. Various life cycle impact assessment methods exist, mainly based on characterization models developed for Europe [91]. In this study, the ReCiPe 2016 midpoint life cycle impact assessment method was selected, as its characterization factors are representative for the global scale and, at least some of them, at the country scale [91]. Midpoint categories were selected against endpoint ones due to better consensus characterization methods, lower statistical uncertainty, and better coverage of impact pathways [90,92].

The ReCiPe 2016 method adopts value choices and provides three sets of characterization factors that group different sources of uncertainty and different assumptions and choices, including the time horizon for long-living pollutants, into three cultural perspectives [89], as follows:

- (1) Individualist: short-term interest (20-year time horizon), impact types that are undisputed, and technological optimism with regard to human adaptation;
- (2) Hierarchist: scientific consensus on the time frame (100-year time horizon) and plausibility of impact mechanisms;
- (3) Egalitarian: precautionary perspective, the longest time frame (1000-year time horizon), and all impact pathways for which data are available.

This study uses the Hierarchist perspective (H), as in most of the literature [93].

Huijbregts et al. [89] provide detailed information about the impact pathways in the ReCiPe 2016 method, the description of impact categories, and modeling steps of individual characterization factors (including classified emissions to the different compartments), as well as more insights about value choices for operationalizing the three cultural perspectives.

All ReCiPe 2016 midpoint (H) impact categories are assessed in this study, except for water consumption (Table 3).

Table 3. Midpoint impact categories used in this study (ReCiPe 2016). Source: Authors’ elaboration, based on [91].

Characterized Impact Categories (Abbreviation)	Unit of Measure
Global warming potential (GWP)	kg CO ₂ -eq
Ozone depletion (OD)	kg CFC11-eq
Ionizing radiation (IR)	kBq Co-60-eq
Photochemical oxidant formation: human health (OF-hh)	kg NO _x -eq
Fine particulate matter formation (PM)	kg PM2.5-eq
Photochemical oxidant formation: terrestrial ecosystems (OF-te)	kg NO _x -eq
Terrestrial acidification (AC)	kg SO ₂ -eq
Freshwater eutrophication (FE)	kg P-eq
Marine eutrophication (ME)	kg N-eq
Terrestrial ecotoxicity (TET)	kg 1,4-DCB
Freshwater ecotoxicity (FET)	kg 1,4-DCB
Marine ecotoxicity (MET)	kg 1,4-DCB
Human toxicity: cancer (HCT)	kg 1,4-DCB
Human toxicity: non-cancer (HnCT)	kg 1,4-DCB
Land use (LU)	m ² × yr annual cropland-eq
Mineral resource scarcity (MRS)	kg Cu-eq
Fossil resource scarcity (FRS)	kg oil-eq

The water consumption impact category was excluded from the assessment, despite its relevance for paddy farming sustainability, as it was not possible to gather specific farm-level data about the volume of water consumed by the crop and not released back to the source, which is required for inventory building [94]. Secondary data about the estimated evapotranspiration of the crop (TRV, HRV) could be used instead. Those data generally consider adopting the best management practices for the specific cultivated varieties, including irrigation water. However, such different management could not be highlighted in the farm survey.

2.2.4. Interpretation

The existence of significant differences in farm management (use of production inputs and related outputs) and characterized impact categories was tested between TRV and HRV per each FU through *t*-tests or Mann–Whitney U-tests, depending on the result of the Shapiro–Wilk test for normal distribution. The software used for statistical analysis was IBM SPSS Statistics version 20 (IBM Corp., Armonk, NY, USA).

A literature review was carried out to facilitate result comparison with published studies (Appendix A).

Contribution analysis and normalization were carried out to identify hotspots using mean values for TRV and HRV [95]. Normalization is an optional step of the life cycle impact assessment phase that compares the magnitude of characterized impacts according to reference information, hence estimations of annual world per capita emissions. Normalization can support the interpretation and communication of the impact assessment results of a single product system by comparing them with a reference situation that is “external” to the case study, thereby enabling the evaluation of the relative importance of the results per impact category, i.e., the identification of hotspots [96]. Normalization involves dividing the characterized results by the annual contributions of an average person, thus expressing the results in person equivalent rather than using the specific units of measure of each impact category, which can deliver more concrete information for policymakers

and decision-makers [97]. Sets of normalization factors for Iran across different years are available from the literature, but just for a few impact categories [98,99]. As a comprehensive set of normalization factors is not available for Iran, the “world” normalization references included in the life cycle impact assessment method were used, as in similar research [100,101].

A sensitivity analysis was carried out to highlight the effect of the methodological choices on the impact assessment results, as in similar research [30]. Impact sensitivity to cultural perspective selection within the ReCiPe 2016 method was analyzed.

3. Results

3.1. Farm Management

In general, inventory data are in line with the literature, e.g., the quantity of seeds [52,102,103], water [102], diesel [30,52,104], fertilizers [55,104], pesticides [30,104], and electricity [50,102] (Tables 4 and 5).

The consumption of the production inputs, paddy yield, and producer price differs significantly between TRV and HRV, considering both the area-based and yield-based FUs. Paddy yield per ha is consistent with similar research [102,103,105] and significantly greater in HRV (+51%) than in TRV [55,56]. The significant differences between TRV and HRV are more marked when 1 t is used as the FU. Paddy yield per ha is significantly greater in HRV (+51%) than in TRV; also, HRV consumes more fertilizers and pesticides on a per area basis, with about +40% nitrogen fertilizers per ha, +70% potassium fertilizers per ha, and almost three times the quantity of insecticides per ha. The greater fertilizer consumption per ha in HRV might be justified by higher expected yields and higher removal of nutrients, as suggested by unobserved differences between the two variety types when compared using the mass-based FU. Cultivating HRV instead of TRV significantly reduces seed consumption, pumped water, electricity, diesel, machinery operation time, and herbicides per t yield (−33% to −40% reduction). In comparison, insecticide quantity is still greater in HRV than in TRV (+135%).

Producer price on the local market is significantly lower for HRV than for TRV, both per ha paddy field (−16%) and per t yield (−45%). Refs. [30,106] report an average farmer price per t paddy yield to align with this study, while [52] note a more significant figure.

3.2. Environmental Impacts

The results confirm previous research, especially concerning GWP [50,102,105], OD [103]; PM [54], AC [103], FE [53,54,104], ME and TET [103], FET [104], MET [54,104], LU [56], and FRS [54,104] (Tables 6 and 7).

As expected from the inventory data analysis, rice variety selection markedly affects most impact assessment results, with statistically significant differences between the two farm groups across the two functional units. The area-scaled impacts differ significantly between HRV and TRV for all impact categories but OF-hh, OF-te, and LU. The impacts per ha are always higher for HRV than TRV. The impacts per t paddy yield differ significantly between the two variety groups for most impact categories. HRV displays significantly lower impacts than TRV concerning GWP, OF-hh, OF-te, FE, LU, and FRS. However, toxicity impacts and MRS are still more remarkable for HRV than TRV. Statistically significant trade-offs emerge from using the two FUs for two impact categories: HRV raises GWP and FRS per ha (+13% and +15%, respectively) while reducing them per unit mass (−28% and −26%, respectively). GWP primarily originates from methane emissions during rice cultivation (almost 80% CH₄ emissions): on average, TRV emits 87 kgCH₄/ha and 21 kgCH₄/t, and HRV 93 kgCH₄/ha and 13 kgCH₄/t. Other relevant elementary flows for GWP are emissions from machinery (production and direct emissions during field operations) and electricity production from fossil resources (natural gas, petroleum) to enable water pumping, as in similar research [107].

Table 4. Inventory data. Functional unit = 1 ha paddy field; TRV = traditional rice varieties; HRV = high-yielding rice varieties; t = *t*-test; U = Mann–Whitney test. Statistical significance: $p < 0.05$. Source: Authors’ elaboration.

Materials/ Resources	Traditional Rice Variety			High-Yielding Rice Variety			Test Results	Significant Difference
	Mean	St. Dev.	Median	Mean	St. Dev.	Median		
Seed (kg/ha/yr)	60.46	11.69	60.00	55.73	9.45	60.00	$U(N_{\text{TRV.}} = 37, N_{\text{HRV.}} = 12) = 180.00, z = -1.01, p > 0.05$	No
Water, pumped (m ³ /ha/yr)	11,956.52	1288.08	12,000.00	12,120.37	1564.52	12,000.00	$U(N_{\text{TRV.}} = 37, N_{\text{HRV.}} = 12) = 218.00, z = -0.09, p > 0.05$	No
Electricity (kWh/ha/yr)	3108.70	334.90	3120.00	3151.30	406.77	3120.00	$U(N_{\text{TRV.}} = 37, N_{\text{HRV.}} = 12) = 218.00, z = -0.09, p > 0.05$	No
Diesel consumption (L/ha/yr)	242.06	79.16	250.00	232.60	73.46	210.00	$U(N_{\text{TRV.}} = 37, N_{\text{HRV.}} = 12) = 201.00, z = -0.49, p > 0.05$	No
Machinery operation (h/ha/yr)	14.17	5.62	12.86	13.50	5.44	12.67	$t(47) = 0.361, p > 0.05$	No
Nitrogen fertilizers (kg N/ha/yr)	101.81	66.84	76.80	140.60	48.40	138.25	$U(N_{\text{TRV.}} = 37, N_{\text{HRV.}} = 12) = 123.00, z = -2.31, p < 0.05$	Yes
Phosphorus fertilizers (kg P ₂ O ₅ /ha/yr)	21.55	10.96	21.00	27.28	7.97	23.33	$U(N_{\text{TRV.}} = 37, N_{\text{HRV.}} = 12) = 160.00, z = -1.46, p > 0.05$	No
Potassium fertilizers (kg K ₂ O/ha/yr)	38.01	28.44	36.70	64.62	21.40	65.06	$U(N_{\text{TRV.}} = 37, N_{\text{HRV.}} = 12) = 104.00, z = -2.79, p < 0.05$	Yes
Insecticides, active ingredients (kg/ha/yr)	2.90	7.08	1.20	10.63	12.83	5.22	$U(N_{\text{TRV.}} = 37, N_{\text{HRV.}} = 12) = 85.00, z = -3.22, p < 0.05$	Yes
Fungicides, active ingredients (kg/ha/yr)	0.39	0.61	0.05	0.06	0.16	0.00	$U(N_{\text{TRV.}} = 37, N_{\text{HRV.}} = 12) = 258.50, z = -1.60, p > 0.05$	No
Herbicides, active ingredients (kg/ha/yr)	3.44	2.34	3.00	3.16	1.94	3.60	$t(47) = 0.35, p > 0.05$	No
Paddy yield (t/ha/yr)	4.52	1.24	4.12	6.87	0.95	6.86	$U(N_{\text{TRV.}} = 37, N_{\text{HRV.}} = 12) = 43.50, z = -4.15, p < 0.001$	Yes
Price (\$)	1136.08	391.10	1001.19	950.11	397.30	741.65	$U(N_{\text{LYV.}} = 37, N_{\text{HRV.}} = 12) = 123.00, z = -2.30, p < 0.05$	Yes

Table 5. Inventory data. Functional unit = 1 t paddy yield; TRV = traditional rice varieties; HRV = high-yielding rice varieties; t = *t*-test; U = Mann–Whitney test. Statistical significance: $p < 0.05$. Source: Authors' elaboration.

Materials/Resources	Traditional Rice Variety			High-Yielding Rice Variety			Test Results	Significant Difference
	Mean	St. Dev.	Median	Mean	St. Dev.	Median		
Seed (kg/t/yr)	14.07	3.76	13.26	8.36	2.19	8.75	$t(47) = 6.45, p < 0.001$	Yes
Water, pumped (m ³ /t/yr)	2773.53	551.26	2834.47	1780.33	220.51	1738.06	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 23.50, z = -4.62, p < 0.001$	Yes
Electricity (kWh/t/yr)	687.76	74.09	690.27	458.70	59.21	454.15	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 0.00, z = -5.19, p < 0.001$	Yes
Diesel consumption (L/t/yr)	57.00	22.58	58.07	35.18	14.91	29.39	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 94.50, z = -2.69, p < 0.05$	Yes
Machinery operation (h/t/yr)	3.20	1.17	3.19	1.97	0.81	1.77	$t(47) = 3.38, p < 0.05$	Yes
Nitrogen fertilizers (kg N/t/yr)	23.78	17.51	16.79	20.64	7.12	20.15	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 201.50, z = -0.48, p > 0.05$	No
Phosphorus fertilizers (kg P ₂ O ₅ /t/yr)	4.86	2.47	4.76	4.00	1.18	3.74	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 159.50, z = -1.45, p > 0.05$	No
Potassium fertilizers (kg K ₂ O/t/yr)	9.14	6.69	9.13	9.22	2.35	8.98	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 208.00, z = -0.33, p > 0.05$	No
Insecticides, active ingredients (kg/t/yr)	0.73	2.01	0.27	1.72	2.15	0.80	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 114.00, z = -2.54, p < 0.05$	Yes
Fungicides, active ingredients (kg/t/yr)	0.08	0.12	0.01	0.01	0.02	0.00	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 156.00, z = -1.67, p > 0.05$	No
Herbicides, active ingredients (kg/t/yr)	0.79	0.50	0.81	0.47	0.30	0.52	$t(47) = 2.06, p < 0.05$	Yes
Price (\$/t/yr)	247.46	23.70	243.24	135.17	38.25	120.65	$U(N_{LYV.} = 37, N_{HRV.} = 12) = 8.00, z = -4.99, p < 0.001$	Yes

Table 6. Characterized impacts. Functional unit = 1 ha paddy field; GWP = global warming potential; OD = ozone depletion; IR = ionizing radiation; OF-hh = photochemical oxidant formation: human health; PM = fine particulate matter formation (PM); OF-te = photochemical oxidant formation: terrestrial ecosystems (OF-te); AC = terrestrial acidification (AC); FE = freshwater eutrophication; ME = marine eutrophication; TET = terrestrial ecotoxicity; FET = freshwater ecotoxicity; MET = marine ecotoxicity (MET); HCT = human toxicity: cancer (HCT); HnCT = human toxicity: non-cancer (HnCT); LU = land use; MRS = mineral resource scarcity; fossil resource scarcity (FRS); TRV = traditional rice varieties; HRV = high-yielding rice varieties; t = t -test; U = Mann–Whitney test. Statistical significance: $p < 0.05$. Source: Authors' elaboration.

Impact Categories	Traditional Rice Variety			High-Yielding Rice Variety			Test Results	Significant Difference
	Mean	St. Dev.	Median	Mean	St. Dev.	Median		
GWP	6905.60	614.82	6897.10	7823.41	415.61	7997.54	$t(47) = -4.81, p < 0.01$	Yes
OD	0.01	5.22×10^{-3}	0.01	0.02	4.16×10^{-3}	0.02	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 50.00, z = -3.99, p < 0.001$	Yes
IR	23.63	7.73	21.39	42.36	11.20	44.01	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 41.00, z = -4.21, p < 0.001$	Yes
OF-hh	9.36	2.24	9.66	10.44	1.59	10.52	$t(47) = -1.54, p > 0.05$	No
PM	7.83	2.38	7.48	11.23	1.69	11.70	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 57.00, z = -3.84, p < 0.001$	Yes
OF-te	9.51	2.25	9.81	10.62	1.60	10.72	$t(47) = -1.59, p > 0.05$	No
AC	41.84	16.24	38.63	61.61	11.79	65.07	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 74.00, z = -3.44, p < 0.05$	Yes
FE	1.39	0.99	1.01	1.95	0.97	1.83	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 139.00, z = -1.93, p > 0.05$	No
ME	3.81	2.01	3.19	6.05	1.44	6.35	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 76.00, z = -3.39, p < 0.05$	Yes
TET	7707.86	20,965.80	641.20	13,510.03	11,808.33	8269.45	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 50.00, z = -4.00, p < 0.001$	Yes
FET	408.71	1040.88	73.64	1142.02	1217.96	804.79	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 46.00, z = -4.09, p < 0.001$	Yes
MET	62.17	181.94	7.13	173.24	118.35	139.67	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 37.00, z = -4.30, p < 0.001$	Yes
HCT	50.48	23.34	40.31	78.25	24.72	79.33	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 88.00, z = -3.11, p < 0.05$	Yes
HnCT	1513.16	1156.70	1511.62	3607.95	1922.60	3786.27	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 74.00, z = -3.44, p < 0.05$	Yes
LU	101.52	17.24	100.71	105.18	14.27	109.78	$t(47) = -0.66, p > 0.05$	No
MRS	8.19	4.35	6.42	19.53	6.34	20.25	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 39.00, z = -4.25, p < 0.001$	Yes
FRS	1209.11	186.90	1220.09	1393.96	115.00	1433.76	$t(47) = -3.22, p < 0.05$	Yes

Table 7. Characterized impacts. Functional = 1 t paddy yield; GWP = global warming potential; OD = ozone depletion; IR = ionizing radiation; OF-hh = photochemical oxidant formation: human health; PM = fine particulate matter formation (PM); OF-te = photochemical oxidant formation: terrestrial ecosystems (OF-te); AC = terrestrial acidification (AC); FE = freshwater eutrophication; ME = marine eutrophication; TET = terrestrial ecotoxicity; FET = freshwater ecotoxicity; MET = marine ecotoxicity (MET); HCT = human toxicity: cancer (HCT); HnCT = human toxicity: non-cancer (HnCT); LU = land use; MRS = mineral resource scarcity; fossil resource scarcity (FRS); TRV = traditional rice varieties; HRV = high-yielding rice varieties; t = t -test; U = Mann–Whitney test. Statistical significance: $p < 0.05$. Source: Authors' elaboration.

Impact Categories	Traditional Rice Variety FU = 1 t			High-Yielding Rice Variety FU = 1 t			Test Results	Significant Difference
	Mean	St. Dev.	Median	Mean	St. Dev.	Median		
GWP	1613.44	353.13	1757.72	1157.64	158.83	1162.65	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 71.00, z = -3.51, p < 0.001$	Yes
OD	3.10×10^{-3}	1.37×10^{-3}	2.79×10^{-3}	3.25×10^{-3}	6.68×10^{-4}	3.42×10^{-3}	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 168.00, z = -1.81, p > 0.05$	No
IR	5.50	2.13	5.11	6.32	1.88	6.83	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 144.00, z = -1.25, p > 0.05$	No
OF-hh	2.16	0.61	2.04	1.54	0.27	1.51	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 58.00, z = -3.81, p < 0.001$	Yes
PM	1.81	0.65	1.72	1.66	0.28	1.65	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 195.00, z = -0.63, p > 0.05$	No
OF-te	2.19	0.61	2.07	1.56	0.27	1.54	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 57.00, z = -3.84, p < 0.001$	Yes
AC	9.67	4.31	9.38	9.06	1.84	9.29	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 220.00, z = -0.05, p > 0.05$	No
FE	0.31	0.22	0.22	0.28	0.14	0.27	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 210.00, z = -0.28, p > 0.05$	No
ME	0.88	0.52	0.77	0.89	0.22	0.93	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 189.00, z = -0.77, p > 0.05$	No
TET	1705.28	4638.45	141.86	1966.52	1718.82	1203.70	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 82.00, z = -3.25, p < 0.05$	Yes
FET	90.42	230.28	16.29	166.23	177.29	117.14	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 54.00, z = -3.91, p < 0.001$	Yes
MET	13.75	40.25	1.58	25.22	17.23	20.33	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 42.00, z = -4.18, p < 0.001$	Yes
HCT	11.17	5.30	8.92	11.39	3.60	11.55	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 199.00, z = -0.53, p > 0.05$	No
HnCT	334.77	255.91	334.43	525.17	279.85	551.13	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 129.00, z = -2.16, p < 0.05$	Yes
LU	23.64	5.92	23.36	15.71	3.47	16.52	$t(47) = 5.68, p < 0.001$	Yes
MRS	1.90	1.12	1.54	2.90	0.97	3.17	$U(N_{TRV.} = 37, N_{HRV.} = 12) = 100.00, z = -2.84, p < 0.05$	Yes
FRS	280.48	65.46	292.47	206.55	33.12	208.57	$t(47) = 5.14, p < 0.001$	Yes

3.3. Hotspot Analysis

Paddy field, fertilizer, and pesticide stages are key contributors to the characterized impacts, though with different patterns between the two farm groups (Figure 4).

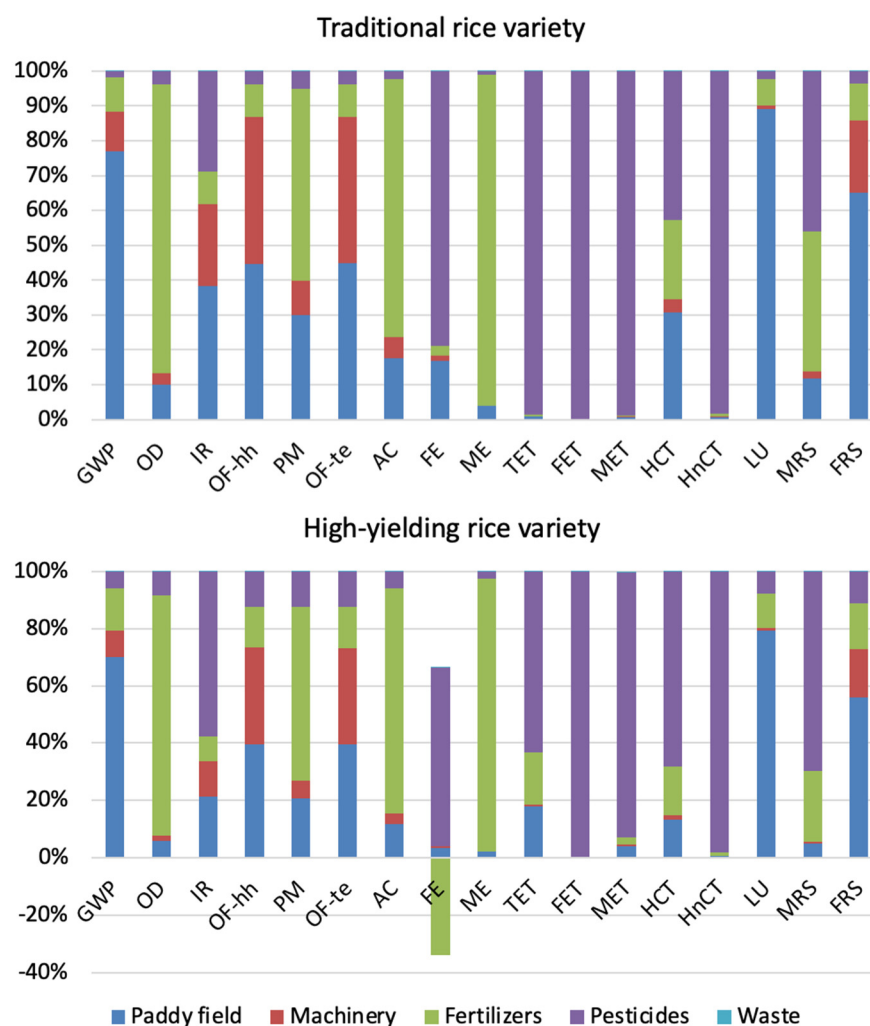


Figure 4. Contribution analysis. GWP = global warming potential; OD = ozone depletion; IR = ionizing radiation; OF-hh = photochemical oxidant formation: human health; PM = fine particulate matter formation (PM); OF-te = photochemical oxidant formation: terrestrial ecosystems (OF-te); AC = terrestrial acidification (AC); FE = freshwater eutrophication; ME = marine eutrophication; TET = terrestrial ecotoxicity; FET = freshwater ecotoxicity; MET = marine ecotoxicity (MET); HCT = human toxicity: cancer (HCT); HnCT = human toxicity: non-cancer (HnCT); LU = land use; MRS = mineral resource scarcity; fossil resource scarcity (FRS). Source: Authors' elaboration.

The paddy field stage shows the largest contribution to three impact categories: (i) GWP (77% in TRV, 70% in HRV), mainly due to direct methane emissions during rice cultivation, i.e., on average TRV emits 87 kgCH₄/ha and 21 kgCH₄/t, and HRV 93 kgCH₄/ha and 13 kgCH₄/t; (ii) LU (89% in TRV, 80% in HRV), mainly due to rice seed production processes; (iii) FRS (65% in TRV, 55% in HRV) mainly originates from the production of electricity for water pumping from natural gas and petroleum. The different contribution of the field stage between TRV and HRV depends on the greater contribution of the fertilizer and pesticide stages in HRV than TRV, given the greater consumption of production inputs (fertilizers, pesticides) in HRV. In TRV, the paddy field is also an important source of emissions that raise IR (contribution = 38%); however, this is different for HRV, where the pesticides stage contributes 58% to IR, reducing the importance of other stages.

The fertilizers stage contributes to four impact categories. Indirect emissions from industrial manufacturing of ammonia (urea production) and sulfuric acid (single super-phosphate production) are primarily responsible for the stage contribution to OD (83% in TRV, 84% in HRV) and PM (55% in TRV, 60% in HRV). Direct emissions from fertilizer application are primarily responsible for the stage contribution to AC (74% in TRV, 78% in HRV), especially nitrogen emissions to air, and ME (95% in TRV and HRV), especially nitrogen emissions to water. Noteworthy, in TRV, fertilizers show a minor contribution to FE (3%) and a negative contribution to HRV, contrary to what is expected from the model behind the characterization factor for FE. That model is based on the calculation of fate factors for phosphorous released to the environment that, in agricultural systems, generally derives from crop nutrition [108]. The low and negative contribution of the stage to FE suggests a suboptimal use of phosphorous fertilizers in both variety groups in HRV.

The pesticides stage has an outstanding contribution to all toxicity impacts (TET: 99% in TRV, 62% in HRV; FET: 100% in TRV and HRV; MET: 99% in TRV, 93% in HRV; HCT: 43% in TRV, 69% in HRV; HnCT: 98% in TRV and HRV), mainly due to direct emissions from pesticide application, but also to chemical factory processes for the production of active ingredients (FET, MET, HnCT). The pesticides stage is also the key contributor to FE in both variety groups, due to indirect emissions from industrial processes, especially the production of organic chemicals for the manufacture of active ingredients. This contribution is exacerbated by the negative contribution of the fertilizers stage to FE.

The machinery stage has a remarkable contribution to OF-hh and OF-te, alongside the paddy field stage, with no significant differences among the two variety groups.

The waste stage has a negligible contribution to all impact categories, which depends on the processes of plastic waste treatment. This reduced contribution is also due to methodological choices, i.e., the restriction of system boundaries to the farm gate, thereby excluding processing and other downstream processes from the assessment.

The normalization of characterized impacts supports the contribution analysis by identifying the pesticide, fertilizer, and paddy field stages as hotspots in both variety groups (Figure 5).

The results point to the toxicity impacts (FET, followed by MET and then HCT) as the prominent group of impact categories affected by paddy farming in the case study area and at HRV as the most impacting variety group concerning those impact categories, regardless of the functional unit (as expected from the analysis of the characterization results). In addition to the toxicity impacts, FE, AC, and FRS show the following highest normalized values. The prevalence of the toxicity impacts indicates pesticides as the critical hotspot of paddy farming. This finding should be interpreted with caution, given the limitations of normalization references [109]. However, other findings support the identification of pesticides as the most relevant hotspot, especially the high normalized FE values by pointing to background pesticide production processes. The high normalization values of AC and FRS suggest that other hotspots are nitrogen fertilizer management and electricity consumption for water pumping (responsible for almost 55% FRS in the paddy field stage).

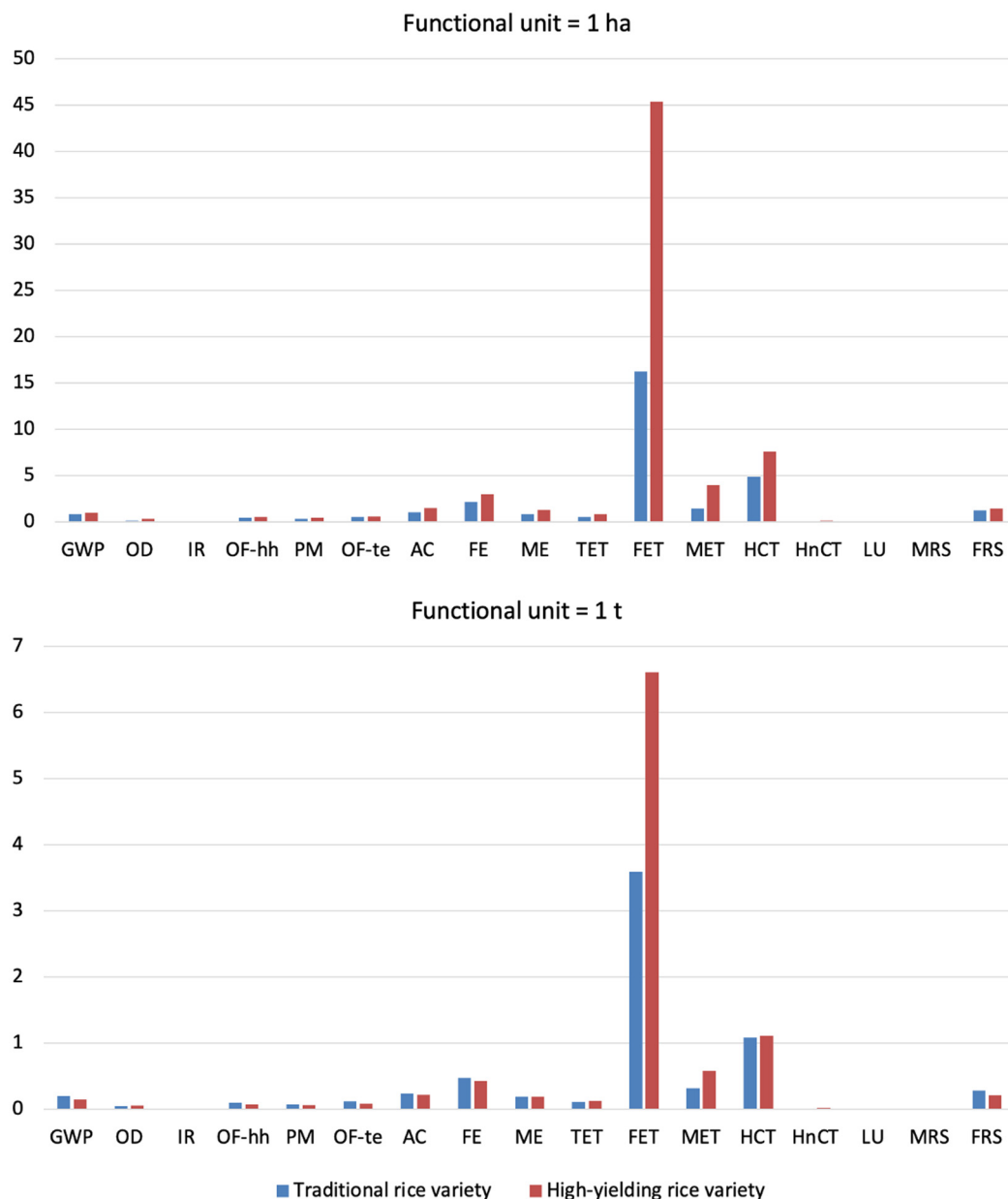


Figure 5. Normalized impacts, Recipe 2016 World normalization factors (midpoint, H). GWP = global warming potential; OD = ozone depletion; IR = ionizing radiation; OF-hh = photochemical oxidant formation: human health; PM = fine particulate matter formation (PM); OF-te = photochemical oxidant formation: terrestrial ecosystems (OF-te); AC = terrestrial acidification (AC); FE = freshwater eutrophication; ME = marine eutrophication; TET = terrestrial ecotoxicity; FET = freshwater ecotoxicity; MET = marine ecotoxicity (MET); HCT = human toxicity: cancer (HCT); HnCT = human toxicity: non-cancer (HnCT); LU = land use; MRS = mineral resource scarcity; fossil resource scarcity (FRS). Source: Authors' elaboration.

3.4. Sensitivity Analysis

The selected cultural perspective in the Recipe 2016 method can deliver important changes in terms of the impact assessment results (Figure 6).

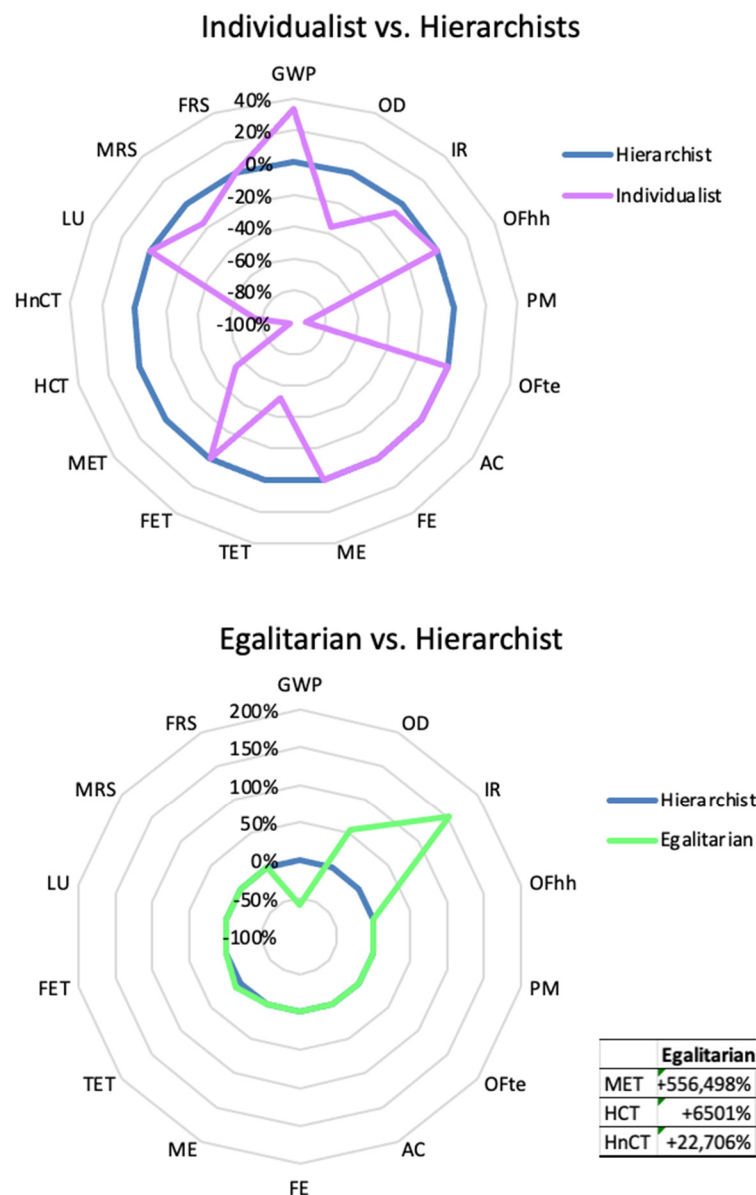


Figure 6. Sensitivity analysis of impact categories calculated using the different cultural perspective of the ReCiPe 2016 midpoint method. Due to the great difference between minimum and maximum values, three impact categories are missing from the Egalitarian vs. Hierarchist graph and tabled separately. GWP = global warming potential; OD = ozone depletion; IR = ionizing radiation; OF-hh = photochemical oxidant formation: human health; PM = fine particulate matter formation (PM); OF-te = photochemical oxidant formation: terrestrial ecosystems (OF-te); AC = terrestrial acidification (AC); FE = freshwater eutrophication; ME = marine eutrophication; TET = terrestrial ecotoxicity; FET = freshwater ecotoxicity; MET = marine ecotoxicity (MET); HCT = human toxicity: cancer (HCT); HnCT = human toxicity: non-cancer (HnCT); LU = land use; MRS = mineral resource scarcity; fossil resource scarcity (FRS); Source: Authors' own elaboration.

Selecting the Individualist against the Hierarchist perspective delivers lower results for 8 out of 18 impact categories and increases CC with 34%. Impact reduction is marked and exceeds -50% for TET, MET, HnCT, PM, and HCT, with PM and HCT decreasing with over 90% . Using the Egalitarian perspective affects 7 out of 18 impact categories, i.e., the same categories as in the Individualist vs. Hierarchist comparison, except for PM and MRS. Just CC decreases (-59%), while OD, IR, TET, MET, HCT, and HnCT increase in a varied manner. The increase in TET is low ($+7\%$), while the other categories grow with over 50% .

Especially MET, HCT, and HnCT show extremely high absolute values, with increase rates that are not comparable with the other impact categories.

4. Discussion

The results show that replacing TRV with HRV in paddy farming may lead to significant increases in the environmental impacts per ha, while enabling the considerable decline in a series of impacts per t paddy rice. Greater area-scaled impacts are due to the higher expected yield of HRV and the required increase in the applied quantities of agronomic inputs. Lower yield-scaled impacts are achieved due to the significant yield difference between the two variety groups, which exceeds the increased demand for most inputs. These findings confirm the research in other developing countries in Asia [57] and, just for GWP, in major rice-producing countries (developing and developed countries) worldwide [58,110].

GWP is a crucial impact of rice farming, the most widely assessed by the scientific literature, and the only one that allows for a comprehensive comparison of study findings [36,111], as in other agricultural sectors [112]. HRV can reduce yield-scaled GWP through reduced field emissions during flooding, machinery use, and water pumping (lower electricity consumption). However, under current management conditions, replacing TRV with HRV can increase area-scaled GWP [113]. To achieve the win-win outcome of ensuring sustainable food security while lowering the paddy contribution to global greenhouse gas emissions, focusing on yield-scaled rather than area-scaled GWP is more appropriate [114]. However, the trade-off analysis is worth consideration as direct emissions mapped to GWP also contribute to other impact categories, such as resource consumption and pollution, which have local implications.

Adopting HRV can reduce electricity consumption per t paddy rice. No significant difference in electricity consumption is highlighted on a per area basis. This might be explained through the purpose of flooding in rice farming, i.e., creating the agronomic conditions for crop development. Therefore, water management on paddies is not directly dependent on the cultivated variety. Despite that, there is room for improvement in water-use efficiency practices, which is extremely relevant given the current and future natural resource constraints [115]. Natural gas and petroleum used for electricity production are hotspots in paddy farming, due to their contribution to FRS. Improving water-use efficiency may generate synergies with FRS and GWP reduction in paddy farming.

Acidification and eutrophication potentials are relevant impact categories in agricultural LCA, being directly dependent on the type and quantity of consumed fertilizers. The research findings show that shifting to HRV does not imply changing the type of fertilizers, but just their quantities, similar to other developing countries in Asia and Africa [116,117]. Compared to TRV, HRV can significantly increase AC per ha, due to a likewise significant increase in nitrogen fertilizer consumption. This pattern might be related to the need to meet the greater nutritional needs of HRV vs. TRV. However, the research evidence does not support the identification of a significantly lower consumption of nitrogen fertilizers and AC reduction per t paddy yield in HRV. Also, hotspot analysis suggests that nitrogen fertilizers are a production hotspot, as in other production contexts [58,118]. Direct emissions from nitrogen fertilizers greatly contribute to ME that represents the persistence of nitrogen exported in the receiving marine coastal waters [119].

In this study, the consumption of phosphorous fertilizers results in very little (TRV) or even a negative (HRV) contribution to FE, i.e., the persistence of phosphorous in freshwaters [108]. This is probably due to the suboptimal use of phosphorous fertilizers by farmers in the case study area. The findings show that FE is an environmental hotspot. However, this is due to industrial processes for the production of pesticides' active ingredients.

Farms cultivating HRV show greater pesticide (especially insecticides) consumption than TRV both per ha and per t. Therefore, in the case study, replacing TRV with HRV has the potential to exacerbate the toxicity impacts on human health and ecosystems. This finding suggests that the management of pesticides offers considerable room for

improvement, as shown in other Asian countries [120]. However, the agronomic rationale behind the greater consumption of pesticides in HRV needs to be clarified. A possible explanation is that farmers tend to apply larger quantities of production inputs focusing on yield increase, often based on heuristics [105], probably aimed at counterbalancing the lower producer price of HRV [30]. This is somewhat supported by findings about producer price per t paddy rice, which turns out to be significantly lower for HRV than TRV. This is due to consumers' perceived greater quality of TRV in the local market [121,122]. Such a difference may lead to the improper management of production inputs by the adopters of HRV to bridge the gap in gross revenues [121,123]. This calls for public policy measures or market instruments (e.g., premium pricing associated with certification and labeling) that compensate farmers for improving the environmental performance of paddy production [58,124].

Hotspot analysis points to pesticides as the most critical life cycle stage, due to its outstanding contribution to toxicity impacts. However, this result should be interpreted with caution. Firstly, the findings about the toxicity impacts could not be confirmed through the comparison with similar studies in Iran and other countries. Secondly, this study uses reference values for external normalization, which may be affected by overestimation bias due to incomplete coverage of toxic substances [96,109]. Despite these limitations, other study findings support the identification of pesticide consumption and the related impacts as hotspots in paddy farming under current management practices, especially when HRVs are cultivated. This is mainly due to the large use of active ingredients for protection against insecticides. The studied HRVs lack traits for resistance to insecticides. Therefore, alternative high-yielding varieties may be cultivated to reduce the risks for human and ecosystem health.

5. Recommendations for Research, Practice, and Policy

5.1. Recommendations for Method Advancement

In LCA studies, diverse FUs embody different perspectives on the sustainability implications of shifting from TRV to HRV, under a set of farm management conditions. The use of area-based FUs supports the identification of the most environmentally friendly practices by showing the overall environmental impacts of paddy production at the territorial level. The use of mass-based FUs offers a productivity perspective by suggesting what practices should be preferred to enable sustainable food security [125,126]. To date, the impacts of variety selection have been studied through a productivity perspective, disregarding the environmental implications at the territorial level. To enable conscious decision-making, further LCA research should look beyond productivity, by providing evidence about the area-scaled impacts of high-yielding varieties, to suggest practical solutions to meet agricultural viability with rural livelihoods.

For most impact categories, the study findings could not be confirmed through the comparison with similar studies in Iran and other countries. This was mainly due to the literature inconsistency, especially the following: (i) different approaches to life cycle inventory building, i.e., the inclusion/exclusion of production inputs and outputs; (ii) different impact assessment methods and even different versions of the same method, which usually underlie different characterization models; and (iii) the focus on just one or very few impact categories, or the exclusion of some impact categories from the assessment. These are shortcomings that may limit the robustness and practical usefulness of impact assessment findings. Harmonized guidelines about the publication of life cycle assessment studies may facilitate the comparison of research findings across multiple impact categories and production contexts, by enabling the provision of accurate information about inventory building and the application of the impact assessment method [60,127].

The external normalization of characterized impacts improves the communication of LCA findings by supporting hotspot analysis and therefore the identification of critical processes to prioritize intervention. However, more flexible and region- and sector-specific normalization references are needed to avoid the misinterpretation of research findings.

5.2. Recommendations for the Improvement in Management Practices

The diffusion of HYV can support Iran's rice sector to face increasing drought and food security challenges. However, variety adoption in the sampled farms is not linked with changes in paddy management practices. This leads to a suboptimal adoption of sustainable intensification practices. HRVs per se are insufficient to improve paddy production's sustainability while increasing the yield; therefore, farm management should transition towards more sustainable practices, starting with a more cost-effective use of production inputs. Adapting agronomic practices to specific cultivar needs is necessary to boost the impact-mitigating and food security potentials of HRV [58].

More attention should be paid to pesticide management on farms, especially through educational campaigns supported by farm extension services:

- (i) To support the diffusion of water-saving practices, e.g., through increased recirculation;
- (ii) To increase awareness about the current impacts and potential growing threats to human health and the environment of uncontrolled chemical pesticides;
- (iii) To help farmers to reduce their dependency on chemical pesticides;
- (iv) To select varieties with insecticide-resistance traits;
- (v) To inform farmers about the potential cost-saving opportunities of diversifying pest and disease control and weeding methods, including increasing the overall effectiveness of product application (when needed);
- (vi) To provide training about integrated pest management practices.

5.3. Policy Recommendations

This study deepens the understanding of the implications of rice intensification through high-yielding varieties as a rural development strategy to face the food and climate emergencies in developing countries, especially those affected by natural resource overexploitation [52,126,127]. The evidence shown in the article expands the understanding of how to improve policy delivery through better targeting based on different sustainability issues.

The lessons learnt from the case study suggest that crop management is heavily dependent on individual farmers' decisions and experience, with great variability across the sample [70]. Farmer decisions are often driven by economic reasoning, such as the availability of subsidies for fertilizer purchases or the preference for herbicides instead of mechanical weeding to save the cost of machinery rental [115]. The adoption of HRV is only sometimes part of a farm modernization strategy and is often accompanied by inadequate levels of mechanization and farmers' training on efficient input management [64,69]. This is a critical aspect that is worth consideration by policymakers. The development of targeted policy measures might be needed to enable a sustainability transition of paddy farming systems, considering the different perspectives offered by the use of multiple functional units based on context-related priorities [128].

The increase in GWP is a major issue in paddy farming. The lessons learnt from this study suggest that HRV can solve just part of the problem. Broad strategies are needed, which may require public support. Especially, machinery owners would need incentives for replacing older with newer (more ecological) agricultural machinery [104]. A national strategic framework would be required to sustain the ecological transition of the energy industry, to increase renewable electricity production to feed into the Iranian national grid, thereby contributing to the combined mitigation of FRS and GWP [107].

Farmers in the case study area have long based fertilizer management on the availability of public subsidies for nitrogen fertilizers, especially urea, thereby applying excess quantities of subsidized products and suboptimal quantities of other complementary nutrients. Therefore, renovated criteria for fertilizer subsidies and the broader use of advisory services should be designed to encourage more rational crop nutrition management [105].

Pesticide management is probably the most critical issue highlighted by this study. Heuristics should be avoided through the development of educational campaigns for farmers and advisors, as well as through the promotion of a wider use of skilled advisory

services. Targeted policies such as result-based payments might also be required for encouraging the use of integrated pest management practices.

Isolated (issue-specific) intervention may not be enough to improve the sustainability of paddy production, especially in developing countries. A set of synergetic measures may be needed to favor the productivity increase and more conscious management of production inputs by farmers, as well the change in consumer purchasing patterns, in the short-term. The lessons learnt from this study suggest the following set of priority areas for timely policy intervention:

- (1) Encouraging machinery renewal via public or private incentives to farmer investments (e.g., low-interest rate on loans for energy-efficient machinery);
- (2) Developing incentives for soil testing to make fertilization more responsive to crop nutritional needs;
- (3) Aligning farmer prices for conventionally produced TRV and HRV to improve the eco-efficiency of paddy production;
- (4) Differentiating producer price (e.g., premium price) based on farms' environmental performance to encourage adopting more sustainable practices;
- (5) Developing incentives to boost farmers' access to advisory services and training to encourage a more thoughtful use of farm inputs;
- (6) Supporting the improvement in social capital, for example, by developing private or public incentives to encourage farmer cooperation and peer-to-peer learning.

6. Conclusions

This study compares the life cycle environmental impacts of the cultivation of traditional rice varieties vs. high-yielding rice varieties on a per yield and per area basis, to show the potential contribution of variety selection to sustainable rice intensification. The case study is a specialized rice-producing region in northern Iran (Qaemshahr, Mazandaran Province). Based on a comparative life cycle assessment of real-world paddy farming, the study quantifies area- and yield-scaled impacts, analyzes hotspots, and highlights trade-offs.

The findings show that HRV (Shiroodi, Neda) could significantly reduce critical environmental impacts per t paddy yield, compared to TRV (Tarom Hashemi), such as global warming potential (−28%), ozone formation, human health, terrestrial ecosystems (−29%), and fossil resource scarcity (−26%). However, the trend is reverted when area-scaled impacts are considered, e.g., global warming potential (+13%), terrestrial acidification (+47%), marine eutrophication (+59%), and fossil resource scarcity (+15%) per ha. This trade-off might be unavoidable to meet the greater demand for the production inputs of HRV to achieve higher yields. HRV increased pesticide use per ha and per t, with no agronomic reason behind that, with greater toxicity impacts.

Hotspot analysis points to human and ecosystem toxicity, freshwater eutrophication, terrestrial acidification, and fossil resource scarcity as the most alarming impacts of paddy production. Those impacts are generated through the consumption of pesticides, nitrogen fertilizers, and electricity for water pumping. Under current management conditions, replacing TRV with HRV can exacerbate those impacts at the territorial level.

Taken together, the research findings call for an urgent improvement in farming practices and especially crop protection patterns. Encouraging a shift to HRV is not enough to enable a transition to sustainable food production. Education and advisory services should be boosted to promote a wide adoption of variety-specific best management practices, as well as awareness about optimal pesticide use, thereby avoiding heuristics. The design of future agro-environmental policies should carefully consider the trade-offs between area-scaled and yield-scaled impacts to find the best balance between the need for sustainable food security and local environmental impacts. Special attention should be paid to environmental hotspots that have the potential to exponentially increase the risks for human and ecosystem health in the future.

The lessons learnt from this study should be helpful in further research about rice intensification. However, some study limitations should be considered, such as the small sample size and the lack of a counterfactual analysis. Extending the study to a broader set of farms would enable the identification of cause–effect relationships between the input data and impact assessment results. A counterfactual analysis would help to understand the extent to which the study findings depend on the specific characteristics of the surveyed farms, e.g., by comparing the same group of farms before and after adopting high-yield varieties. Linking the environmental assessment with the analysis of farm household variables may improve the understanding of the impact of demographic and social factors on farm management. Given the significant impact of pesticides, more qualitative research is needed about pesticide use, especially to understand the barriers and drivers to adopting sustainable pest and weed control methods.

Author Contributions: Conceptualization, O.G. and Z.A.; methodology, O.G., Z.A., A.D. and S.M.; formal analysis and investigation, O.G. and Z.A.; data curation, Z.A.; writing—original draft preparation, O.G.; writing—review and editing, O.G., Z.A., A.D. and S.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets generated during and analyzed during the current study are available from the corresponding author on reasonable request.

Acknowledgments: The authors are grateful to Bardia Bahrami Kootenai and Faramaz Sadeghi for providing farmer contacts and supporting data collection.

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

Appendix A

Refereed journal articles (original research or literature reviews) were identified through Scopus search (October 2023), as follows:

- The string “(‘life cycle assessment’ OR LCA) AND rice AND Iran” was run over the field “title, abstract, keywords” with no time boundaries; the output was 14 papers;
- Papers were checked for system boundary comparability with this study (cradle-to-farm gate); four papers were discarded;
- The reference lists of the 10 retrieved papers were screened to find additional relevant literature; 6 more relevant papers were identified;
- The final output was 16 papers (Table A1).

Table A1. Life cycle assessment of rice farming in Iran. Scopus database (October 2023): FU: functional unit; GM: genetically modified; n.a.: information not available from the article; * quantities displayed not for all items; ** absolute values for impact categories not displayed; *** milled rice. Source: Authors’ own elaboration.

Reference	Province	Varieties	Production Inputs/Outputs		Life Cycle Impact Assessment	
			FU	Items	FU	Method
[54]	Mazandaran; Guilan	Non-GM vs. GM	n.a.	n.a.	1 t	ReCiPe 2016; Impact, 2002+; Cumulative Energy Demand; TRACI
[53]	Mazandaran; Guilan	Low- vs. medium-yielding (GM and non-GM)	n.a.	n.a.	1 t	ReCiPe 2016; Cumulative Energy Demand

Table A1. Cont.

Reference	Province	Varieties	Production Inputs/Outputs		Life Cycle Impact Assessment	
			FU	Items	FU	Method
[129]	Guilan	Not assessed	n.a.	n.a.	1 t	Characterization models identified for selected impact categories
[49]	Mazandaran; Guilan	Not assessed	1 ha	Area; seed; chemical fertilizers; pesticides; manure *	1 t	ReCiPe 2016; IPCC 2013 GWP100a
[52]	Fars	Not assessed	1 ha	Machinery weight; diesel; seed; chemical fertilizers; pesticides; water; paddy yield; farmer price	1 t	CML 2 baseline 2000 V2/world **
[50]	Guilan	Not assessed	1 ha; 1t	Machinery weight; diesel; electricity; chemical fertilizers; Manure; Pesticides; Seed	1 ha; 1 t	CML 2 baseline 2000 V2/world
[102]	Golestan	Not assessed	1 ha	Diesel; water; electricity; chemical fertilizers; pesticides; seed; paddy yield *	1 kg	Characterization models identified for selected impact categories
[56]	Mazandaran	Local vs. improved	1 ha	Area; seed; electricity; machinery hours; diesel; fertilizers; paddy yield *	1 t	ReCiPe; Cumulative Energy Demand; CML non-baseline; IPCC 2013 GWP100a
[104]	Guilan; Mazandaran; Golestan	Low- vs. high-yielding (non-GM)	1 ha	Diesel; electricity; chemical fertilizers; pesticides; water; paddy yield; milled rice yield *	1 t ***	ReCiPe
[105]	Guilan	Not assessed	1 ha	Machinery weight; diesel; electricity; chemical fertilizers; pesticides; seed; paddy yield	1 t	CML
[130]	Guilan	Not assessed	1 ha	Machinery weight; diesel; electricity; chemical fertilizers; pesticides; seed; paddy yield	1 t	CML **
[103]	Guilan; Mazandaran; Golestan	Not assessed	1 ha	Diesel; seed; chemical fertilizers; manure; pesticides; paddy yield	1 t	ReCiPe 2016 midpoint (H)
[106]	Mazandaran	Not assessed	1 ha	Diesel; lubricant oil; seed; nylon; chemical fertilizers; manure; pesticides; electricity; paddy yield; farmer price *	1 t	IMPACT 2002+
[30]	Mazandaran	Not assessed	1 ha	Diesel; lubricant oil; seed; nylon; chemical fertilizers; pesticides; electricity; paddy yield; farmer price	1 t	ReCiPe 2016 midpoint (H) **
[55]	Guilan	Traditional vs. high-yielding (non-GM)	1 ha	Diesel; chemical fertilizers; paddy yield	1 t	Characterization models identified for selected impact categories
[29]	Guilan; Mazandaran	Not assessed	1 ha; 1 t	Machinery weight; diesel; gasoline; electricity; chemical fertilizers; pesticides; herbicides; plastics; electricity; seed; paddy yield	1 ha; 1 t	CML-IA baseline

References

1. Campbell, B.M.; Beare, D.J.; Bennett, E.M.; Hall-Spencer, J.M.; Ingram, J.S.I.; Jaramillo, F.; Ortiz, R.; Ramankutty, N.; Sayer, J.A.; Shindell, D. Agriculture Production as a Major Driver of the Earth System Exceeding Planetary Boundaries. *Ecol. Soc.* **2017**, *22*, art8. [\[CrossRef\]](#)
2. Richardson, K.; Steffen, W.; Lucht, W.; Bendtsen, J.; Cornell, S.E.; Donges, J.F.; Drüke, M.; Fetzer, I.; Bala, G.; Von Bloh, W.; et al. Earth beyond Six of Nine Planetary Boundaries. *Sci. Adv.* **2023**, *9*, eadh2458. [\[CrossRef\]](#) [\[PubMed\]](#)
3. Gerten, D.; Heck, V.; Jägermeyr, J.; Bodirsky, B.L.; Fetzer, I.; Jalava, M.; Kummu, M.; Lucht, W.; Rockström, J.; Schaphoff, S.; et al. Feeding Ten Billion People Is Possible within Four Terrestrial Planetary Boundaries. *Nat. Sustain.* **2020**, *3*, 200–208. [\[CrossRef\]](#)
4. UN. *Transforming Our World: The 2023 Agenda For sustainable Development*; United Nations: New York, NY, USA, 2015.

5. OECD-FAO. *OECD-FAO Agricultural Outlook 2020–2029*; OECD-FAO Agricultural Outlook; OECD: Paris, France, 2020; ISBN 978-92-64-31767-3.
6. Tan, B.L.; Norhaizan, M.E. Rice Demands: A Brief Description. In *Rice By-Products: Phytochemicals and Food Products Application*; Springer International Publishing: Cham, Switzerland, 2020; pp. 7–11. ISBN 978-3-030-46152-2.
7. de Miranda, M.S.; Fonseca, M.L.; Lima, A.; de Moraes, T.F.; Aparecido Rodrigues, F. Environmental Impacts of Rice Cultivation. *Am. J. Plant Sci.* **2015**, *06*, 2009–2018. [\[CrossRef\]](#)
8. Zhuang, Y.; Liu, H.; Zhang, L.; Li, S. Research Perspectives on Paddy Field Systems: Ecological Functions and Environmental Impacts. *Int. J. Agric. Sustain.* **2020**, *18*, 505–520. [\[CrossRef\]](#)
9. Chen, X.; Cui, Z.; Fan, M.; Vitousek, P.; Zhao, M.; Ma, W.; Wang, Z.; Zhang, W.; Yan, X.; Yang, J.; et al. Producing More Grain with Lower Environmental Costs. *Nature* **2014**, *514*, 486–489. [\[CrossRef\]](#) [\[PubMed\]](#)
10. Yamano, T.; Arouna, A.; Labarta, R.A.; Huelgas, Z.M.; Mohanty, S. Adoption and Impacts of International Rice Research Technologies. *Glob. Food Secur.* **2016**, *8*, 1–8. [\[CrossRef\]](#)
11. Yuan, S.; Linquist, B.A.; Wilson, L.T.; Cassman, K.G.; Stuart, A.M.; Pede, V.; Miro, B.; Saito, K.; Agustiani, N.; Aristya, V.E.; et al. Sustainable Intensification for a Larger Global Rice Bowl. *Nat. Commun.* **2021**, *12*, 7163. [\[CrossRef\]](#) [\[PubMed\]](#)
12. Yuan, S.; Stuart, A.M.; Laborte, A.G.; Rattalino Edreira, J.I.; Dobermann, A.; Kien, L.V.N.; Thuy, L.T.; Paothong, K.; Traesang, P.; Tint, K.M.; et al. Southeast Asia Must Narrow down the Yield Gap to Continue to Be a Major Rice Bowl. *Nat. Food* **2022**, *3*, 217–226. [\[CrossRef\]](#)
13. Chen, L.; Xie, H.; Wang, G.; Qian, X.; Wang, W.; Xu, Y.; Zhang, W.; Zhang, H.; Liu, L.; Wang, Z.; et al. Reducing Environmental Risk by Improving Crop Management Practices at High Crop Yield Levels. *Field Crops Res.* **2021**, *265*, 108123. [\[CrossRef\]](#)
14. Darzi-Naftchali, A.; Bagherian-Jelodar, M.; Mashhadi-Kholerdi, F.; Abdi-Moftikolaei, M. Assessing Socio-Environmental Sustainability at the Level of Irrigation and Drainage Network. *Sci. Total Environ.* **2020**, *731*, 138927. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Sabiha, N.-E.; Salim, R.; Rahman, S. Eco-Efficiency of High-Yielding Variety Rice Cultivation after Accounting for on-Farm Environmental Damage as an Undesirable Output: An Empirical Analysis from Bangladesh. *Aust. J. Agric. Resour. Econ.* **2017**, *61*, 247–264. [\[CrossRef\]](#)
16. Alhashim, R.; Deepa, R.; Anandhi, A. Environmental Impact Assessment of Agricultural Production Using Lca: A Review. *Climate* **2021**, *9*, 164. [\[CrossRef\]](#)
17. Garnett, T. Three Perspectives on Sustainable Food Security: Efficiency, Demand Restraint, Food System Transformation. What Role for Life Cycle Assessment? *J. Clean. Prod.* **2014**, *73*, 10–18. [\[CrossRef\]](#)
18. Guinée, J.B.; Heijungs, R. Life Cycle Sustainability Analysis: Framing Questions for Approaches. *J. Ind. Ecol.* **2011**, *15*, 656–658. [\[CrossRef\]](#)
19. Heijungs, R.; Huppes, G.; Guinée, J. *A Scientific Framework for LCA*; CALCAS Project; Institute of Environmental Sciences, Leiden University (CML): Leiden, Belgium, 2009.
20. ISO 14040:2006; Environmental Management—Life Cycle Assessment—Principles and Framework. ISO: Geneva, Switzerland, 2006.
21. ISO 14044:2006; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. ISO: Geneva, Switzerland, 2006.
22. Finnveden, G.; Moberg, Å. Environmental Systems Analysis Tools—An Overview. *J. Clean. Prod.* **2005**, *13*, 1165–1173. [\[CrossRef\]](#)
23. Hoogmartens, R.; Van Passel, S.; Van Acker, K.; Dubois, M. Bridging the Gap between LCA, LCC and CBA as Sustainability Assessment Tools. *Environ. Impact Assess. Rev.* **2014**, *48*, 27–33. [\[CrossRef\]](#)
24. Reinmann, K.; Finkbeiner, M.; Horvath, A.; Matsuno, Y. *Evaluation of Environmental Life Cycle Approaches for Policy and Decision Making Support in Micro and Macro Level Applications*; European Commission, Joint Research Centre, Institute for Environment and Sustainability: Luxembourg, 2010.
25. Hellweg, S.; Mila i Canals, L. Emerging Approaches, Challenges and Opportunities in Life Cycle Assessment. *Science* **2014**, *344*, 1109–1113. [\[CrossRef\]](#)
26. Gava, O.; Bartolini, F.; Venturi, F.; Brunori, G.; Pardossi, A. Improving Policy Evidence Base for Agricultural Sustainability and Food Security: A Content Analysis of Life Cycle Assessment Research. *Sustainability* **2020**, *12*, 1033. [\[CrossRef\]](#)
27. Rajagopal, D.; Vanderghem, C.; MacLean, H.L. Life Cycle Assessment for Economists. *Annu. Rev. Resour. Econ.* **2017**, *9*, 361–381. [\[CrossRef\]](#)
28. Statistical Centre of Iran. *Selected Results of Crop Survey, the Year1397*; Statistical Centre of Iran: Tehran, Iran, 2018.
29. Kouchaki-Penchah, H.; Alizadeh, M.R.; Karbalaee Aghamolki, M.T. Measuring Eco-Efficiency of Rice Cropping Systems in Iran: An Integrated Economic and Environmental Approach. *Sustain. Energy Technol. Assess.* **2023**, *57*, 103281. [\[CrossRef\]](#)
30. Saber, Z.; van Zelm, R.; Pirdashti, H.; Schipper, A.M.; Esmaeili, M.; Motevali, A.; Nabavi-Pelesaraei, A.; Huijbregts, M.A.J. Understanding Farm-Level Differences in Environmental Impact and Eco-Efficiency: The Case of Rice Production in Iran. *Sustain. Prod. Consum.* **2021**, *27*, 1021–1029. [\[CrossRef\]](#)
31. Salehi, F.; Abdollahi, Z.; Abdollahi, M. *Good Food Basket for the Iranian Community*; Ministry of Health and Medical Education: Shahrak-e Gharb, Tehran, 2013.
32. Soltani, A.; Alimagham, S.M.; Nehbandani, A.; Torabi, B.; Zeinali, E.; Zand, E.; Vadez, V.; van Loon, M.P.; van Ittersum, M.K. Future Food Self-Sufficiency in Iran: A Model-Based Analysis. *Glob. Food Secur.* **2020**, *24*, 100351. [\[CrossRef\]](#)

33. Sobhani, S.R.; Arzhang, P.; Soltani, E.; Soltani, A. Proposed Diets for Sustainable Agriculture and Food Security in Iran. *Sustain. Prod. Consum.* **2022**, *32*, 755–764. [\[CrossRef\]](#)
34. Beltran-Peña, A.; Rosa, L.; D’Odorico, P. Global Food Self-Sufficiency in the 21st Century under Sustainable Intensification of Agriculture. *Environ. Res. Lett.* **2020**, *15*, 095004. [\[CrossRef\]](#)
35. Nasrollahi, H.; Shirazizadeh, R.; Shirmohammadi, R.; Pourali, O.; Amidpour, M. Unraveling the Water-Energy-Food-Environment Nexus for Climate Change Adaptation in Iran: Urmia Lake Basin Case-Study. *Water* **2021**, *13*, 1282. [\[CrossRef\]](#)
36. Pittelkow, C.M.; Adviento-Borbe, M.A.; van Kessel, C.; Hill, J.E.; Linquist, B.A. Optimizing Rice Yields While Minimizing Yield-Scaled Global Warming Potential. *Glob. Chang. Biol.* **2014**, *20*, 1382–1393. [\[CrossRef\]](#)
37. Ghanbari, S.; Mansouri Daneshvar, M.R. Urban and Rural Contribution to the GHG Emissions in the MECA Countries. *Environ. Dev. Sustain.* **2021**, *23*, 6418–6452. [\[CrossRef\]](#)
38. Mansouri Daneshvar, M.R.; Ebrahimi, M.; Nejadsoleymani, H. An Overview of Climate Change in Iran: Facts and Statistics. *Environ. Syst. Res.* **2019**, *8*, 7. [\[CrossRef\]](#)
39. Khorsandi, M.; Homayouni, S.; van Oel, P. The Edge of the Petri Dish for a Nation: Water Resources Carrying Capacity Assessment for Iran. *Sci. Total Environ.* **2022**, *817*, 153038. [\[CrossRef\]](#) [\[PubMed\]](#)
40. Mesgaran, M.B.; Madani, K.; Hashemi, H.; Azadi, P. Iran’s Land Suitability for Agriculture. *Sci. Rep.* **2017**, *7*, 7670. [\[CrossRef\]](#)
41. Abtahi, M.; Fakhri, Y.; Oliveri Conti, G.; Keramati, H.; Zandsalimi, Y.; Bahmani, Z.; Hosseini Pouya, R.; Sarkhosh, M.; Moradi, B.; Amanidaz, N.; et al. Heavy Metals (As, Cr, Pb, Cd and Ni) Concentrations in Rice (*Oryza sativa*) from Iran and Associated Risk Assessment: A Systematic Review. *Toxin Rev.* **2017**, *36*, 331–341. [\[CrossRef\]](#)
42. Zafarzadeh, A.; Rahimzadeh, H.; Mahvi, A.H. Health Risk Assessment of Heavy Metals in Vegetables in an Endemic Esophageal Cancer Region in Iran. *Health Scope* **2018**, *7*, e12340. [\[CrossRef\]](#)
43. Mahdavian, S.M.; Ahmadpour Borazjani, M.; Mohammadi, H.; Asgharipour, M.R.; Najafi Alamdarlo, H. Assessment of Food-Energy-Environmental Pollution Nexus in Iran: The Nonlinear Approach. *Environ. Sci. Pollut. Res.* **2022**, *29*, 52457–52472. [\[CrossRef\]](#)
44. Blengini, G.A.; Busto, M. The Life Cycle of Rice: LCA of Alternative Agri-Food Chain Management Systems in Vercelli (Italy). *J. Environ. Manag.* **2009**, *90*, 1512–1522. [\[CrossRef\]](#) [\[PubMed\]](#)
45. Fusi, A.; Bacenetti, J.; González-García, S.; Vercesi, A.; Bocchi, S.; Fiala, M. Environmental Profile of Paddy Rice Cultivation with Different Straw Management. *Sci. Total Environ.* **2014**, *494–495*, 119–128. [\[CrossRef\]](#) [\[PubMed\]](#)
46. Harada, H.; Kobayashi, H.; Shindo, H. Reduction in Greenhouse Gas Emissions by No-Tilling Rice Cultivation in Hachirogata Polder, Northern Japan: Life-Cycle Inventory Analysis. *Soil Sci. Plant Nutr.* **2007**, *53*, 668–677. [\[CrossRef\]](#)
47. Thanawong, K.; Perret, S.R.; Basset-Mens, C. Eco-Efficiency of Paddy Rice Production in Northeastern Thailand: A Comparison of Rain-Fed and Irrigated Cropping Systems. *J. Clean. Prod.* **2014**, *73*, 204–217. [\[CrossRef\]](#)
48. Xue, J.-F.; Pu, C.; Liu, S.-L.; Zhao, X.; Zhang, R.; Chen, F.; Xiao, X.-P.; Zhang, H.-L. Carbon and Nitrogen Footprint of Double Rice Production in Southern China. *Ecol. Indic.* **2016**, *64*, 249–257. [\[CrossRef\]](#)
49. Habibi, E.; Niknejad, Y.; Fallah, H.; Dastan, S.; Tari, D.B. Life Cycle Assessment of Rice Production Systems in Different Paddy Field Size Levels in North of Iran. *Environ. Monit. Assess.* **2019**, *191*, 202. [\[CrossRef\]](#)
50. Khoshnevisan, B.; Rajaeifar, M.A.; Clark, S.; Shamahirband, S.; Anuar, N.B.; Mohd Shuib, N.L.; Gani, A. Evaluation of Traditional and Consolidated Rice Farms in Guilan Province, Iran, Using Life Cycle Assessment and Fuzzy Modeling. *Sci. Total Environ.* **2014**, *481*, 242–251. [\[CrossRef\]](#)
51. Youseftabar, S.; Sharifabad, H.H.; Heravan, I.M. Life Cycle Assessment of Rice Cropping Systems in Traditional and Semi-Mechanized Planting Patterns in Northern Iran. *AGBIR* **2021**, *37*, 195–202.
52. Houshyar, E.; Chen, B.; Chen, G.Q. Environmental Impacts of Rice Production Analyzed via Social Capital Development: An Iranian Case Study with a Life Cycle Assessment/Data Envelopment Analysis Approach. *Ecol. Indic.* **2019**, *105*, 675–687. [\[CrossRef\]](#)
53. Dastan, S.; Ghareyazie, B.; Teixeira da Silva, J.A.; Pishgar-Komleh, S.H. Assessment of the Life Cycle of Genetically Modified and Non-Genetically Modified Rice Cultivars. *Arab. J. Geosci.* **2020**, *13*, 362. [\[CrossRef\]](#)
54. Dastan, S.; Ghareyazie, B.; Pishgar, S.H. Environmental Impacts of Transgenic Bt Rice and Non-Bt Rice Cultivars in Northern Iran. *Biocatal. Agric. Biotechnol.* **2019**, *20*, 101160. [\[CrossRef\]](#)
55. Tayefeh, M.; Sadeghi, S.M.; Noorhosseini, S.A.; Bacenetti, J.; Damalas, C.A. Environmental Impact of Rice Production Based on Nitrogen Fertilizer Use. *Environ. Sci. Pollut. Res.* **2018**, *25*, 15885–15895. [\[CrossRef\]](#) [\[PubMed\]](#)
56. Morandini, N.P.; Petroudi, E.R.; Mobasser, H.R.; Dastan, S. Life Cycle Assessment of Crop Rotation Systems on Rice Cultivars in Northern Iran. *Int. J. Plant Prod.* **2020**, *14*, 531–548. [\[CrossRef\]](#)
57. Shew, A.M.; Durand-Morat, A.; Putman, B.; Nalley, L.L.; Ghosh, A. Rice Intensification in Bangladesh Improves Economic and Environmental Welfare. *Environ. Sci. Policy* **2019**, *95*, 46–57. [\[CrossRef\]](#)
58. McFadden, B.R.; Nalley, L.L.; Popp, M.P. How Greenhouse Gas Emission Policy and Industry Pressure Could Affect Producer Selection of Rice Cultivars. *Agric. Resour. Econ. Rev.* **2013**, *42*, 325–348. [\[CrossRef\]](#)
59. Pradhan, P.; Fischer, G.; van Velthuis, H.; Reusser, D.E.; Kropp, J.P. Closing Yield Gaps: How Sustainable Can We Be? *PLoS ONE* **2015**, *10*, e0129487. [\[CrossRef\]](#)
60. Khatri, P.; Pandit, A.B. Systematic Review of Life Cycle Assessments Applied to Sugarcane Bagasse Utilization Alternatives. *Biomass Bioenergy* **2022**, *158*, 106365. [\[CrossRef\]](#)

61. Mendonça, L.A.; Loomis, J.J.; Limont, M.; Bartz, M.L.C.; Rauen, W.B. Elements of the Water-Food-Environment Nexus for Integrated Sustainability Analysis. *Sci. Total Environ.* **2023**, *905*, 166866. [\[CrossRef\]](#)
62. Mazandaran Province Agricultural Jihad Organization Introduction of the Organization. Available online: <https://jkmaz.ir/Home/ShowDetailsMenuContent?MenuId=9> (accessed on 6 August 2022).
63. Mahdavi, H.; Allahyari, M.S.; Damalas, C.A.; Dunn, E.S. Drivers and Barriers for Organic Rice (*Oryza sativa* L.) Production in Northern Iran: Experts' Consensus Using the Delphi Method. *Biol. Agric. Hortic.* **2020**, *36*, 96–106. [\[CrossRef\]](#)
64. Amini, S.; Rohani, A.; Aghkhani, M.H.; Abbaspour-Fard, M.H.; Asgharipour, M.R. Sustainability Assessment of Rice Production Systems in Mazandaran Province, Iran with Emergy Analysis and Fuzzy Logic. *Sustain. Energy Technol. Assess.* **2020**, *40*, 100744. [\[CrossRef\]](#)
65. Sharifzadeh, M.S.; Abdollahzadeh, G. The Impact of Different Education Strategies on Rice Farmers' Knowledge, Attitude and Practice (KAP) about Pesticide Use. *J. Saudi Soc. Agric. Sci.* **2021**, *20*, S1658077X21000333. [\[CrossRef\]](#)
66. Khoshbakht, K.; Hammer, K. Savadkouh (Iran)—An Evolutionary Centre for Fruit Trees and Shrubs. *Genet. Resour. Crop Evol.* **2006**, *53*, 641–651. [\[CrossRef\]](#)
67. Sarvestani, Z.T.; Pirdashti, H.; Sanavy, S.A.M.M.; Balouchi, H. Study of Water Stress Effects in Different Growth Stages on Yield and Yield Components of Different Rice (*Oryza sativa* L.) Cultivars. *Pak. J. Biol. Sci.* **2008**, *11*, 1303–1309. [\[CrossRef\]](#) [\[PubMed\]](#)
68. Ashoori, D.; Allahyari, M.S.; Bagheri, A.; Damalas, C.A. Adoption Determinants of Modern Rice Cultivars among Smallholders of Northern Iran. *Agriculture* **2019**, *9*, 232. [\[CrossRef\]](#)
69. Esfandiari, M.; Mirzaei Khalilabad, H.R.; Boshrahadi, H.M.; Mehrjerdi, M.R.Z. Factors Influencing the Use of Adaptation Strategies to Climate Change in Paddy Lands of Kamfiruz, Iran. *Land Use Policy* **2020**, *95*, 104628. [\[CrossRef\]](#)
70. Yousefian, M.; Soltani, A.; Dastan, S.; Ajamnoroozie, H. Yield Gap Assessment in Rice-Grown Fields Using CPA and BLA Approaches in Northern Iran. *Int. J. Plant Prod.* **2021**, *15*, 203–217. [\[CrossRef\]](#)
71. Goli, I.; Azadi, H.; Nooripoor, M.; Baig, M.B.; Viira, A.-H.; Ajtai, I.; Özgüven, A.I. Evaluating the Productivity of Paddy Water Resources through SWOT Analysis: The Case of Northern Iran. *Water* **2021**, *13*, 2964. [\[CrossRef\]](#)
72. Modiri, E.; Barari Tari, D.; Amiri, E.; Niknejad, Y.; Fallah, H.; Khazaei, M. Assessment and Estimation of Evapotranspiration of Rice Plant in Northern Provinces of Iran. *Geogr. (Reg. Plan.)* **2019**, *8*, 561–572.
73. Mirzaei, A.; Knierim, A.; Fealy Nahavand, S.; Mahmoudi, H. Gap Analysis of Water Governance in Northern Iran: A Closer Look into the Water Reservoirs. *Environ. Sci. Policy* **2017**, *77*, 98–106. [\[CrossRef\]](#)
74. Shirzadi Laskookalayeh, S.; Mardani Najafabadi, M.; Shahnazari, A. Investigating the Effects of Management of Irrigation Water Distribution on Farmers' Gross Profit under Uncertainty: A New Positive Mathematical Programming Model. *J. Clean. Prod.* **2022**, *351*, 131277. [\[CrossRef\]](#)
75. Motevalli, A.; Moradi, H.R.; Javadi, S. A Comprehensive Evaluation of Groundwater Vulnerability to Saltwater Up-Coning and Sea Water Intrusion in a Coastal Aquifer (Case Study: Ghaemshahr-Juybar Aquifer). *J. Hydrol.* **2018**, *557*, 753–773. [\[CrossRef\]](#)
76. Pourgholam-Amiji, M.; Liaghat, A.; Khoshravesh, M.; Azamathulla, H.M. Improving Rice Water Productivity Using Alternative Irrigation (Case Study: North of Iran). *Water Supply* **2021**, *21*, 1216–1227. [\[CrossRef\]](#)
77. Brentrup, F.; Küsters, J.; Kuhlmann, H.; Lammel, J. Environmental Impact Assessment of Agricultural Production Systems Using the Life Cycle Assessment Methodology: I. Theoretical Concept of a LCA Method Tailored to Crop Production. *Eur. J. Agron.* **2004**, *20*, 247–264. [\[CrossRef\]](#)
78. Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E.; Weidema, B. The Ecoinvent Database Version 3 (Part i): Overview and Methodology. *Int. J. Life Cycle Assess.* **2016**, *21*, 1218–1230. [\[CrossRef\]](#)
79. Krejcie, R.V.; Morgan, D.W. Determining Sample Size for Research Activities. *Educ. Psychol. Meas.* **1970**, *30*, 607–610. [\[CrossRef\]](#)
80. Vahedi, A. Energy Analysis of Three Rice Cultivar Using Different Production Methods, Case Study: Iran. *Agric. Eng. Int. CIGR J.* **2021**, *23*, 148–158.
81. Carrijo, D.R.; Lundy, M.E.; Linnquist, B.A. Rice Yields and Water Use under Alternate Wetting and Drying Irrigation: A Meta-Analysis. *Field Crops Res.* **2017**, *203*, 173–180. [\[CrossRef\]](#)
82. IPCC Cropland. In *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*; Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P., Federici, S., Eds.; IPCC-Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2019; Volume 4, ISBN 978-4-88788-232-4.
83. Nemecek, T.; Kägi, T. *Life Cycle Inventories of Agricultural Production Systems*; Agroscope Reckenholz-Taenikon Research Station ART: Zürich, Switzerland; Swiss Centre for Life Cycle Inventories: Dübendorf, Switzerland, 2007; p. 360.
84. Galloway, J.N.; Schlesinger, W.H.; Levy, H.; Michaels, A.; Schnoor, J.L. Nitrogen Fixation: Anthropogenic Enhancement-Environmental Response. *Glob. Biogeochem. Cycles* **1995**, *9*, 235–252. [\[CrossRef\]](#)
85. Erickson, J.E.; Cisar, J.L.; Volin, J.C.; Snyder, G.H. Comparing Nitrogen Runoff and Leaching between Newly Established St. Augustinegrass Turf and an Alternative Residential Landscape. *Crop Sci.* **2001**, *41*, 1889–1895. [\[CrossRef\]](#)
86. Audsley, E.; Alber, S.; Clift, R.; Cowell, S.; Crettaz, P.; Gaillard, G.; Hausheer, J.; Jolliet, O.; Kleijn, R.; Mortensen, B.; et al. *Harmonisation of Environmental Life Cycle Assessment for Agriculture*; Final Report, Concerted Action AIR3-CT94-2028; Silsoe Research Institute: Silsoe, UK; European Commission, DG VI Agriculture: Brussels, Belgium, 2003; p. 101.
87. Margni, M.; Rossier, D.; Crettaz, P.; Jolliet, O. Life Cycle Impact Assessment of Pesticides on Human Health and Ecosystems. *Agric. Ecosyst. Environ.* **2002**, *93*, 379–392. [\[CrossRef\]](#)

88. Lovarelli, D.; Bacenetti, J. Exhaust Gases Emissions from Agricultural Tractors: State of the Art and Future Perspectives for Machinery Operators. *Biosyst. Eng.* **2019**, *186*, 204–213. [\[CrossRef\]](#)
89. Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.D.M.; Hollander, A.; Zijp, M.; van Zelm, R. *A Harmonized Life Cycle Impact Assessment Method at Midpoint and Endpoint Level Report I: Characterization*; National Institute for Public Health and the Environment: Bilthoven, The Netherlands, 2016.
90. Hauschild, M.Z.; Goedkoop, M.; Guinée, J.; Heijungs, R.; Huijbregts, M.; Joliet, O.; Margni, M.; De Schryver, A.; Humbert, S.; Laurent, A.; et al. Identifying Best Existing Practice for Characterization Modeling in Life Cycle Impact Assessment. *Int. J. Life Cycle Assess.* **2013**, *18*, 683–697. [\[CrossRef\]](#)
91. Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; Hollander, A.; van Zelm, R. ReCiPe2016: A Harmonised Life Cycle Impact Assessment Method at Midpoint and Endpoint Level. *Int. J. Life Cycle Assess.* **2017**, *22*, 138–147. [\[CrossRef\]](#)
92. Bare, J.C.; Hofstetter, P.; Pennington, D.W.; de Haes, H.A.U. Midpoints versus Endpoints: The Sacrifices and Benefits. *Int. J. Life Cycle Assess.* **2000**, *5*, 319. [\[CrossRef\]](#)
93. Dekker, E.; Zijp, M.C.; van de Kamp, M.E.; Temme, E.H.M.; van Zelm, R. A Taste of the New ReCiPe for Life Cycle Assessment: Consequences of the Updated Impact Assessment Method on Food Product LCAs. *Int. J. Life Cycle Assess.* **2020**, *25*, 2315–2324. [\[CrossRef\]](#)
94. Nemecek, T.; Bengoa, X.; Lansche, J.; Roesch, A.; Faist-Emmenegger, M.; Rossi, V.; Humbert, S. *Methodological Guidelines for the Life Cycle Inventory of Agricultural Products*; World Food LCA Database (WFLDB); Quantis and Agroscope: Lausanne, Switzerland; Zurich, Switzerland, 2019.
95. Frigerio, V.; Casson, A.; Limbo, S. Comparison of Different Methodological Choices in Functional Unit Selection and Results Implication When Assessing Food-Packaging Environmental Impact. *J. Clean. Prod.* **2023**, *396*, 136527. [\[CrossRef\]](#)
96. Prado, V.; Wender, B.A.; Seager, T.P. Interpretation of Comparative LCAs: External Normalization and a Method of Mutual Differences. *Int. J. Life Cycle Assess.* **2017**, *22*, 2018–2029. [\[CrossRef\]](#)
97. Pizzol, M.; Laurent, A.; Sala, S.; Weidema, B.; Verones, F.; Koffler, C. Normalisation and Weighting in Life Cycle Assessment: Quo Vadis? *Int. J. Life Cycle Assess.* **2017**, *22*, 853–866. [\[CrossRef\]](#)
98. Mirhaji, H.; Khojastehpour, M.; Abaspour-Fard, M.H. Environmental Impact Study of Wheat Production in Marvdasht Area of IRAN. *J. Nat. Environ.* **2013**, *66*, 223–232. [\[CrossRef\]](#)
99. Nikkhah, A. Life Cycle Assessment of the Agricultural Sector in Iran (2007–2014). *Environ. Prog. Sustain. Energy* **2018**, *37*, 1750–1757. [\[CrossRef\]](#)
100. Mousavi-Avval, S.H.; Rafiee, S.; Sharifi, M.; Hosseinpour, S.; Notarnicola, B.; Tassielli, G.; Renzulli, P.A. Application of Multi-Objective Genetic Algorithms for Optimization of Energy, Economics and Environmental Life Cycle Assessment in Oilseed Production. *J. Clean. Prod.* **2017**, *140*, 804–815. [\[CrossRef\]](#)
101. Naderi, S.A.; Dehkordi, A.L.; Taki, M. Energy and Environmental Evaluation of Greenhouse Bell Pepper Production with Life Cycle Assessment Approach. *Environ. Sustain. Indic.* **2019**, *3–4*, 100011. [\[CrossRef\]](#)
102. Mohammadi, A.; Rafiee, S.; Jafari, A.; Keyhani, A.; Dalgaard, T.; Knudsen, M.T.; Nguyen, T.L.T.; Borek, R.; Hermansen, J.E. Joint Life Cycle Assessment and Data Envelopment Analysis for the Benchmarking of Environmental Impacts in Rice Paddy Production. *J. Clean. Prod.* **2015**, *106*, 521–532. [\[CrossRef\]](#)
103. Rezaei, M.; Soheilifard, F.; Keshvari, A. Impact of Agrochemical Emission Models on the Environmental Assessment of Paddy Rice Production Using Life Cycle Assessment Approach. *Energy Sources Part A Recovery Util. Environ. Eff.* **2021**, *0*, 1–16. [\[CrossRef\]](#)
104. Motevali, A.; Hashemi, S.J.; Tabatabaekoloor, R. Environmental Footprint Study of White Rice Production Chain-Case Study: Northern of Iran. *J. Environ. Manag.* **2019**, *241*, 305–318. [\[CrossRef\]](#) [\[PubMed\]](#)
105. Nabavi-Pelesaraei, A.; Rafiee, S.; Mohtasebi, S.S.; Hosseinzadeh-Bandbafha, H.; Chau, K. Integration of Artificial Intelligence Methods and Life Cycle Assessment to Predict Energy Output and Environmental Impacts of Paddy Production. *Sci. Total Environ.* **2018**, *631–632*, 1279–1294. [\[CrossRef\]](#) [\[PubMed\]](#)
106. Saber, Z.; Esmaeili, M.; Pirdashti, H.; Motevali, A.; Nabavi-Pelesaraei, A. Exergoenvironmental-Life Cycle Cost Analysis for Conventional, Low External Input and Organic Systems of Rice Paddy Production. *J. Clean. Prod.* **2020**, *263*, 121529. [\[CrossRef\]](#)
107. Nikkhah, A.; Firouzi, S.; El Haj Assad, M.; Ghnimi, S. Application of Analytic Hierarchy Process to Develop a Weighting Scheme for Life Cycle Assessment of Agricultural Production. *Sci. Total Environ.* **2019**, *665*, 538–545. [\[CrossRef\]](#)
108. Helmes, R.J.K.; Huijbregts, M.A.J.; Henderson, A.D.; Joliet, O. Spatially Explicit Fate Factors of Phosphorous Emissions to Freshwater at the Global Scale. *Int. J. Life Cycle Assess.* **2012**, *17*, 646–654. [\[CrossRef\]](#)
109. De Laurentiis, V.; Amadei, A.; Sanyé-Mengual, E.; Sala, S. Exploring Alternative Normalization Approaches for Life Cycle Assessment. *Int. J. Life Cycle Assess.* **2023**, *28*, 1382–1399. [\[CrossRef\]](#)
110. Biswas, J.C.; Mamiruzzaman, M.; Haque, M.M.; Hossain, M.B.; Naher, U.A.; Akhtar, S.; Rahman, M.M.; Akhter, S.; Ahmed, F.; Biswas, J.K. Greenhouse Gas Emissions from Paddy Fields in Bangladesh Compared to Top Twenty Rice Producing Countries and Emission Reduction Strategies. *Paddy Water Environ.* **2022**, *20*, 381–393. [\[CrossRef\]](#)
111. Hussain, S.; Peng, S.; Fahad, S.; Khaliq, A.; Huang, J.; Cui, K.; Nie, L. Rice Management Interventions to Mitigate Greenhouse Gas Emissions: A Review. *Environ. Sci. Pollut. Res.* **2015**, *22*, 3342–3360. [\[CrossRef\]](#) [\[PubMed\]](#)
112. Gava, O.; Antón, A.; Carmassi, G.; Pardossi, A.; Incrocci, L.; Bartolini, F. Reusing Drainage Water and Substrate to Improve the Environmental and Economic Performance of Mediterranean Greenhouse Cropping. *J. Clean. Prod.* **2023**, *413*, 137510. [\[CrossRef\]](#)

113. Bakhshandeh, E.; Jamali, M.; Emadi, M.; Francaviglia, R. Greenhouse Gas Emissions and Financial Analysis of Rice Paddy Production Scenarios in Northern Iran. *Agric. Water Manag.* **2022**, *272*, 107863. [[CrossRef](#)]
114. Islam Bhuiyan, M.S.; Rahman, A.; Kim, G.W.; Das, S.; Kim, P.J. Eco-Friendly Yield-Scaled Global Warming Potential Assists to Determine the Right Rate of Nitrogen in Rice System: A Systematic Literature Review. *Environ. Pollut.* **2021**, *271*, 116386. [[CrossRef](#)] [[PubMed](#)]
115. Wang, H.; Zhang, Y.; Zhang, Y.; McDaniel, M.D.; Sun, L.; Su, W.; Fan, X.; Liu, S.; Xiao, X. Water-Saving Irrigation Is a ‘Win-Win’ Management Strategy in Rice Paddies—With Both Reduced Greenhouse Gas Emissions and Enhanced Water Use Efficiency. *Agric. Water Manag.* **2020**, *228*, 105889. [[CrossRef](#)]
116. Rakshit, M. Some Economics of Fertiliser Subsidy. *J. Quant. Econ.* **2018**, *16*, 209–228. [[CrossRef](#)]
117. Tyson, J.; Diwakar, V.; Adetutu, M.; Bishop, J. *Inclusive Economic Growth in Kenya: The Spatial Dynamics of Poverty*; ODI reports; Overseas Development Institute (ODI): London, UK, 2020.
118. Jamali, M.; Bakhshandeh, E.; Emadi, M. Effects of Water Source and Technology on Energy Use and Environmental Impacts of Rice Production in Northern Iran. *Water Resour. Res.* **2022**, *58*, e2021WR031546. [[CrossRef](#)]
119. Cosme, N.; Mayorga, E.; Hauschild, M.Z. Spatially Explicit Fate Factors of Waterborne Nitrogen Emissions at the Global Scale. *Int. J. Life Cycle Assess.* **2018**, *23*, 1286–1296. [[CrossRef](#)]
120. Harun, S.N.; Hanafiah, M.M.; Aziz, N.I.H.A. An LCA-Based Environmental Performance of Rice Production for Developing a Sustainable Agri-Food System in Malaysia. *Environ. Manag.* **2021**, *67*, 146–161. [[CrossRef](#)] [[PubMed](#)]
121. Amirnejad, H.; Fazelian, S.; Yekani, S.A.H. Determining the water economic value for quality and high-yielding rice (case study Behshahr plain, Mazandaran province). *J. Agric. Econ. Res.* **2018**, *10*, 241–259.
122. Abedani, P.; Ramezani, Y.; Firoozzare, A. Identifying and Prioritizing Factors Affecting Consumers Preferences in Choosing Iranian and Foreign Rice (Case Study Location: Mashhad). *J. Agric. Econ. Dev.* **2022**, *36*, 1–15. [[CrossRef](#)]
123. Amirnejad, H.; Mirkarimi, S.; Tonakbar, P.; Heidari, N. Investigation of consumer’s preferences of rice by applying choice modeling approach with emphasis on national production: Case study of Gorgan. *J. Agric. Econ. Res.* **2019**, *11*, 279–391.
124. Masuda, K. Eco-Efficiency Assessment of Intensive Rice Production in Japan: Joint Application of Life Cycle Assessment and Data Envelopment Analysis. *Sustainability* **2019**, *11*, 5368. [[CrossRef](#)]
125. Zheng, H.; Huang, H.; Yao, L.; Liu, J.; He, H.; Tang, J. Impacts of Rice Varieties and Management on Yield-Scaled Greenhouse Gas Emissions from Rice Fields in China: A Meta-Analysis. *Biogeosciences* **2014**, *11*, 3685–3693. [[CrossRef](#)]
126. Tricase, C.; Lamonaca, E.; Ingrao, C.; Bacenetti, J.; Lo Giudice, A. A Comparative Life Cycle Assessment between Organic and Conventional Barley Cultivation for Sustainable Agriculture Pathways. *J. Clean. Prod.* **2018**, *172*, 3747–3759. [[CrossRef](#)]
127. Jourdain, M.; Loubet, P.; Trebucq, S.; Sonnemann, G. A Detailed Quantitative Comparison of the Life Cycle Assessment of Bottled Wines Using an Original Harmonization Procedure. *J. Clean. Prod.* **2020**, *250*, 119472. [[CrossRef](#)]
128. Fan, J.; Liu, C.; Xie, J.; Han, L.; Zhang, C.; Guo, D.; Niu, J.; Jin, H.; McConkey, B.G. Life Cycle Assessment on Agricultural Production: A Mini Review on Methodology, Application, and Challenges. *Int. J. Environ. Res. Public Health* **2022**, *19*, 9817. [[CrossRef](#)] [[PubMed](#)]
129. Firouzi, S.; Nikkhah, A.; Aminpanah, H. Rice Single Cropping or Ratooning Agro-System: Which One Is More Environment-Friendly? *Environ. Sci. Pollut. Res.* **2018**, *25*, 32246–32256. [[CrossRef](#)] [[PubMed](#)]
130. Nabavi-Pelesaraei, A.; Rafiee, S.; Mohtasebi, S.S.; Hosseinzadeh-Bandbafha, H.; Chau, K. Energy Consumption Enhancement and Environmental Life Cycle Assessment in Paddy Production Using Optimization Techniques. *J. Clean. Prod.* **2017**, *162*, 571–586. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.