Investigating the impact of integrating land consolidation with agricultural mechanization on the technical, energy, and environmental dimensions of paddy production

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Abstract

This research investigates how the integration of land consolidation and agricultural mechanization can enhance the technical efficiency, energy consumption, and environmental sustainability of paddy cultivation compared to conventional farming practices. Our primary objective is to assess whether consolidated and mechanized farming systems result in higher productivity and lower energy use, while also reducing environmental impacts such as greenhouse gas emissions, water consumption, and soil erosion. Conventional farming methods, characterized by fragmented land holdings, often lead to inefficiencies and environmental harm. By merging smaller plots into larger, contiguous fields, we aim to boost farming efficiency and facilitate the adoption of agricultural machinery. This study will analyze three distinct cultivation scenarios: i) conventional fragmented fields relying on manual labor, ii) integrated fields utilizing manual labor, and iii) integrated fields employing mechanization. We will evaluate key technical indicators, including crop yield, labor productivity, and crop quality, alongside energy consumption metrics like fuel and electricity usage. Furthermore, will assess the environmental implications of each scenario, focusing on greenhouse gas emissions, water usage, and soil erosion. The findings from this research will enhance our understanding of the combined effects of land consolidation and mechanization in paddy farming. Additionally, the insights gained will provide valuable guidance for policymakers and farmers, promoting sustainable practices in paddy cultivation that support food security while minimizing negative environmental impacts. This investigation aims to distinguish itself by examining the synergistic potential of land consolidation and mechanization, rather than considering them in isolation as has been done in previous studies.

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Introduction

Rice cultivation, commonly referred to as paddy production, is a vital agricultural practice that greatly contributes to food security and the sustenance of rural communities worldwide. Nevertheless, traditional approaches to paddy production frequently entail labor-intensive techniques and inefficient resource utilization, resulting in a multitude of technical, energy, and environmental obstacles (Koga and Tajima, 2011). Recently, there has been an increasing focus on studying the effects of land consolidation and agricultural mechanization on rice cultivation. Land consolidation involves merging smaller land plots into larger, more productive areas, while agricultural mechanization utilizes machinery and technology to improve efficiency in farming operations (Devendra and Leng, 2011). Studying the influence of combining land consolidation and agricultural mechanization on rice farming in different cultivation scenarios is essential for grasping the potential advantages and obstacles linked to these methods (Marohn *et al*., 2013). This assessment includes examining technical factors like enhancing yield, labor needs, and efficiency in production. It also assesses energy considerations, including fuel usage and energy efficiency, along with environmental effects like greenhouse gas emissions, water consumption, and soil degradation (Algarni *et al*., 2023). Through analyzing various cultivation scenarios, researchers and policymakers can acquire an understanding of the possible trade-offs and synergies between land integration, agricultural mechanization, and sustainable paddy production (Nabavi-Pelesaraei *et al*., 2018). This information can guide decision-making processes to create strategies and policies that support efficient resource utilization, increase productivity, and reduce adverse environmental effects. It is crucial to study the effects of land consolidation and agricultural mechanization on technical, energy, and environmental aspects in paddy production to advance sustainable and resilient agricultural systems (Kaab *et al*., 2019a). It offers valuable knowledge on how these methods can enhance food security, support rural livelihoods, and promote environmental sustainability within the realm of rice farming. The influence of land consolidation and farm machinery on rice cultivation has captured the attention of agricultural experts and decision-makers (Van Loon *et al*., 2020). Nevertheless, a thorough evaluation of this influence is required, considering the technical, energy, and environmental aspects involved in various cultivation settings. An inventive method to analyze this impact could involve adopting a systems thinking approach that acknowledges the interconnectedness and feedback loops within different elements of the agricultural system (Mohammadi Kashka *et al.*, 2023). This strategy entails gathering data on various elements of rice cultivation, including land utilization, crop yield, energy usage, greenhouse gas emissions, and water consumption. With this information, scientists can create models to forecast the effects of land management and agricultural mechanization on technical, energy, and ecological considerations in various farming scenarios (Grados and Schrevens, 2019). These models have the potential to identify both trade-offs and synergies among various factors, enabling the development of strategies that maximize the agricultural system's overall performance. An additional cutting-edge method involves utilizing advanced technologies like remote sensing, drones, and precision agriculture to gather data on diverse elements of paddy cultivation (Goossens *et al*., 2017). Lately, there has been a strong focus in the agricultural industry on studying how energy consumption and environmental emissions affect agricultural products. (Khan *et al*., 2010) found that rice exhibits an energy efficiency of 70.6%, with a notable portion of the energy input in rice cultivation attributed to chemical fertilizers (43%). In a separate study by (Khan *et al*., 2009), the researchers calculated the proportion of water energy utilized in canal and pump irrigation systems for wheat, rice, and barley. Khosruzzaman *et al.* (2010) conducted a study on rice production in Bangladesh, analyzing input and output energy values. Likewise, Kosemani and Bamgboye (2020) observed that optimizing resource management on large farms can enhance energy efficiency. Recent research by Guo *et al*. (2022) and Yue *et al.* (2022) investigated the impact of mechanization on fuel, fertilizer, and water usage in fully mechanized and semi-mechanized rice production systems. Furthermore, Mohammadi *et al.* (2015) compared the environmental effects of rice cultivation in spring and summer, finding that spring planting had a lower environmental impact.

The novelty of this research lies in its comprehensive examination of the synergistic effects of land consolidation and agricultural mechanization on paddy cultivation, an aspect not adequately addressed in prior studies. By integrating these two approaches, the research goes beyond evaluating them in isolation, focusing instead on how their combined application can significantly enhance technical efficiency, reduce energy consumption, and promote environmental sustainability. The study's primary objective is to determine whether the adoption of consolidated and mechanized farming systems can lead to increased productivity and decreased energy use, while simultaneously mitigating adverse environmental impacts such as greenhouse gas emissions, excessive water consumption, and soil erosion. Conventional farming practices, which typically involve fragmented land holdings and rely heavily on manual labor, often result in inefficiencies that contribute to environmental degradation. This research proposes that by merging smaller plots into larger, contiguous fields, farmers can improve efficiency and facilitate the use of agricultural machinery. To investigate this, three distinct cultivation scenarios will be analyzed: conventional fragmented fields that depend on manual labor, integrated fields that still rely on manual labor, and integrated fields optimized through mechanization. Key technical indicators including crop yield, labor productivity, and crop quality will be evaluated alongside energy consumption metrics such as fuel and electricity usage. Additionally, the environmental implications of each scenario will be assessed, with a focus on greenhouse gas emissions, water usage, and soil erosion. Through these analyses, the research aims to provide a deeper understanding of how the integration of land consolidation and mechanization can transform paddy farming practices. The insights gained from this study are intended to offer valuable guidance for policymakers and farmers alike, promoting sustainable agricultural practices that ensure food security while minimizing negative environmental impacts.

This data could be used to develop more accurate models that capture the spatial and temporal variability of different factors in the agricultural system. Overall, examining the impact of land consolidation and agricultural mechanization on paddy production in a comprehensive and innovative manner could provide valuable insights for policymakers and agricultural practitioners on how to optimize the performance of the agricultural system while minimizing its environmental impact. The aim of the study is to examine the impact of land consolidation and agricultural mechanization on technical, energy, and environmental aspects in paddy production across different cultivation scenarios.

i) Assess the technical efficiency of land consolidation and agricultural mechanization in paddy production. This involves evaluating the effectiveness of integrating multiple plots of land and implementing mechanized farming techniques in improving productivity and yield; ii) evaluate the energy efficiency of land consolidation and agricultural mechanization. This includes examining the energy inputs required for various cultivation scenarios, such as fuel consumption for machinery and irrigation systems, and comparing them to the energy outputs in terms of crop yield;

iii) analyze the environmental impacts of land consolidation and agricultural mechanization. This involves assessing the effects on soil quality, water consumption, greenhouse gas emissions, and biodiversity in different cultivation scenarios; iv) analyze the cumulative exergy demand (CExD) of paddy production in different method of cultivation. In general, the research endeavors to offer perspectives on the possible advantages and drawbacks of merging land and utilizing machinery in cultivating rice paddy. This will aid policymakers and farmers in making informed choices to enhance efficiency, energy conservation, and ecological sustainability in paddy farming.

Materials and Methods

This research gathered data in Guilan province, Iran, known for its distinctive climate and natural features in comparison to other regions of the country. Positioned on the southwest coast of the Caspian Sea, the province is situated at latitudes between 36°34' and 38°27'N and at longitudes between 48° 53' and 50° 34'E (Ministry of Agriculture Jihad, 2021). The location of the case study is depicted in Figure 1.

One hundred and twenty paddy producers were randomly surveyed to collect data on agricultural input parameters including seed quantities, fertilizer, biocides, energy conduits, equipment and machinery, cultivated land areas, and paddy yield. The sampling size was determined using the method described by Kaab *et* *al.* (2019b), and the data was gathered through face-to-face questionnaires.

$$n=\frac{\frac{z^2pq}{d^2}}{1+\frac{1}{N}\left(\frac{z^2pq}{d^2}-1\right)} \quad \text{(Eq. 1)}$$

The required sample size (n) is determined by the number of farms per target population (N), the reliability coefficient (z) which equals 1.96 representing a 95% confidence level, the estimated proportion of an attribute in the population (p) which equals 0.5, the complement of the estimated proportion (q) which also equals 0.5, and the permitted error ratio deviation from the average population (d) which equals 0.05.

Paddy cultivation

Hashemi and Khazar rice are two popular varieties of rice that are produced in different regions of Iran. The production process for both types of rice involves several steps, including cultivation, harvesting, processing, and packaging. Paddy cultivation typically takes place in flooded fields, known as paddy fields, where the rice plants are grown. The cultivation process involves preparing the field, planting the rice seeds, and maintaining the proper water levels and soil conditions for the rice to grow. Once the rice plants have matured and the grains have developed, they are ready to be harvested. The harvesting process involves cutting the rice plants and collecting the grains, which are then dried to prepare them for processing. The processing of rice involves several steps, including milling, polishing, and sorting. The rice grains are first milled to remove the outer husk, bran, and germ, leaving behind the white rice kernel. The rice is then polished to remove any remaining bran and make the grains shiny. Finally, the rice is sorted to remove any impurities and ensure uniformity in size and quality. After processing, the rice is packaged in various sizes and types of packaging, such as bags or containers, for distribution and sale. The production of Hashemi and Khazar rice follows these general steps, but the specific details of the production process may vary depending on the region and the methods used by individual producers. Both types of rice are known for their high quality and are popular choices for cooking traditional Persian dishes (Molaee Jafrodi *et al*., 2022).

Energy use

Energy is a fundamental driver of societal development and national success, playing a vital role in fostering economic growth, enhancing social well-being, and improving overall quality of life and security in a community (Ghasemi-Mobtaker *et al*., 2020). All forms of energy have the inherent capability to perform work, as energy signifies the potential to do so. Despite their diverse forms, the energy content of inputs and outputs serves as a reflection of the system's energy equivalence (Taherzadeh-Shalmaei *et al*., 2021). For instance, in the context of gathering inputs for paddy production, which includes human labor, machinery, diesel fuel, chemical fertilizers, biocides, water, electricity, and seeds, data was collected through questionnaires and farmer interviews. The amounts of each input and output were assessed per hectare of arable land and then converted into energy equivalents using specific coefficients for comparative purposes. The energy equivalent of each input is detailed in Table 1.

The energy performance of each planting system was assessed by analyzing various energy metrics such as energy ratio, efficiency, productivity, specific energy, and net energy efficiency. This evaluation involved estimating the total input and output energies (Mohseni *et al*., 2018). The correlation between input and output

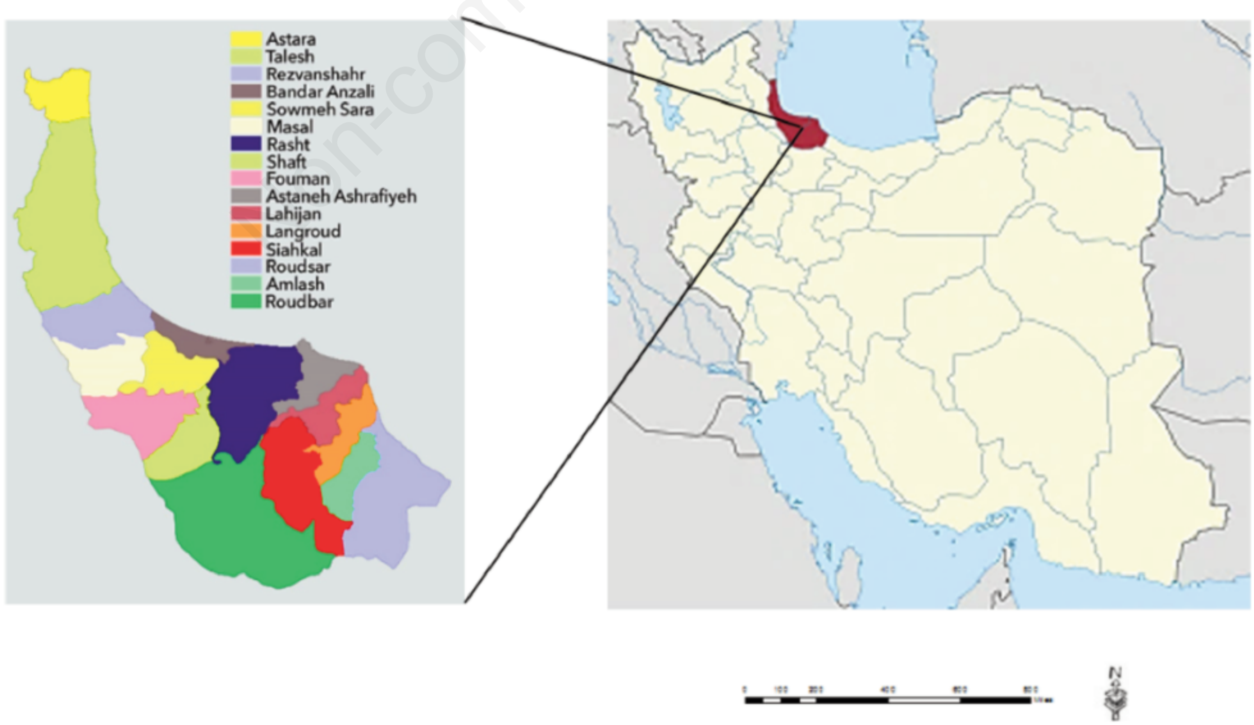

Figure 1. The studied area is located in northern Iran.

energy per hectare was examined using these metrics, taking into account factors like crop and soil types, tillage methods, use of chemical and livestock fertilizers, storage, maintenance, and harvesting procedures (Askari Sari and Mohammadi, 2015). Energy efficiency, represented by Eq. 2 as the ratio of energy input to energy output within a system, was a key aspect considered in these assessments.

$$\text{Energy use efficiency} = \frac{\text{Output energy (MJ)}}{\text{Input energy (MJ)}} \quad \text{(Eq. 2)}$$

$$\text{Energy productivity} = \frac{\text{Production (kg)}}{\text{Input energy (MJ)}} \quad \text{(Eq. 3)}$$

$$\text{Specific energy} = \frac{\text{Input energy (MJ)}}{\text{Production (kg)}} \quad \text{(Eq. 4)}$$

$$\text{Net energy} = \text{Output energy (MJ)} - \text{Input energy (MJ)} \quad \text{(Eq. 5)}$$

Eq. 3 describes energy productivity as the ratio of goods and services produced to the energy consumed, highlighting the value added for a specific energy input. A higher value signifies greater energy efficiency and productivity (Yang *et al*., 2011). In contrast, Eq. 4 defines energy intensity as the energy consumed per unit of goods and services output, crucial for understanding energy efficiency and production energy requirements. Energy productivity and energy intensity are inversely correlated; increased energy productivity corresponds to decreased energy intensity. Thus, a higher energy productivity index indicates reduced energy consumption in goods and services production, while a lower index suggests the contrary. Eq. 5 specifies net energy gain as the surplus energy acquired by subtracting input energy from total output energy, typically measured in consistent units. In agricultural settings, particularly for energy crops, the goal is often to maximize net energy gain (Kaab *et al*., 2020).

Life cycle assessment analysis

According to ISO14040, life cycle assessment (LCA) is a systematic evaluation of the inputs, outputs, and environmental impacts of a production system throughout its entire life cycle. LCA is a valuable tool for decision-making and management, particularly regarding environmental aspects (Elyasi *et al*., 2022). Recently, two main approaches to LCA have emerged. One emphasizes detailed documentation of a product's history, initial flows, and resultant environmental impacts, while the other involves analyzing and comparing potential environmental effects of various systems and product processes (Ghasemi-Mobtaker *et al*., 2022). The meticulous development of an LCA for a production system involves defining its purpose and scope, selecting the functional unit (FU) and reference, establishing system boundaries, and devising appropriate inventory and allocation methods for greenhouse gas emissions in primary products and by-products (Kazemi *et al*., 2023).

There are two primary approaches for conducting LCA studies: the comprehensive life cycle impact assessment (LCIA) study covering all four stages, and the life cycle inventory (LCI) incorporating three stages without including the LCIA stage. Analyzing the results of the life cycle is essential for decision-making. The general framework for LCA comprises four key stages: defining purpose and scope, inventory analysis, impact assessment, and result interpretation. The initial step involves setting goals, boundaries, FU, and study assumptions. During inventory analysis, data is gathered, and inputs and outputs are quantified. Impact assessment assesses potential environmental repercussions based on the results of the inventory analysis. Lastly, interpreting the results provides conclusions and recommendations for decision-makers, aiming to deliver a clear and coherent presentation of the LCA findings (Nunes e*t al*., 2017). The assessment examined all environmental factors related to producing one ton of paddy as the functional unit, with study boundaries illustrated in Figure 2.

In LCA, off-farm emissions encompass various inputs like human labor, electricity, water, seeds, biocides, chemical fertilizers, diesel fuel, and machinery. Conversely, on-farm emissions are linked to agricultural machinery such as tractors and trailers employed for farm activities. The assessment of emissions related to machinery usage, diesel fuel combustion, and chemical fertilizers utilizes data from Tables 2 to 4. The proper maintenance of clean fuel is crucial for optimal performance since mishandling can lead to fuel contamination, resulting in pollutants like water, dust particles, and microbial growth, potentially causing black sludge. Hence, ensuring fuel quality is essential for effective operation, extended service life, and emission regulation in engines (Soam *et al*., 2017). Strategic crop production heavily depends on rice fertilizer, crucial for enhancing crop yields. However, excessive use of fertilizers can have negative impacts such as reduced yields and increased environmental emissions. Chemical fertilizers can harm air and water quality, releasing greenhouse gases and heavy metals into the soil. To assess the extent of these environmental emissions, the coefficients of the input consumption values

Table 1. The coefficients of energy inputs and outputs in the production of paddy.

Items	Unit	Energy equivalent (MJ unit^{-1})	References
Inputs			
Human labor	h	1.96	Taherzadeh-Shalmaei *et al.*, 2023
Machinery	kg yr*	62.70	Mobtaker *et al.* 2022
Diesel fuel	L	56.31	Mobtaker *et al.* 2020
Chemical fertilizers	kg		
Nitrogen		78.10	Kaab *et al.*, 2023
Phosphate		17.40	Canakci and Akinci, 2006
Potassium		13.70	
Biocides	kg	250	Taki *et al.*, 2013
Electricity	kWh	12	Mohseni *et al.*, 2018
Seed	kg	14.7	Šarauskis *et al.*, 2018
Output	kg		
Paddy		17	Šarauskis *et al.*, 2018

*The economic life of machine (year).

are multiplied, as outlined in the research findings of Mostashari-Rad *et al*. (2021). In this study, various methods such as CML 2 baseline, Impact 2002+, Eco-indicator 99, ReCiPe 2016, EDIP'97, EDIP2003, and EPS2000 (Dreyer *et al*., 2003; Hauschild and Barlaz, 2010; Jolliet *et al*., 2003; Kouchaki-Penchah *et al*., 2017; Molaee Jafrodi *et al*., 2022; Reyes and Sepulveda, 2006; Saber *et al*., 2021) were utilized for environmental impact assessment. The ReCiPe 2016 method, implemented through SimaPro software, was specifically employed in this study. The analysis focused on calculating the emissions index for pollutants in paddy production and assessing the resulting damage to ecosystem, human health, and resources as endpoints. Mid-points were determined based on Figure 3, and the impact of each mid-point was quantified and aggregated using standard units.

CExD index

The first law of thermodynamics regulates energy, which is affected by the material flow characteristics and energy content within a system, and it quantifies the amount of energy. In contrast, exergy integrates both the first and second laws of thermodynamics and assesses both the quantity and quality of energy. The CExD index, denoted in equivalent units (MJ eq.), represents the total resources required to manufacture a product or deliver a service (Cheng *et al*., 2024). It is divided into eight categories: fossil, nuclear, hydro, biomass, other renewable energy, water, minerals, and metals. The CExD Index is constructed based on a methodology established by the Ecoinvent Center, and information on various energy forms is sourced from the Ecoinvent 2.2 database. This research examines seven impact categories, encompassing non-renewable (fossil), renewable (potential), non-renewable (primary), renewable (biomass), renewable (water), non-renewable (metals), and non-renewable (mineral) energy sources (Taki and Yildizhan, 2018).

Results and Discussion

Energy use analysis

The input energy was calculated by considering input consumption and agricultural operations. Energy information for different cultivation methods is presented in Supplementary Tables 1 and 2. For the Hashemi variety, the average total paddy input ener-

Table 2. Equivalent of direct emission of 1 MJ diesel fuel for 1 MJ burning in EcoInvent database.

Emission	Amount (g MJ^{-1} diesel)
CO_2	74.5
SO_2	2.41E-02
CH_4	3.08E-03
Benzene	1.74E-04
Cd	2.39E-07
Cr	1.19E-06
Cu	4.06E-05
N_2O	2.86E-03
Ni	1.67E-06
Zn	2.39E-05
Benzo (a) pyrene	7.16E-07
NH_3	4.77E-04
Se	2.39E-07
PAH	7.85E-05
HC, as NMVOC	6.80E-02
NO_x	1.06
CO	1.50E-01
Particulates (b2.5 μm)	1.07E-01

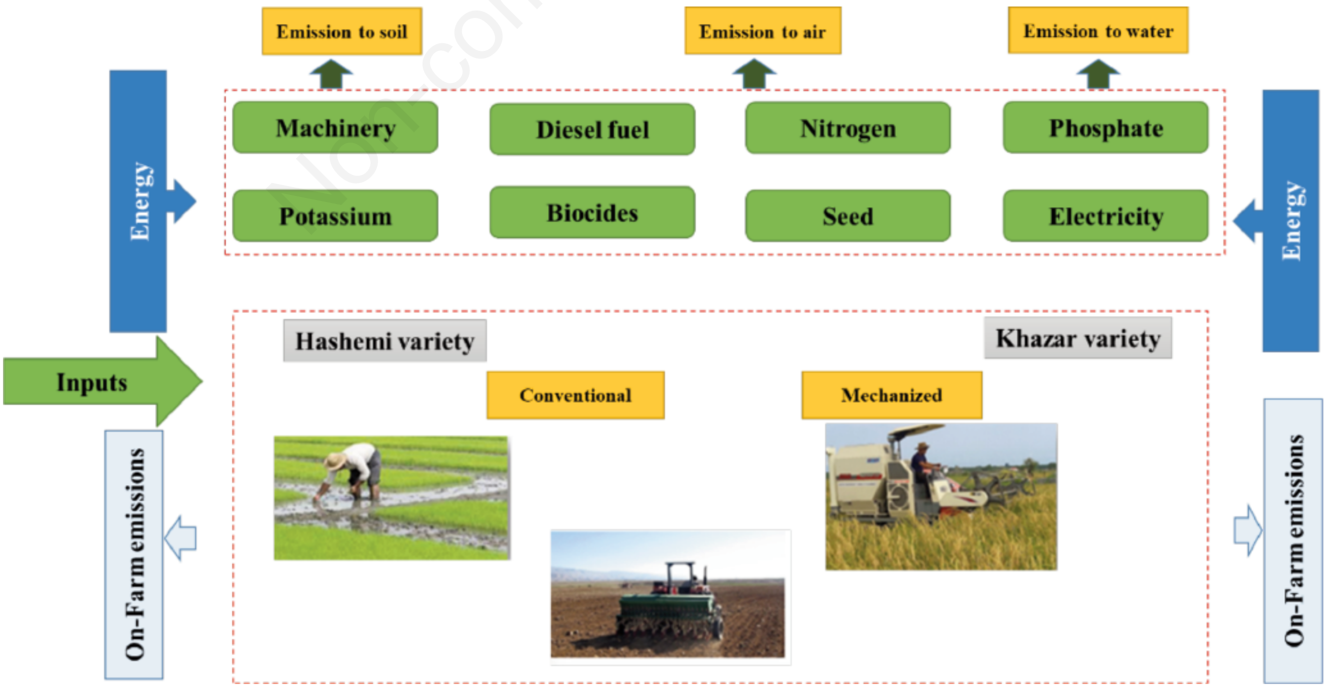

Figure 2. The system boundary varies for different methods of paddy cultivation.

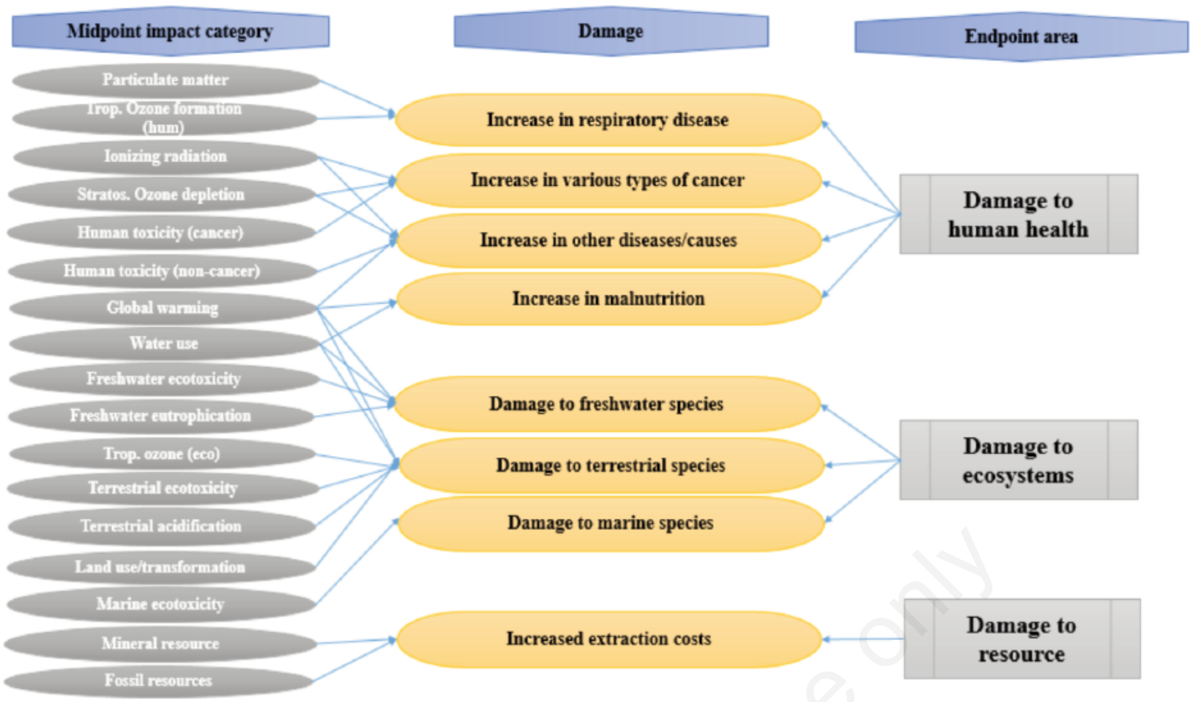

Figure 3. ReCiPe2016 method addresses various mid-points.

Table 3. Coefficients for calculating the on-farm emissions related to application of inputs in paddy production (IPCC, 2006).

Characteristic		Coefficient (emission result)
Emissions of fertilizers		
1	$\left[\frac{\text{kg } N_2O - N}{\text{kg } N_{\text{in fertilzers applied}}}\right]$	0.01 (to air)
2	$\left[\frac{\text{kg } NH_3 - N}{\text{kg } N_{\text{in fertilizers applied}}}\right]$	0.1 (to air)
3	$\left[\frac{\text{kg } N_2O - N}{\text{kg } N_{\text{in atmospheric deposition}}}\right]$	0.001 (to air)
4	$\left[\frac{\text{kg } NO_3^- - N}{\text{kg } N_{\text{in fertilzers applied}}}\right]$	0.1 (to water)
5	$\left[\frac{\text{kg P emission}}{\text{kg } P_{\text{in fertilizers applied}}}\right]$	0.02 (to water)
6	$\left[\frac{\text{kg } NO_x}{\text{kg } N_2O_{\text{ from fertilizers and soil}}}\right]$	0.21 (to air)
Conversion of emissions		
1	Conversion from kg $CO_2 - C$ to kg CO_2	$\left(\frac{44}{12}\right)$
2	Conversion from kg $N_2O - N_2$ to kg N_2O	$\left(\frac{44}{28}\right)$
3	Connversion from kg NH_3 - N to kg NH_3	$\left(\frac{17}{14}\right)$
4	Conversion from kg NO_3 - N to kg NO_3	$\left(\frac{62}{14}\right)$
5	Conversion from kg P_2O_5 to kg P	$\left(\frac{62}{164}\right)$
Emissions from human labor 1	$\left[\frac{\text{kg } CO_2}{\text{man - h Human labor}}\right]$	0.7 (to air)

gy was 76659.71 MJ ha^{-1} in the conventional method and 89056.86 MJ ha^{-1} in the mechanized method. Similarly, for the Khazar variety, the values were 78719.54 MJ ha^{-1} and 93106.52 MJ ha^{-1} for the conventional and mechanized methods, respectively. A comparison between intensive planting systems (SRI) and traditional rice fields showed that the average input energy for the studied systems, including all energy consumption related to various aspects of cultivation, was 2424.229 MJ ha^{-1}. The total output energy in the production systems was estimated to be 191341 MJ ha^{-1} (Habibi *et al*., 2019).

Supplementary Figure 1 a,b displays the percentage share of each input in the production of paddy in the Hashemi and Khazar varieties, respectively. In both conventional and mechanized methods, electricity consumption is the highest contributor, accounting for approximately 42-45% of the energy inputs. Machinery represents the second highest energy input, comprising around 33-37% of the energy inputs. This information is valuable for analyzing energy consumption patterns in rice production and identifying areas for potential improvement in energy efficiency and sustainability.

Table 5 displays the calculations for the primary energy indicators. The energy ratios for the Hashemi and Khazar traditional methods are 0.78 and 1.12, respectively, indicating a notably higher output energy compared to input energy. The productivity energy index shows no significant difference in the amount of paddy produced concerning the input energy for all three methods. However, the specific energy for the mechanized method in the Hashemi and Khazar varieties is 24.74 and 16.93 MJ kg^{-1}, respectively, indicating a high input energy relative to the amount of paddy produced.

Life cycle assessment

Supplementary Table 3 displays the environmental emissions resulting from inventory, focusing on the significant carbon dioxide emissions generated by diesel consumption in the mechanized process of Khazar variety. This results in the release of 427.89 kg of CO^2 into the atmosphere. The use of chemical fertilizers also leads to the emission of N_2O and NH_3 into the air and water, causing nitrate and phosphate contamination. Human labor accounts for approximately 25% of the carbon dioxide emissions from diesel fuels.

According to Table 6, the ReCiPe2016 method calculated three categories of effects. For the Hashemi variety, the resource impact category for conventional and mechanized methods was 162.82 and 182.25 USD2013, respectively. For the Khazar variety, the resource impact category for conventional and mechanized methods was 112.49 and 126.19 USD2013, respectively. The ecosystem category shows the lowest environmental emissions.

Table 4. Coefficients for calculating the on-farm emissions to soil of heavy metal related to application of chemical fertilizers in paddy production (IPCC, 2006).

Characteristic		Heavy metals						
		Cd	Cu	Zn	Pb	Ni	Cr	Hg
1	$\left[\frac{\text{mg Heavy metal}}{kg\ N_{in\ fertilzer\ applied}}\right]$	6	26	203	5409	20.9	77.9	0.1
2	$\left[\frac{\text{mg Heavy metal}}{kg\ P_{in\ fertilzer\ applied}}\right]$	90.5	207	1923	154	202	1245	0.7
3	$\left[\frac{\text{mg Heavy metal}}{kg\ K_{in\ fertilzer\ applied}}\right]$	0.2	8.7	11.3	1.5	4.5	10.5	0.1

Table 5. Different energy indices in paddy production.

Energy indices (unit)	Hashemi variety		Khazar variety	
	Conventional	Mechanized	Conventional	Mechanized
Energy use efficiency (ratio)	0.78	0.69	1.12	1.00
Energy productivity (kg MJ^{-1})	0.05	0.04	0.07	0.06
Specific energy (MJ kg^{-1})	21.90	24.74	15.14	16.93
Net energy gain (MJ ha^{-1})	-17159.71	-27856.86	9680.46	393.48

Table 6. The environmental impact values for different methods of paddy production based on 1 ton.

Impact categories	Unit	Hashemi variety		Khazar variety	
		Conventional	Mechanized	Conventional	Mechanized
Human health	DALY	0.058	0.062	0.039	0.041
Ecosystems	species.yr*	6.72E-05	7.18E-05	4.59E-05	4.83E-05
Resources	USD2013	162.82	182.25	112.49	126.19

DALY, disability adjusted life years: a damage of 1 is equal to: loss of 1 life year of 1 individual, or 1 person suffers 4 years from a disability with a weight of 0.25; *species.yr: the unit for ecosystems is the local species loss integrated over time.

Supplementary Figure 2 a,b illustrates that electricity is the primary contributor, accounting for over 40% of the environmental emissions across all damage categories. Conventional rice production emits 3.0710 kg CO_2eq kg^{-1}, while organic rice production emits 4.0154 kg CO_2eq kg^{-1} (Jirapornvaree *et al*., 2021).

The environmental emissions resulting from inventory, focusing on the significant carbon dioxide emissions generated by diesel consumption in the mechanized process of the Khazar variety, which results in the release of 427.89 kg of CO_2 into the atmosphere. The use of chemical fertilizers also leads to the emission of N_2O and NH_3 into the air and water, causing nitrate and phosphate contamination. Human labor accounts for approximately 25% of the CO_2 from diesel fuels. The ReCiPe2016 method calculated three categories of effects. For the Hashemi variety, the resource impact category for conventional and mechanized methods was 162.82 and 182.25 USD2013, respectively. For the Khazar variety, the resource impact category for conventional and mechanized methods was 112.49 and 126.19 USD2013, respectively. Additionally, the ecosystem category shows the lowest environmental emissions. That electricity is the primary contributor to environmental emissions, accounting for over 40% across all damage categories. A LCA was conducted to evaluate the sustainable remediation of contaminated agricultural soil in China, considering primary, secondary, and tertiary impacts associated with restoring polluted land. The study emphasized the importance of considering spatially diverse impacts in land management and crop growth. By comparing four different risk management scenarios at a contaminated field in Southern China, the research revealed a specific pattern of primary and secondary impacts, with alternative planting showing higher tertiary impacts compared to phytoextraction and chemical stabilization, challenging a belief held by some policymakers. The study also highlighted the global environmental repercussions of compensating for the loss of rice paddy fields in Southern China by deforesting land in the Amazon rainforest, leading to a significant climate change impact (Zeng e*t al*., 2011).

CExD index

The CExD method, as outlined in Table 7, identified seven types of energy. Notably, the non-renewable fossil energy type exhibited significant values in the conventional and mechanized cultivation of the Hashemi variety (21666.32 and 24537.68 MJ ton^{-1}), as well as for the Khazar variety (14938.53 and 16847.06 MJ ton^{-1}). Mechanized cultivation of the Khazar variety demonstrated a substantial energy output of 1498.68 MJ ton^{-1} of renewable biomass energy. Various input factors contribute to the generation of energy in different forms, as depicted in Supplementary Figure 3 a,b. Electricity and machinery play crucial roles in all energy forms, with machinery positively influencing the production of renewable water form. Nitrogen fertilizers notably contribute to the non-renewable minerals form, while non-renewable fossil energy stems from electricity consumption.

Discussion

A recent study by Hakeem *et al*. (2023) reported that the average energy consumption for rice production is 12906.8 MJ ha^{-1}. Studies in Myanmar have shown that alternative rice planting techniques require less input energy compared to traditional methods, with the modified SRI method being particularly energy efficient. Data from rice producers in Golestan province, Iran, revealed that the energy inputs and outputs for rice production were 34423.28 and 120088.4 MJ ha^{-1}, respectively (Mardani *et al*., 2022). In contrast to findings in various regions of Thailand, where the highest input energy comes from chemical fertilizers, pesticides, and herbicides, studies in the United States indicate that machinery and fuel account for 25% of the energy used for corn production, while 45% is attributed to chemical fertilizer usage. These insights provide valuable information for understanding energy consumption in agricultural production (Chamsing *et al*., 2006). According to Kazemipoor *et al*. (2015), the energy ratio and productivity values for rice production in various regions of Iran ranged from 1.39 to 1.67 and 0.064 to 0.070 kg MJ^{-1}. In contrast, (Ibrahim *et al*., 2012) reported energy and productivity ratios of 4.1 and 0.3 kg MJ^{-1}, respectively. Furthermore, Khan *et al*. (2010) estimated the energy productivity for rice production in Australia at 0.41 kg MJ^{-1}, while noting an energy intensity of 2.44 MJ kg^{-1}. Additionally, the use of chemical fertilizers results in the release of heavy metals into the soil, with lead being the most prominent contributor and mercury being the least significant. Recent research indicates that direct rice production using direct seed culture can lower CH_4 emissions but might increase N_2O emissions as well (Yadav *et al*., 2020). There is a notable relationship between NH_3 emissions and nitrogen fertilizer application, with emissions rising with increased nitrogen usage. Studies have recorded annual N_2O emissions from Australian rain-fed wheat fields, attributing it to nitrogen fertilizer utilization (Brentrup *et al*., 2004). Due to the significant greenhouse gas emissions, particularly N_2O from farms, it is essential to consider sustainable and ecological management practices like reducing tillage, using organic fertilizers, and incorporating nitrogen-fixing plants in crop rotation as alternatives to chemical fertilizers (Nikkhah *et al*., 2015). In addition Fallahpour *et al*. (2012) found that the overuse of nitrogen fertilizer does not lead to higher crop yields and can result in significant environmental impacts in

Table 7. The analysis of CExD shows the energy forms results for one ton of paddy in various production methods.

Energy form	Unit	Hashemi variety		Khazar variety	
		Conventional	Mechanized	Conventional	Mechanized
Non-renewable, fossil	MJ ton^{-1}	21666.32	24537.68	14938.53	16847.06
Renewable, potential	MJ ton^{-1}	640.94	748.76	440.19	506.23
Non-renewable, primary	MJ ton^{-1}	80.22	75.39	54.05	47.6^3
Renewable, biomass	MJ ton^{-1}	1594.45	1498.68	1108.20	972.91
Renewable, water	MJ ton^{-1}	776.06	640.14	569.35	429.64
Non-renewable, metals	MJ ton^{-1}	837.60	974.99	570.08	641.94
Non-renewable, minerals	MJ ton^{-1}	231.23	227.71	156.19	149.33

the production of wheat and barley. Iriarte *et al.* (2010) observed that the overuse of chemical fertilizers in sunflower and canola production leads to significant environmental effects, particularly related to global warming and exploitation. Furthermore, it has been revealed that rapeseed has a higher environmental impact per hectare than rice, and the rotation of rapeseed-rice has a lower environmental impact per square millimeter compared to rice-rice rotation. Eutrophication is the primary contributor to environmental effects in paddy production, followed by environmental acidification. Ammonia (NH_3) emissions significantly contribute to environmental degradation and acidification, while nitrate loss (NO_3-) is the main contributor to eutrophication (Vural Gursel *et al*., 2021). In another study, the environmental impacts of paddy rice production in northern Iran were assessed using agrochemical emission models. Two scenarios based on site-specific information were utilized, and the ReCiPe 2016 methodology was employed to quantify environmental impacts. The research identified rice seed production, diesel fuel, urea, phosphate fertilizer, and Diazinon as major environmental hotspots in paddy rice production. Additionally, the study revealed that emission models had a significant impact on impact scores across various environmental categories. The potential of using rice straw as livestock feed to mitigate greenhouse gas emissions was also highlighted as a viable alternative to burning paddy residue on the farm (Keramati *et al*., 2021).

An analysis of paddy production using the CExD method revealed a non-renewable fossil energy utilization rate of 35,426.81 MJ ha^{-1} (Nabavi-Pelesaraei *et al*., 2018). The study highlighted the significant impact of diesel fuel and natural gas combustion on the CExD analysis (Khanali *et al*., 2017). Exergoenvironmental aspects were examined in various paddy production systems in Iran, introducing the concept of life cycle cost (LCC) and emissions costs as new factors in these scenarios. The evaluation of environmental life cycle damages showed that diesel fuel and nitrogen had the most significant impact on resource damage in certain systems, with on-farm emissions identified as the largest contributor to environmental impact in the surveyed systems. The analysis also indicated that non-renewable fossil fuel was the primary energy consumer, with diesel fuel being the most substantial form of energy in all three systems (Saber *et al*., 2020) It was recognized that direct emissions and field operations are significant contributors to the environmental impact in organic rice systems. Similar research in other crops has demonstrated that the use of chemical fertilizers, particularly urea, and fossil fuels had the most significant effect on greenhouse gas (GHG) emissions and global warming potential (Hokazono and Hayashi, 2012).

The analysis of energy consumption from various regions significantly influences the evaluation of paddy production's sustainability by providing a comparative framework to understand energy inputs, resource allocation, and environmental impacts. Knowing how energy consumption patterns differ across regions helps identify best practices and energy-efficient methods that can be adopted to minimize the environmental footprint of rice production. In the context of the study, the considerable CO_2 resulting from diesel fuel consumption during the mechanized cultivation of the Khazar variety, alongside the adverse effects of chemical fertilizers, highlight critical areas for improvement. The reported emissions, such as 427.89 kg of CO_2, serve as a benchmark for assessing the environmental impacts of different farming practices. This information is vital for formulating strategies aimed at reducing greenhouse gas emissions associated with paddy production, in line with sustainability goals. The negative environmental impacts analyzed, including the release of nitrogen oxides (N_2O and NH_3) and their contribution to acidification and eutrophication, are essential to addressing sustainability in paddy production. The data emphasizing the high resource impact values associated with mechanized methods (e.g., 182.25 USD2013 for Hashemi) underscore the need for transitioning to more sustainable agricultural practices. The results also align with literature suggesting that alternative farming methods, like the modified System of Rice Intensification (SRI), can reduce reliance on energy-intensive inputs, thereby enhancing resource efficiency and minimizing environmental damage.

Furthermore, the environmental emissions linked to electricity usage, which account for over 40% of total damage in all categories, indicate that shifts towards renewable energy sources could play a significant role in achieving sustainability in paddy production. Integrating practices such as reduced tillage, organic fertilizers, and the use of nitrogen-fixing plants also aligns with broader goals to improve sustainability by lessening the reliance on chemical fertilizers, reducing emissions, and enhancing soil health. Additionally, the mention of specific environmental hotspots (e.g., diesel fuel, nitrogen fertilizers) in the LCA of paddy production supports the push for targeted interventions to limit environmental degradation. This focus on identifying and addressing key contributors to greenhouse gas emissions can aid policymakers, farmers, and stakeholders in mitigating the environmental impacts of rice cultivation. Ultimately, drawing insights from energy consumption studies across different regions not only informs practices that can decrease the environmental impact of paddy production but also contributes to the global objectives of sustainability, biodiversity preservation, and climate change mitigation.

Conclusions

The combination of land and agricultural mechanization has a significant impact on technical, energy, and environmental factors in paddy production. The utilization of modern machinery and technology in land preparation, planting, and harvesting has increased efficiency and productivity, leading to higher yields and reduced labor costs. However, the adoption of mechanization has also resulted in increased energy consumption and environmental impacts, such as soil compaction and greenhouse gas emissions. The effects of land consolidation and agricultural mechanization on paddy production vary depending on the cultivation scenario. Smallholder farming systems have limited mechanization adoption due to high machinery costs and small landholdings. In contrast, large-scale commercial farming systems have embraced mechanization, resulting in increased productivity and profitability. Sustainable mechanization efforts in paddy production should prioritize adopting energy-efficient machinery and practices that minimize environmental impacts. Additionally, policies supporting smallholder farmers' access to affordable mechanization technologies could promote inclusive growth in the agricultural sector. Research indicates that the Khazar variety is more energy-efficient and has better environmental indicators than the Hashemi variety in both production methods. Therefore, promoting the Khazar variety in the study area is recommended. Overall, the integration of land and agricultural mechanization has the potential to transform paddy production, but careful consideration must be given to the technical, energy, and environmental impacts to ensure sustainable and inclusive growth. The use of modern machinery and technology during land preparation, planting, and harvesting has enhanced efficiency and productivity, resulting in increased yields and lower labor costs. However, this shift towards mechanization brings challenges, including higher energy consumption and negative environmental impacts such as soil compaction and greenhouse gas emissions. The effects of land consolidation and mechanization on paddy production are not uniform; they differ based on the farming context. Smallholder farmers face barriers to adopting mechanization due to the high costs of machinery and their limited landholdings. Conversely, large-scale commercial farmers have widely embraced mechanization, leading to improved productivity and profitability. For sustainable mechanization in paddy production to be achieved, it is essential to focus on the adoption of energy-efficient machinery and practices that lessen environmental harm. Additionally, implementing policies that facilitate smallholder farmers' access to affordable mechanization technologies could foster inclusive growth within the agricultural sector. Research findings emphasize that the Khazar variety of rice is more energy-efficient and exhibits better environmental performance compared to the Hashemi variety in different production scenarios. Consequently, promoting the Khazar variety in the study region is advised.

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Online supplementary material.

Supplementary Table 1. Energy inputs and outputs vary across different paddy production systems.
Supplementary Table 2. Energy inputs and outputs vary across different paddy production systems.
Supplementary Table 3. On-farm emissions of different production of paddy in based on 1 hectare.
Supplementary Figure 1a. Distribution of energy sources in the production of Hashemi variety paddy.
Supplementary Figure 1b. Distribution of energy sources varies in the production of Khazar variety paddy.
Supplementary Figure 2a. The Hashemi variety of paddy production contributes to the emission of environmental impact categories through its input usage in various production processes.
Supplementary Figure 2b. The Khazar variety of paddy production contributes to the emission of environmental impact categories through its input usage in various production processes.
Supplementary Figure 3a. The Hashemi variety of paddy production relies on various inputs to consume energy forms for different stages of production.
Supplementary Figure 3b. The Khazar variety of paddy production relies on various inputs to consume energy forms for different stages of production.