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The impact of rice cultivation methods on environmental sustainability using life cycle assessment and cumulative exergy demand

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Abstract

Rice or Paddy cultivation has a significant impact on the environment, especially concerning water usage and greenhouse gas emissions. In this study, a life cycle assessment (LCA) and cumulative exergy demand (CExD) analysis were carried out to compare the environmental effects of paddy cultivation under various scenarios. The ReCiPe2016 method was utilized to evaluate three different impact categories. Specifically, 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 showed the lowest environmental emissions. It was found that electricity was the primary contributor, accounting for over 40% of the environmental emissions across all damage categories. The CExD method identified seven types of energy, with non-renewable fossil energy showing significant values in both 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 exhibited a notable energy output of 1498.68 MJ ton^{-1} of renewable biomass energy. By conducting a thorough comparison using LCA and CExD, it becomes possible to pinpoint the most sustainable practices for paddy cultivation, considering the full scope of environmental impacts and resource consumption. This valuable information can guide decision-making and facilitate the development of more sustainable agricultural practices.

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Introduction

Rice cultivation, also known as paddy production, is a vital agricultural activity that plays a crucial role in ensuring food security and supporting rural livelihoods in many regions around the world. However, traditional methods of paddy production often require a lot of labor and are not very efficient in their use of resources, leading to various technical, energy, and environmental challenges (Koga and Tajima, 2011). In recent years, there has been a growing interest in studying the impact of land integration and agricultural mechanization on paddy production. Land integration involves consolidating small, fragmented land holdings into larger, more efficient units, while agricultural mechanization uses machinery and technology to automate and streamline farming processes (Devendra and Leng, 2011). In addition, it assesses the energy implications, such as fuel consumption and energy efficiency, as well as the environmental impacts, including greenhouse gas emissions, water usage, and soil degradation (Algarni et al., 2023). Through the analysis of various cultivation scenarios, researchers and policymakers can gain insights into the potential trade-offs and synergies between land integration, agricultural mechanization, and sustainable paddy production (Nabavi-Pelesaraei et al., 2018). This knowledge can guide decision-making processes, facilitating the development of strategies and policies that support efficient resource utilization, improved productivity, and reduced negative environmental impacts. Overall, the examination of the influence of land integration and agricultural mechanization on technical, energy, and environmental aspects in paddy production is crucial for advancing sustainable and resilient agricultural systems (Kaab et al., 2019a). It offers valuable insights into how these practices can enhance food security, rural livelihoods, and environmental sustainability within the context of rice cultivation. The effect of integrating land and implementing agricultural mechanization on paddy production has attracted attention from agricultural researchers and policymakers (Kaab et al., 2023). However, there is a need for a more comprehensive examination of this impact, considering the technical, energy, and environmental factors involved in various cultivation scenarios. An innovative approach to studying this impact could involve using a systems thinking approach that takes into account the interconnectedness and feedback loops between different components of the agricultural system (Mohammadi Kashka et al., 2023).

In recent years, there has been a focus in the agricultural industry on studying the effects of energy usage and environmental emissions on agricultural products. According to Khan et al. (2010), rice demonstrates an energy efficiency of 70.6%, with the majority of input energy in rice fields attributed to chemical fertilizers (43%). Another study by Khan et al. (2009) estimated the ratio of water energy in canal and pump irrigation systems for wheat, rice, and barley. Khosruzzaman et al. (2010) studied rice production in Bangladesh and reported input and output energy values. Furthermore, Kosemani and Bamgboye (2020) noted that large farms can maximize energy efficiency through improved resource management. Additionally, research by Guo et al. (2022) examined the differences between fully mechanized and semi-mechanized rice production, emphasizing the effects of mechanization on fuel, fertilizer, and water usage. The environmental impact of rice production was assessed in both spring and summer cultivation systems, revealing that spring planting resulted in lower environmental effects compared to summer (Mohammadi et al., 2015). 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 integration 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 novelty of this study lies in its comprehensive approach to comparing the environmental impact of paddy cultivation under different scenarios using LCA and

CExD. LCA is a widely used method for assessing the environmental impact of a product or process throughout its entire life cycle, while CExD measures the total amount of exergy required to produce a product or service. The aim of the study is to provide a holistic understanding of the environmental impact of paddy cultivation by considering various factors such as land use, water consumption, energy input, and greenhouse gas emissions. By comparing different scenarios, the study aims to identify the most sustainable practices for paddy cultivation and provide valuable insights for policymakers, farmers, and other stakeholders in the agricultural sector. The study will contribute to the existing body of knowledge on sustainable agriculture and provide practical recommendations for improving the environmental performance of paddy cultivation. Additionally, by using both LCA and CExD, the study will offer a more comprehensive and robust analysis of the environmental impact, allowing for a deeper understanding of the trade-offs and potential synergies between different environmental indicators.

Materials and methods

For this study we collected data in Guilan Province, Iran, which is renowned for its unique climate and natural characteristics compared to other parts of the country. Located on the southwest coast of the Caspian Sea, the province spans latitudes between 36° 34′ and 38° 27′ N and longitudes between 48° 53′ and 50° 34′ E (Ministry of Jihad-e-Agriculture of Iran, 2021). The specific location of the case study is illustrated in Figure 1. A random survey of 120 paddy producers was conducted to gather data on agricultural input factors such as seed quantities, fertilizer, biocides, energy conduits, equipment and machinery, cultivated land areas, and paddy yield. The sample size was determined using the method outlined by Kaab et al., (2019b), shown in Equation 1 and the data was collected through in-person questionnaires.

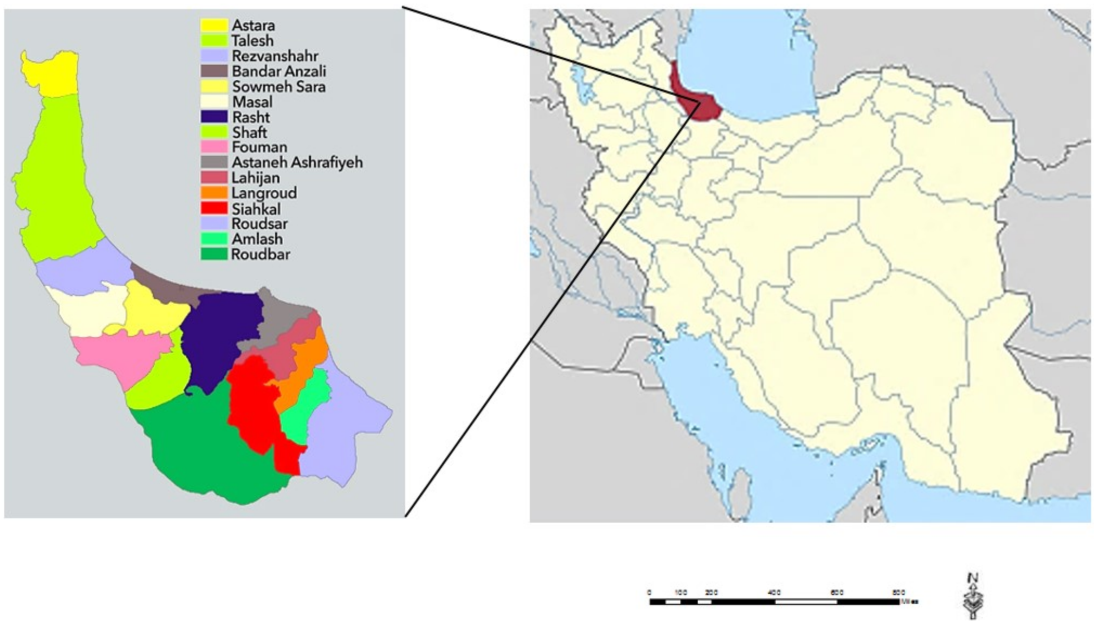


Figure 1. The study area located in north of Iran.

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

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).

LCA analysis

As per ISO14040, Life Cycle Assessment (LCA) involves systematically evaluating the inputs, outputs, and environmental effects of a production system throughout its entire life cycle. LCA is a valuable tool for decision-making and management, especially concerning environmental considerations (Elyasi et al., 2022). In recent years, two main approaches to LCA have emerged. One focuses on thoroughly documenting a product's history, initial flows, and resulting environmental impacts, while the other involves analyzing and comparing potential environmental impacts of different systems and product processes (Ghasemi-Mobtaker et al., 2022). Careful design of an LCA for a production system involves defining its purpose and scope, selecting the functional unit (FU) and reference, establishing system boundaries, and creating appropriate inventory and allocation methods for greenhouse gas emissions in primary products and by-products (Kazemi et al., 2023). There are two approaches to conducting LCA studies: the comprehensive Life Cycle Impact Assessment (LCIA) study, which covers all four stages, and the Life Cycle Inventory (LCI), which includes three stages without considering the LCIA stage. The analysis of life cycle results serves as the basis for decision-making. The general framework for the steps of LCA consists of four key stages: defining the purpose and scope, inventory analysis, impact assessment, and interpretation of results. The first step involves establishing the objectives, boundaries, functional unit (FU), and assumptions of the study. Inventory analysis involves gathering data and quantifying inputs and outputs. Impact assessment assesses potential environmental consequences based on the results of the inventory analysis. Finally, the interpretation of results provides conclusions and recommendations for decision makers and aims to present a clear and consistent expression of the LCA results (Nunes et al., 2017). The analysis focused on all environmental factors related to the production of one ton of paddy as the FU, with the study boundaries depicted in Figure 2.

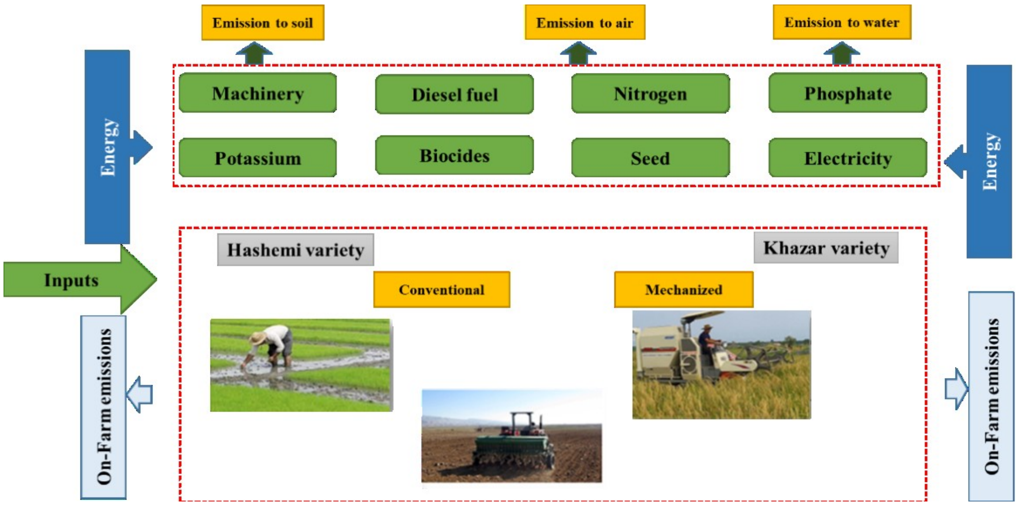


Figure 2. The system boundary for different methods of paddy cultivation.

In life cycle assessment (LCA), inputs categorized as Off-Farm emissions include human labor, electricity, water, seeds, biocides, chemical fertilizers, diesel fuel, and machinery. Conversely, agricultural machinery like tractors and trailers used for various farm tasks contribute to On-Farm emissions. Data from Table 1, Table 2, and Table 3 is collected to evaluate emissions related to machinery usage, diesel fuel combustion, and chemical fertilizers. Maintaining uncontaminated fuel is crucial for optimal performance, as mishandling can result in fuel pollution, leading to contaminants such as water, dust particles, and microbial growth, which can cause black sludge. Therefore, ensuring fuel quality is essential for efficient operation, extended service life, and emission control in engines (Soam et al., 2017; Kaab et al., 2024). Strategic crop production heavily depends on rice fertilizer, which is essential for increasing crop yields. However, excessive fertilizer use can have negative effects, such as reducing yields and increasing environmental emissions. Chemical fertilizers can harm air and water quality and lead to the release of greenhouse gases and heavy metals into the soil. To assess these environmental emissions, the coefficients of the input consumption values are multiplied, as detailed in the findings of (Ghasemi-Mobtaker et al., 2020).

Table 1. 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

Table 2. Coefficients for calculating the On-Farm emissions related to application of inputs in paddy production (IPCC, 2006).

	Characteristic	Coefficient (Emission result)
	A. Emissions of fertilizers	
1	$\left[\frac{[\text{kg } N_2O - N]}{\text{kg } N_{\text{in fertilzers applied}}}\right]$	0.01 (to air)
2	$\left[\frac{\text{kg } NH_3 \text{ - } N}{\text{kg } N_{\text{in fertilizers applied}}}\right]$	0.1 (to air)
3	$\left[\frac{\text{kg } N_2O \text{ - } N}{\text{kg } N_{\text{in atmospheric deposition}}}\right]$	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)
	B. Conversion of emissions	
1	Coversion from kg CO_2 – C to kg CO_2	$\left(\frac{44}{12}\right)$
2	Coversion from kg N_2O – N_2 to kg N_2O	$\left(\frac{44}{28}\right)$
3	Conversion 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	$\left(\frac{62}{164}\right)$
	C. Emissions from human labor	
1	$\left[\frac{\text{kg } CO_2}{\text{man - h Human labor}}\right]$	0.7 (to air)

Table 3. 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	$\left[\dfrac{\text{mg Heavy metal}}{kg\ N_{in\ fertilzer\ applied}}\right]$	6	26	203	5409	20.9	77.9	0.1
2	$\left[\dfrac{\text{mg Heavy metal}}{kg\ P_{in\ fertilzer\ applied}}\right]$	90.5	207	1923	154	202	1245	0.7
3	$\left[\dfrac{\text{mg Heavy metal}}{kg\ K_{in\ fertilzer\ applied}}\right]$	0.2	8.7	11.3	1.5	4.5	10.5	0.1

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. The ReCiPe 2016 method was specifically employed for environmental impact assessment using SimaPro software. The study calculated the emissions index for pollutants in paddy production and focused on assessing damage to ecosystems, human health, and resources as endpoints. Mid-points were established based on Figure 3, and the impact of each mid-point was determined, quantified, and aggregated using standard units.

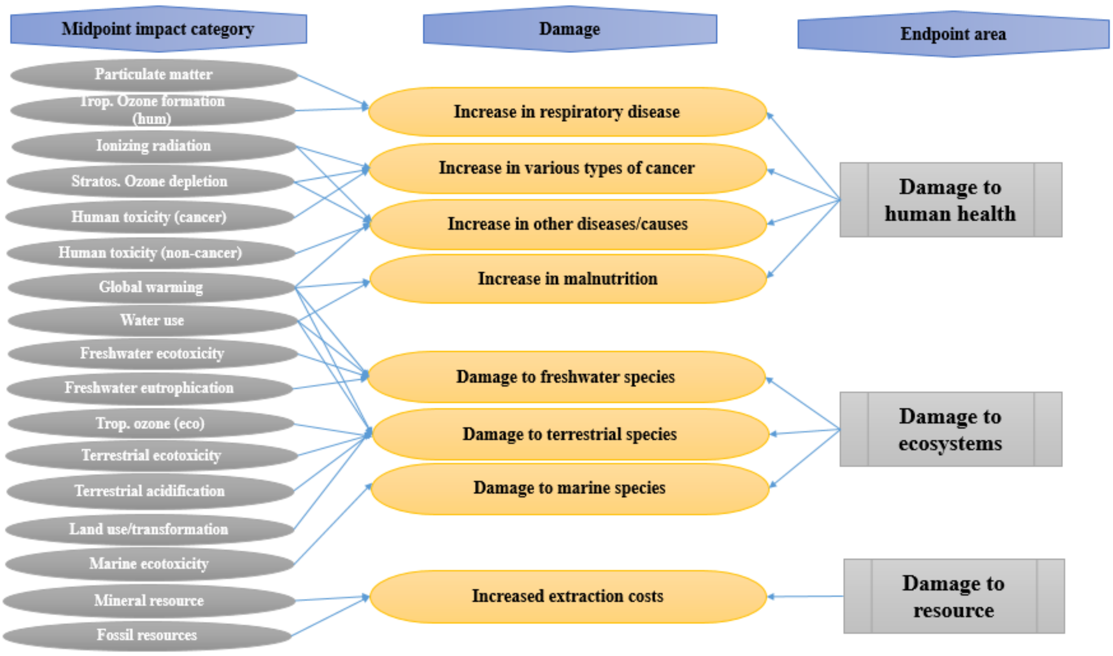


Figure 3. ReCiPe2016 method addresses various mid-points.

CExD

The first law of thermodynamics governs the influence of material flow properties and energy content on the quantity of energy in a system. Exergy, on the other hand, encompasses both the first and second laws of thermodynamics, measuring both the quantity and quality of energy. The CExD index, expressed in equivalent (MJ eq.), represents the total resources required to produce a product or provide a service (Cheng et al., 2024). It is divided into eight subgroups: fossil, nuclear, hydro, biomass, other renewable energy, water, minerals, and metals. The CExD Index is based on a methodology developed by the Ecoinvent Center, and data on different forms of energy are sourced from the Ecoinvent 2.2 database. This study considers seven impact categories, including non-renewable (fossil), renewable (potential), non-renewable (primary), renewable (biomass), renewable (water), non-renewable (metals), and non-renewable (mineral) energy forms (Taki and Yildizhan, 2018).

Results and discussion

LCA analysis

Table 4 presents data on environmental emissions related to inventory, focusing on the significant carbon dioxide emissions resulting from diesel consumption in the mechanized process of Khazar variety. This process leads to the release of 427.89 kg of CO_2 into the atmosphere. Additionally, the use of chemical fertilizers contributes to the release of N_2O and NH_3 into the air and water, leading to nitrate and phosphate contamination. Human labor accounts for approximately 25% of the carbon dioxide emissions from diesel fuels. Furthermore, the use of chemical fertilizers results in the release of heavy metals into the soil, with lead being the primary contributor and mercury being the least significant. Recent studies have indicated that direct rice production using direct seed culture can reduce CH_4 emissions, but it may also lead to an increase in N_2O emissions (Yadav et al., 2020). There is a clear correlation between NH_3 emissions and nitrogen fertilizer application, with emissions increasing alongside higher nitrogen consumption. Research has documented annual N_2O emissions from Australian rain-fed wheat fields, linking it to nitrogen fertilizer use (Kaab et al., 2021). Given the significant greenhouse gas emissions, particularly N_2O from farms, it is essential to consider sustainable and ecological management practices such as reducing tillage, utilizing organic fertilizers, and integrating nitrogen-fixing plants in crop rotation as alternatives to chemical fertilizers (Nikkhah et al., 2015).

Table 4. On-Farm emissions of different production of paddy in 1 ha.

Item (unit)	Hashemi variety		Khazar variety	
1. Emissions by diesel fuel to air (kg)	Conventional	Mechanized	Conventional	Mechanized
(a). Carbon dioxide (CO2)	339.80	402.72	352.38	427.89
(b). Sulfur dioxide (SO2)	0.10	0.13	0.11	0.13
(c). Methane (CH4)	0.014	0.016	0.014	0.017
(d). Benzene	0.0007	0.0009	0.0008	0.0009
(e). Cadmium (Cd)	0.000001	0.000001	0.000001	0.000001
(f). Chromium (Cr)	0.000005	0.000006	0.000006	0.000007
(g). Copper (Cu)	0.000185	0.000219	0.00019	0.00023
(h). Dinitrogen monoxide (N2O)	0.013	0.015	0.013	0.016
(i). Nickel (Ni)	0.000008	0.000009	0.000008	0.00001
(j). Zink (Zn)	0.000109	0.000129	0.00011	0.00013
(k). Benzo (a) pyrene	0.000003	0.000004	0.000003	0.000004
(l). Ammonia (NH_3)	0.0021	0.0025	0.0022	0.0027
(m). Selenium (Se)	0.000001	0.000001	0.000001	0.000001
(n). PAH (polycyclic hydrocarbons)	0.00035	0.00042	0.00037	0.00045
(o). Hydro carbons (HC, as NMVOC)	0.31	0.36	0.32	0.39
(p). Nitrogen oxides (NOx)	4.83	5.73	5.013	6.08
(q). Carbon monoxide (CO)	0.684167	0.81	0.70	0.8615
(r). Particulates (b2.5 μm)	0.48	0.57	0.50	0.614
2. Emissions by fertilizers to air (kg)				
(a). NH_3 by chemical fertilizers	15.78	12.14	15.78	12.142
3. Emissions by fertilizers to water (kg)				
(a). Nitrate	17.27	13.28	17.27142857	13.28
(b). Phosphate	1.31	1.41	1.309859155	1.419

Table 4. On-Farm emissions of different production of paddy in 1 ha.

Item (unit)	Hashemi variety		Khazar variety	
4. Emission by N_2O of fertilizers and soil to air (kg)				
(a). Nitrogen oxides (NO_x)	27.3	21.00	27.3	21
5. Emission by human labor to air (kg)				
(a). Carbon dioxide (CO_2)	231.00	210.00	224	196
6. Emission by heavy metals of fertilizers to soil (mg)				
(a). Cadmium (Cd)	6222.00	6496.10	6222.00	6495.10
(b). Copper (Cu)	16322.00	16646.60	16322.00	16603.10
(c). Zink (Zn)	142448.00	146063.40	142448.00	146006.90
(d). Lead (Pb)	712500.00	551012.00	712500.00	551004.50
(e). Nickel (Ni)	15107.00	15526.00	15107.00	15503.50
(f). Chromium (Cr)	85457.00	89429.00	85457.00	89376.50
(g). Mercury (Hg)	61.00	62.30	61.00	61.80

Table 5 presents the results of the ReCiPe2016 method, which calculated three categories of effects. Specifically, for the Hashemi variety, the resource impact category for conventional and mechanized methods was 162.82 and 182.25 USD2013, respectively. Meanwhile, for the Khazar variety, the resource impact category for conventional and mechanized methods was 112.49 and 126.19 USD2013, respectively. The ecosystem category displayed the lowest environmental emissions. Additionally, Figures 4 and 5 demonstrate that electricity is the primary contributor, responsible 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). Furthermore, research has shown that the excessive use of nitrogen fertilizer does not lead to higher crop yields and can result in significant environmental impacts in the production of wheat and barley (Fallahpour et al., 2012). Similarly, the overuse of chemical fertilizers in sunflower and canola production has been observed to lead to significant environmental effects, particularly related to global warming and exploitation (Iriarte et al., 2010). It has also 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).

Table 5. The environmental impact values for different methods of 1 ton paddy production.

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 [b]	6.72E-05	7.18E-05	4.59E-05	4.83E-05
Resources	USD2013	162.82	182.25	112.49	126.19

[a] 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.

[b] species.yr: the unit for ecosystems is the local species loss integrated over time.

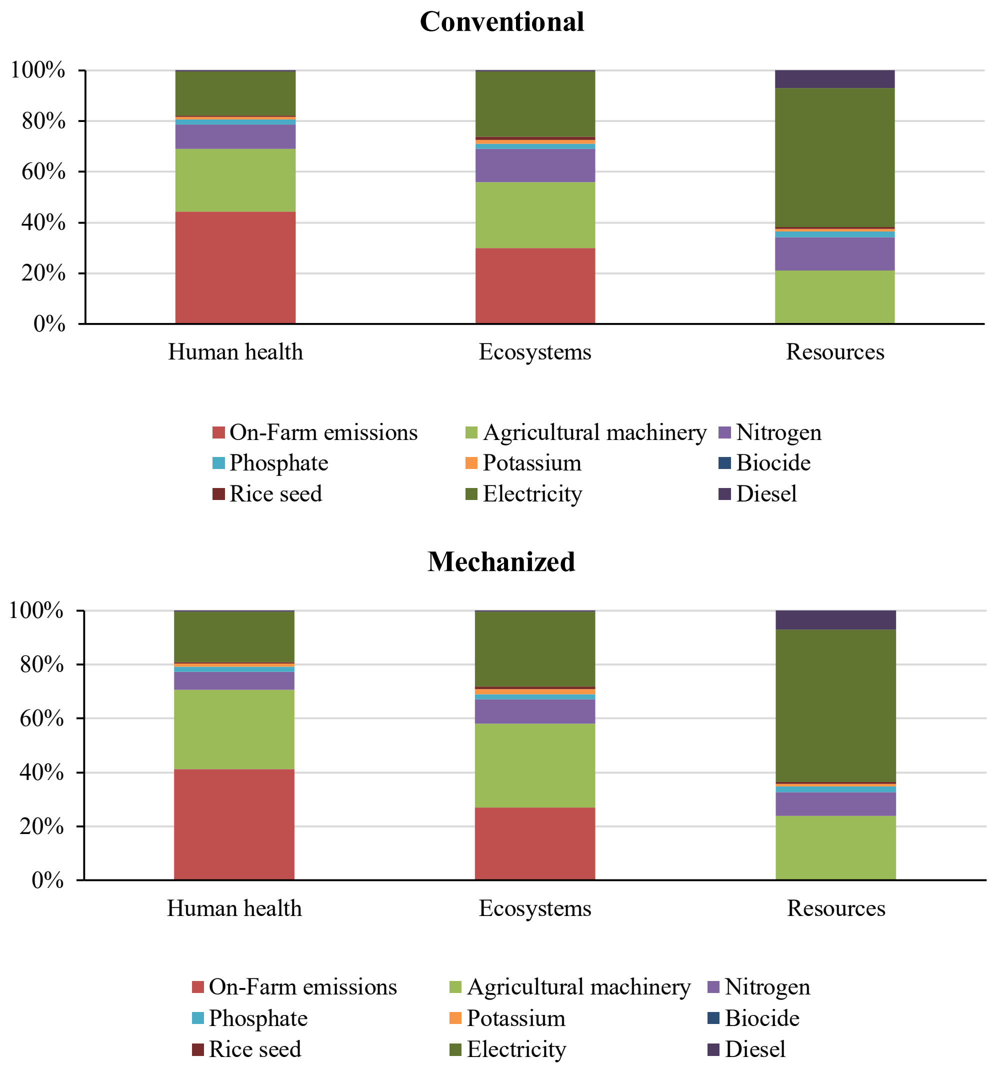
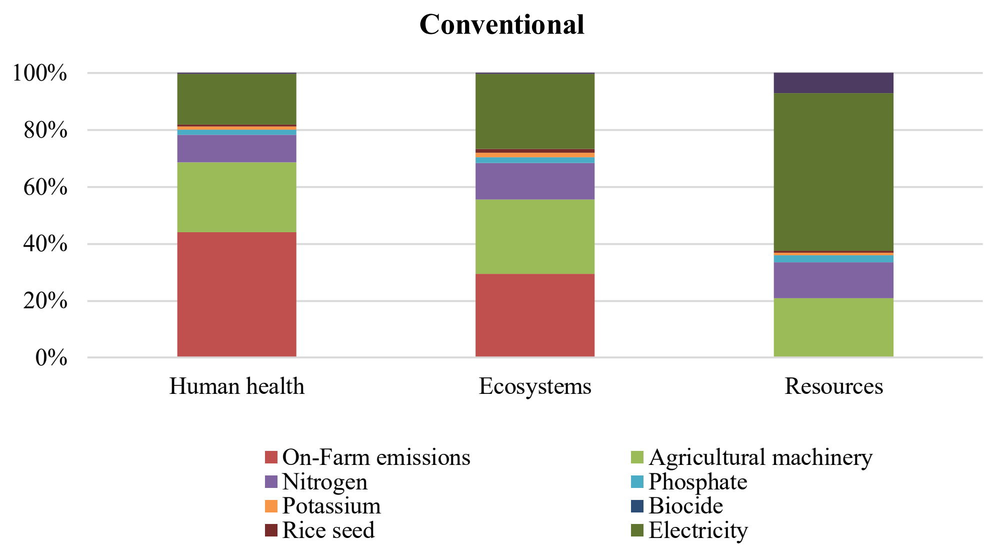


Figure 4. The Hashemi variety of paddy production contributes to the emission of environmental impact categories through its input usage in various production processes.



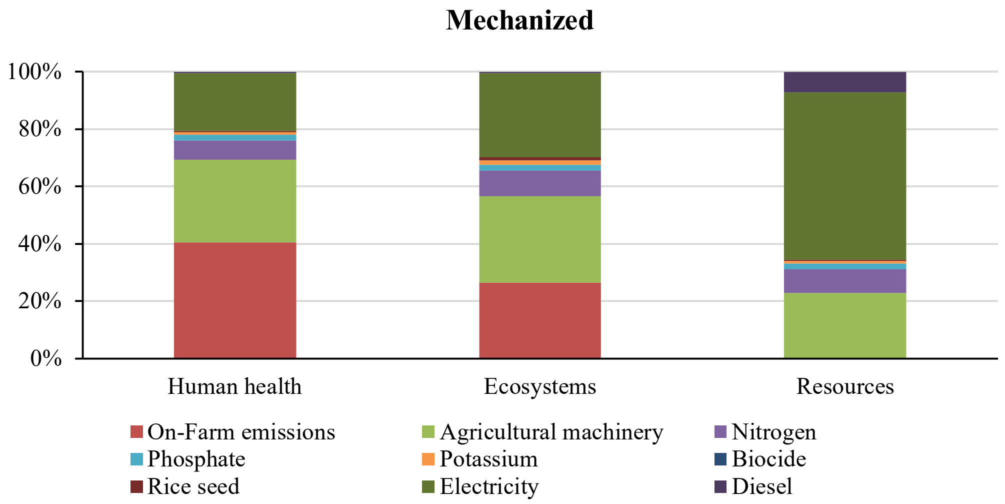


Figure 5. The Khazar variety of paddy production contributes to the emission of environmental impact categories through its input usage in various production processes.

An LCA was conducted to assess the sustainable remediation of contaminated agricultural soil in China, considering primary, secondary, and tertiary impacts of restoring polluted land and emphasizing the importance of spatially diverse impacts in land management and crop growth. Comparing four risk management scenarios at a contaminated field in Southern China, the study revealed a specific pattern of impacts, challenging a belief held by some policymakers. It 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 significant climate change impact (Zeng et al., 2011). The environmental impacts of paddy rice production in northern Iran were assessed using agrochemical emission models and the ReCiPe 2016 methodology. The study identified rice seed production, diesel fuel, urea, phosphate fertilizer, and Diazinon as major environmental hotspots in paddy rice production and 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). The study assessed environmental impacts using LCA, highlighting emissions related to marine aquatic ecotoxicity, fossil fuel depletion, and global warming potential. Electricity played a significant role in various environmental impacts. The study also analyzed the cumulative exergy demand, showing that non-renewable fossil energy use was mainly due to electricity and nitrogen fertilizer in wheat farming (Ghasemi-Mobtaker et al., 2020).

CExD analysis

The CExD method, outlined in Table 6, identified seven types of energy. Notably, the non-renewable fossil energy type showed 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. The diminishing availability of petroleum resources and the escalating demand for emission-friendly attributes in fossil fuel combustion have spurred a surge in research towards clean, accessible, and cost-effective energy alternatives. Simultaneously, the environmental impact associated with biodiesel production and combustion has gained significant attention in recent years. While prior studies have predominantly examined production processes and exhaust emissions, a holistic evaluation necessitates a thorough investigation spanning from farm-to-combustion. Environmental analyses that overlook energy consumption fail to provide a comprehensive assessment of the efficiency of biodiesel production. To address this, the CExD methodology has emerged as a novel approach for quantifying the useful energy consumed within systems, a perspective notably absent in many biofuel production studies (Nabavi-Pelesaraei et al., 2022). The environmental impacts of horticultural inputs can be assessed using the LCA method, which evaluates resources depleted and released in the environment. In this study, the environmental damages of various horticultural crops in Guilan province of Iran were analyzed using the LCA technique and CExD analysis. Citrus, hazelnut, kiwifruit, tea, and watermelon cropping systems were compared, with hazelnut production showing the highest pollution levels. On-Orchard emissions and nitrogen fertilizer were found to be major contributors to environmental impacts in all systems. Hazelnut production also required the highest energy input among the crops studied. Citrus production was determined to have the lowest emissions and was recommended as the most sustainable option for horticultural crop cultivation. Implementing organic fertilizers, upgrading equipment, and improving irrigation systems could further enhance the sustainability of horticultural production (Mostashari-Rad et al., 2021).

Table 6. The analysis of CExD shows the energy forms 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	47.63
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

Various input factors contribute to the generation of energy in different forms, as depicted in Figure 6 and 7. 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. The CExD analysis of paddy production found a non-renewable fossil energy utilization rate of 35,426.81 MJ ha-1 (Nabavi-Pelesaraei et al., 2018). Diesel fuel and natural gas combustion significantly contributed to the CExD method analysis (Khanali et al., 2017). Exergoenvironmental aspects in various paddy production systems in Iran introduced the concept of life cycle cost (LCC) and emissions costs as a new factor in these scenarios. They evaluated environmental life cycle damages and found that diesel fuel and nitrogen had the most significant impact on resource damage in certain systems. On-Farm emissions were identified as the largest contributor to environmental impact in the surveyed systems. The analysis also revealed that non-renewable fossil fuel was the main 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 effect in organic rice systems. Similar research in other crops has shown that the use of chemical fertilizers, particularly urea, and fossil fuels had the most significant effect on GHG emissions and global warming potential (Hokazono and Hayashi, 2012).

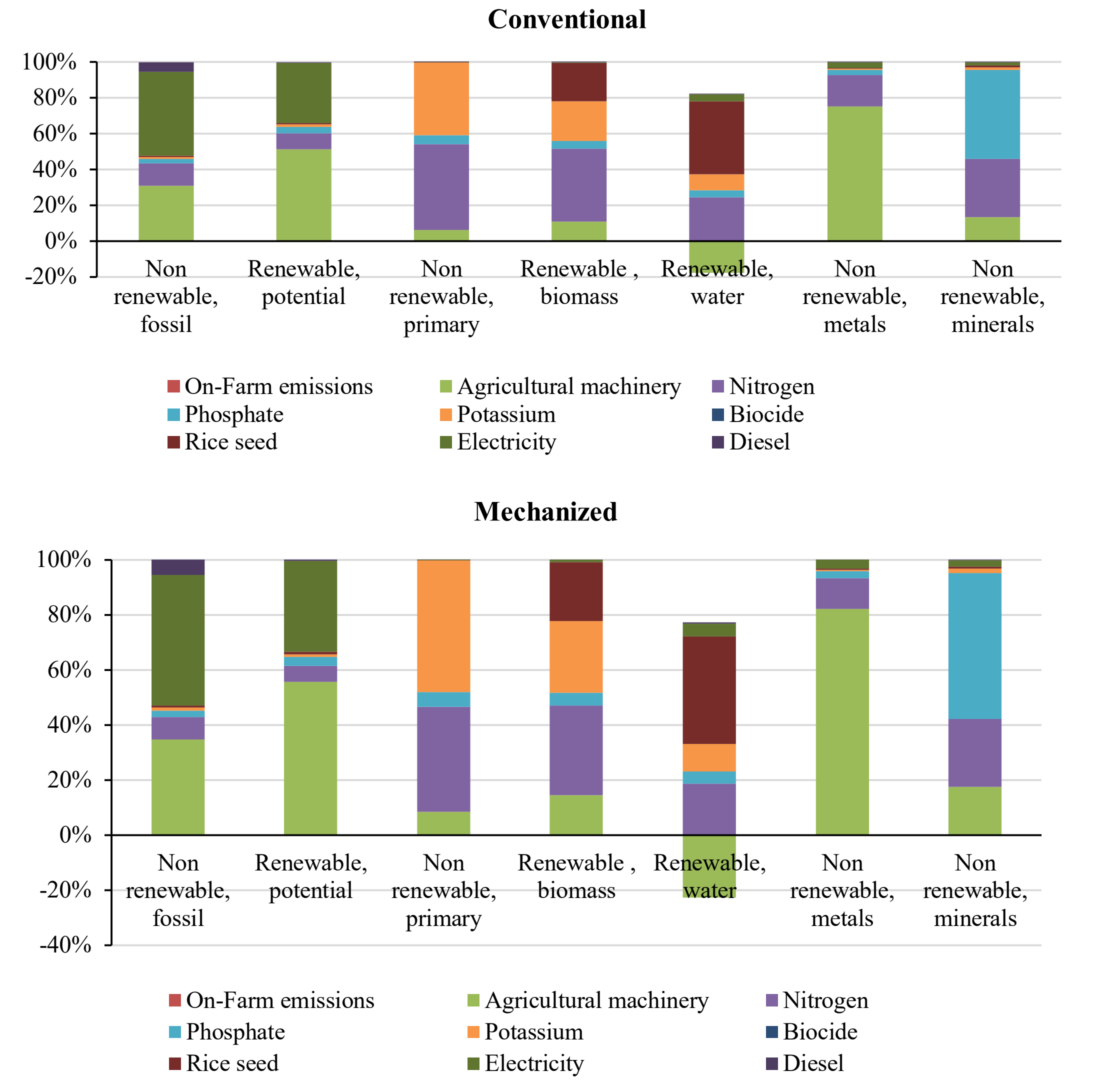
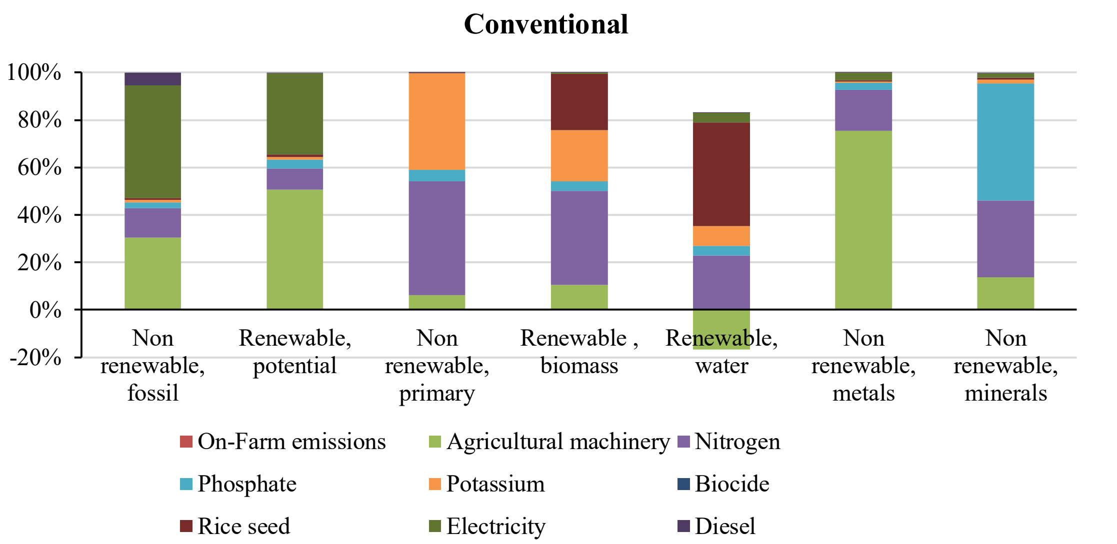


Figure 6. The Hashemi variety of paddy production relies on various inputs to consume energy forms for different stages of production.



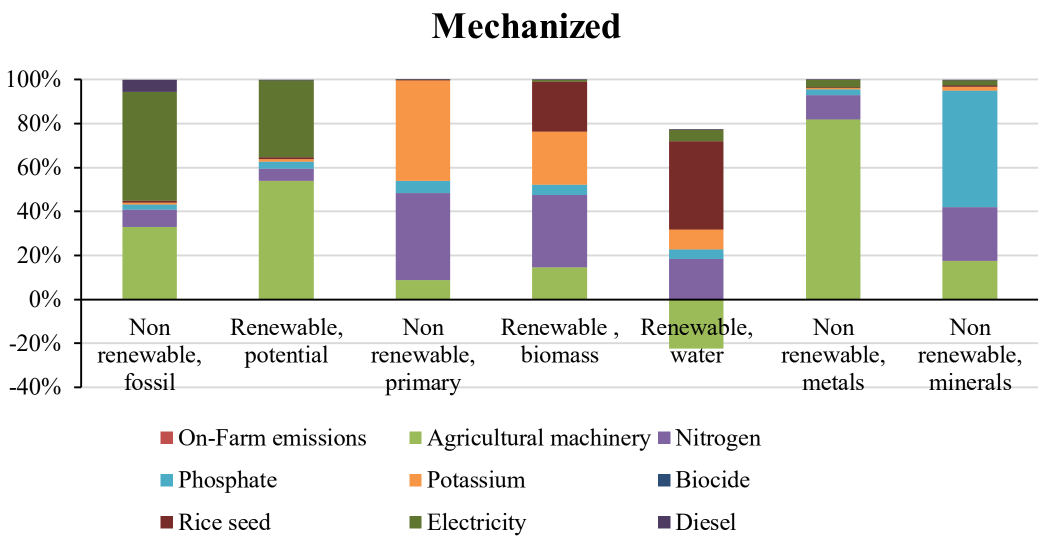


Figure 7. The Khazar variety of paddy production relies on various inputs to consume energy forms for different stages of production.

Conclusions

Analyzing the environmental impact of paddy cultivation through LCA and CExD assessments across different scenarios provides a holistic understanding of its sustainability. By evaluating energy and resource inputs, emissions, and waste outputs, we can pinpoint areas for improvement and implement more eco-friendly practices in rice production. This data can inform policy decisions to reduce the environmental footprint of agriculture and promote sustainable practices. The analysis revealed that paddy cultivation has a significant impact on water use and greenhouse gas emissions. The study utilized the ReCiPe2016 method to assess resource impacts, with conventional and mechanized methods showing higher impacts for the Hashemi variety compared to the Khazar variety. Electricity was found to be a major contributor to environmental emissions in all categories. The CExD method identified seven types of energy, with non-renewable fossil energy playing a significant role in both cultivation methods for the two varieties studied. However, mechanized cultivation of the Khazar variety showed a notable output of renewable biomass energy. Through a comprehensive comparison using LCA and CExD, we can determine the most sustainable practices for paddy cultivation, considering a wide range of environmental impacts and resource consumption. This information is crucial for making informed decisions and promoting sustainable agricultural practices.

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