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Original Article

Environmental impact assessment of rice production in Indonesia: A case study from Jatibarang, West Java

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Abstract

The agricultural sector is one of the contributors to global warming, for example by rice cultivation that produces the greenhouse gases methane and carbon dioxide. This study aims to assess the environmental performance of rice production in Jatibarang District, Indramayu Regency, West Java Province, as one of the largest rice producers in Indonesia. The method used in this study is life cycle assessment, highlighting the rice production stage with the most significant impact. SimaPro 9.2.0 software and the Recipe 2016 Midpoint method were used to determine the environmental impact of rice production. A total of 18 environmental impacts of rice production were assessed, and the analysis focused on the effects on global warming, acidification, and eutrophication. The impact assessment resulted in a value of 734 kg CO_2 eq for global warming, 3.13 kg SO_2 eq for terrestrial acidification, and 0.228 kg P eq for freshwater eutrophication. The hotspot analysis shows that using chemical fertilizers in the form of urea and NPK gave the most significant contribution to the overall impact evaluated. The application of LCA in the agricultural sector can provide information to help policymakers understand the potential environmental impacts of rice production at various spatial scales.

Keywords: global warming, eutrophication, acidification, agriculture, paddy rice

1. Introduction

Global food output must increase 70% over the next three decades to feed 9.7 billion people (United Nations [UN], 2019). Increasing agricultural output is necessary to meet this need. However, this requires more water, fertilizers, pesticides, and energy per unit area. This can cause water, land, and air pollution in the cultivated region, endangering numerous creatures, including humans (Gaffney, Challender, Califf, & Harden, 2019; Hu, Liu, Chen, & Zhu, 2021). The agriculture sector emits 14-28% of net anthropogenic greenhouse gases, contributing to global warming (Gan *et al*., 2014). The environmental and health risks of hazardous chemicals have raised concerns about nitrogen (N) and phosphorus (P) fertilizers, two essential agricultural inputs. Rice farming uses pesticides and fertilizers, which harm the environment (Tang *et al*., 2020).

Rice production is a major source of agricultural greenhouse gas (GHG) emissions. These emissions are 1.3%–1.8% of global anthropogenic greenhouse gas emissions (Maraseni *et al*., 2018). Note that rice is one of the four most extensively produced staple crops worldwide (Food and Agriculture Organization of the United Nations [FAO], 2020). Rice farming covers 11% of global arable land and emits 10.1% of agricultural emissions (Meijide, Gruening, Goded, Seufert, & Cescatti, 2017). Rice production releases toxic gaseous emissions, contributing to local and worldwide environmental challenges, including global warming (Escobar *et al*., 2022). Rice production emits large amounts of CO_2, CH_4, and N_2O (Ahmad, Zoli, Latella, & Bacenetti, 2023).

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Rice cultivation can deplete resources and harm biodiversity, as well as emit greenhouse gases (Jeswani, Hellweg, & Azapagic, 2018). Thus, sustainable rice growing requires extensive research and strategy development.

Indonesia produces the third most rice after China and India (U.S. Department of Agriculture [USDA], 2022). Indonesia produced 54–55 million tons of rice in 2019–2021. Indonesia's top rice producers are East Java, Central Java, and West Java (Badan Pusat Statistik [BPS], 2022). West Java's Indramayu regency is known for rice farming. It is the region's largest rice grower, producing 700,000–900,000 tons annually (Badan Pusat Statistik Jawa Barat [BPS], 2022). Given its importance in meeting rice demand, rice growing sustainability must be addressed. Due to increased sustainability awareness, consumers are required to consider environmental and ethical issues when buying goods and food. An environmental impact evaluation of rice or paddy production could address sustainability.

Environmental assessment is a recognised method for sustainable agriculture. Life cycle assessment (LCA) can be used to examine the environmental impacts of a product's life cycle in an industrial system (Dastan, Ghareyazie, & Pishgar, 2019). This comprehensive methodology uses a systematic collection of methods to convert individual activities' material and energy inputs and outputs into acceptable environmental impacts (Bacenetti, Lovarelli, Tedesco, Pretolani, & Ferrante, 2018). The LCA method is promising for assessing the environmental sustainability of agri-food product manufacturing (Nabavi-Pelesaraei, Rafiee, Mohtasebi, Hosseinzadeh-Bandbafha, & Chau, 2018). LCA has been used in many recent studies to estimate the environmental impact of agro-food systems, including growing grains, legumes, and tea (Rezaei, Soheilifard, & Keshvari, 2021).

The environmental impact of rice production has been quantified in several Asian countries such as Thailand (Yodkhum, Gheewala, & Sampattagul, 2017), Bangladesh Jimmy, Khan, Hossain, & Sujauddin, 2017), Malaysia (Harun, Hanafiah, & Aziz, 2021), Iran (Habibi, Niknejad, Fallah, Dastan, & Tari, 2019) and China (He, Qiao, Liang, Knudsen, & Martin, 2018). Several publications have emerged regarding studies on the sustainability of rice production in Indonesia, including studies on the sustainability of rice production in Bengkulu (Barchia, Ishak, Utama, & Novanda, 2021), West Java (Rachman *et al.*, 2022), Riau (Yusuf, Pato, Tang, & Karnila, 2019), and Jambi (Kurnia, Rosyani, & Farida, 2021). However, these publications examine aspects of sustainability in general without focusing on ecological aspects, by analyzing emissions that arise as a result of rice production using the LCA method. Therefore, analyzing the environmental impact of rice farming in Indonesia is important considering that rice is the nation's main food source. This effort aims to improve the long-term sustainability of rice farming practices in the country. Therefore, the main objective of this research is to examine the environmental impacts associated with paddy or rice production operations in Jatibarang, Indonesia. This will be accomplished by assessing the key factors responsible for generating adverse environmental effects during the rice growing process. This study contributes to the existing literature on LCA studies of rice production in Asia, focusing on Indonesia. The findings of this research hold significant implications for policymakers, as they can serve as a valuable resource for informing decision-making processes, increasing awareness, and promoting engagement across all sectors toward achieving sustainable agricultural practices. Rice farmers and industrial enterprises can utilize the findings of this study to enhance their competitive advantage and foster the adoption of ecologically sustainable production practices.

2. Materials and Methods

The methodology employed in this study, known as the Life Cycle Assessment (LCA) approach, adheres to the ISO 14040 (2006) and ISO 14044 (2006) standards. It has four distinct steps, namely the definition of objectives and scope, the compilation of a life cycle inventory (LCI), the assessment of life cycle impact (LCIA), and the interpretation of the resulting data.

2.1 Definition of Objectives and Scope

The Life Cycle Assessment (LCA) investigation aimed to assess the ecological ramifications associated with rice cultivation in the Jatibarang District of Indramayu Regency, located in the West Java Province of Indonesia. The designated unit of measurement is equivalent to one metric ton of rice. The system employed in this study is limited to the cradle-to-gate approach, encompassing the stages of land preparation, sowing, and harvest, focusing on rice production. The constraints of the method utilized in this investigation are shown in Figure 1.

2.2 Life cycle inventory analysis

The primary focus of this study pertains to conventional rice-growing techniques. Most tasks involved in traditional rice growing are carried out by manual labor. An inventory analysis of inputs utilized in rice growing was conducted, employing primary data encompassing resource inputs and agricultural operations. The data were gathered through field notes and direct interviews with farmers. Conventional farming practices involve using many agricultural chemicals, including pesticides, synthetic fertilizers, insecticides, herbicides, and fungicides, as presented in Table 1.

2.3 Life cycle impact assessment

This study's life cycle impact assessment methodology is ReCiPe 2016 Midpoint. The evaluation of impacts is conducted using SimaPro, a software tool, in conjunction with the ecoinvent 3 database. This approach supplements the available field data and other relevant local data. The selection of effect categories for analysis was determined by considering probable associated impacts and the policy context, which includes Global warming potential (GWP), Stratospheric ozone depletion (SOD), Ionizing radiation (IR), Ozone formation-Human health (OF-HH), Fine particulate matter formation (FPMF), Ozone formation-Terrestrial ecosystems (OF-TE), Terrestrial acidification (TA), Freshwater eutrophication (FE), Marine eutrophication (ME), Terrestrial ecotoxicity (TEC), Freshwater ecotoxicity (FEC), Marine ecotoxicity (MEC), Human carcinogenic

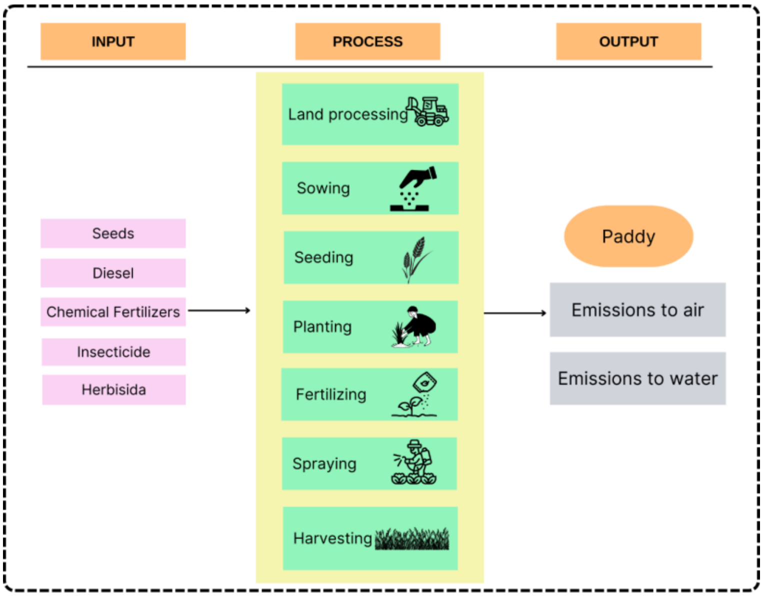


Figure 1. System boundaries

Table 1. Inventory of paddy-production process (120 kg paddy)

Input	Total	Unit
Seed	2	kg
Diesel for tractors	3	L
Urea fertilizer	22	kg
Fertilizer NPK 16-16-16	10	kg
Fertilizer NPK 15-15-15	20	kg
Insecticide	125	mL
Fungicide	125	mL
Herbicide	40	mL

Table 2. Environmental impacts of producing 1 ton of paddy

Impact category	Unit	Total
GWP	kg CO_2 eq	734
SOD	kg CFC_{11} eq	3.6×10^{-2}
IR	kBq Co-60 eq	14.2
OF-HH	kg NOx eq	1.51
FPMF	kg PM2.5 eq	9.94×10^{-1}
OF-TE	kg NOx eq	1.54
TA	kg SO_2 eq	3.13
FE	kg P eq	2.28×10^{-1}
ME	kg N eq	7.45×10^{-2}
TEC	kg 1,4-DCB	3.2×10^{3}
FEC	kg 1,4-DCB	33.8
MEC	kg 1,4-DCB	44.8
HCT	kg 1,4-DCB	35.3
HNCT	kg 1,4-DCB	724
LU	m2a crop eq	40.7
MRS	kg Cu eq	5.93
FRS	kg oil eq	244
WC	m^3	37.7

toxicity (HCT), Human non-carcinogenic toxicity (HNCT), Land use (LU), Mineral resource scarcity (MRS), Fossil resource scarcity (FRS) and Water consumption (WC).

3. Results and Discussion

3.1 Environmental impact analysis

This study examines the environmental consequences associated with the rice production process, which have been classified into various effect categories, as illustrated in Table 2.

According to the data presented in Table 2, it is evident that the production of 1 ton of paddy rice in the Jatibarang region results in a GWP value of 734 kg CO_2 eq. The findings from research examining the environmental impacts of producing 1 ton of rice in multiple Asian nations indicate variations in the values of GWP. The life cycle assessment (LCA) conducted on a quantity of 1 ton of rice in Iran has resulted in a GWP value of 2,426.2 kg CO_2 eq (Firouzi, Nikkhah, & Aminpanah, 2018) and 427,4 kg CO_2 eq (Morandini, Petroudi, Mobasser, & Dastan, 2020); in China it resulted in a GWP value of 2,504.20 kg CO_2 eq (Xu, Zhang, Liu, Xue, & Di, 2013); and 1,390 kg CO_2 eq in Malaysia (Rahman *et al.*, 2019). This observation demonstrates that variations in countries or within regions of a single country can yield varied GWP outcomes. A research investigation conducted in China examined the ecological effects associated with rice cultivation throughout five distinct provinces, yielding various results by each respective region. The previous variables, including the soil properties, fertilizer application rate, irrigation system, and agricultural methodology, significantly influence this phenomenon (Xu, Zhang, Liu, Xue, & Di, 2013). Water systems play a significant role in influencing various environmental issues. One of the contributing factors to the elevated GWP value observed in irrigation systems is the substantial energy consumption required for the operation of pumping mechanisms to facilitate the movement of significant volumes of water (Giuliana, Lucia, Marco, & Simone, 2022). The GWP results obtained in this study were significantly reduced due to the exclusion of the irrigation system as an input. This exclusion is because the irrigation system in Jatibarang depends only on rainfall and river water without a pump. The variation in GWP across different countries can be attributed to several key elements**:** system boundaries, inputs, rice yields, and diverse agricultural practices (Ahmad, Zoli, Latella, & Bacenetti, 2023).

This study determined that the impact values associated with TA and FE were 3.13 kg SO_2 eq and 0.228 kg P eq per metric ton of paddy. The findings of this study demonstrate a much-reduced amount compared to a previous impact assessment conducted on rice production in Thailand that reported TA and FE impacts of 11.7 kg SO_2 and 0.65 kg P eq per metric ton of paddy, respectively (Mahmood & Gheewala, 2023). The observed difference can be attributed to variations in the quantities of fertilizer used. In Thailand, a higher quantity of fertilizer was applied, leading to a more significant influence on TA and FE.

3.2 Hotspot identification

Figure 2 presents the outcomes of the environmental impact assessment, whereby various sub-systems have been defined to facilitate the identification of hotspots. These hotspots correspond to the stages that influence each impact category the most.

According to the data presented in Figure 2, it can be concluded that using urea and NPK fertilizers significantly contributes to various environmental problems. Using chemical fertilizers is common in rice production, wherein chemicals are applied multiple times from planting to harvest. During the initial phase of cultivation, urea is applied as a fertilizer. Subsequently, at intervals of 10 days following the transplantation, a combination of urea and NPK fertilizer is utilized. This fertilization regimen is repeated three times before reaching the harvest stage. The quantity range of chemical fertilizer required to produce approximately 120 kg of rice starts from 50 kg, comprising a combination of urea and NPK fertilizer. The prevalence of excessive fertilizer application can be attributed to the inadequate nutrient levels in the soil, requiring increased reliance on chemical fertilizers in order to achieve maximum crop productivity (Paramesh *et al*., 2023). The extensive utilization of fertilizers leads to an increase in energy consumption.

One notable factor that has the potential to contribute to global warming significantly is the utilization of urea and NPK fertilizers. This is due to the inclusion of emissions generated throughout the production process of chemical fertilizers, such as urea and NPK, in the database. These emissions sources include mining raw materials, making fertilizer, packaging, and transportation. The associated processes serve as contributors to the emission of greenhouse gases, which in turn contribute to the phenomenon of global warming (Wu *et al*., 2021). The results of a research study evaluating the assessment of global warming potential associated with the chemical fertilizer production indicate that a significant proportion (about 60%) of greenhouse gas emissions can be attributed to power plants. In comparison, the fertilizer production process accounts for around 26% of these emissions (Chen, Geng, Hong, Yang, & Ma, 2018).

3.3 Contribution of pollutants to global warming

According to the results presented in Figure 3a, it is evident that CO_2 plays a substantial role in the overall effect on global warming. CO_2 is the primary contributor, accounting for 77% of the total emissions, followed by N_2O and methane CH_4. The most significant amount of greenhouse gases is derived from the utilization of fossil fuels, such as diesel for agricultural machinery, as well as the fuels employed in manufacturing chemical fertilizers (urea and NPK) and pesticides. The CH_4 emissions primarily originate from the rice planting stage, whereas most CO_2 emissions are attributed to manufacturing chemicals used during the process. Notably, the stage involving the production of chemicals exhibits the highest energy consumption among the various stages of rice production (Wang, Xia, Zhang, & Liu, 2010).

Rice cultivation has a substantial role in releasing greenhouse gases, the primary driver of global warming. The application of fertilizers in agricultural practices produces an apparent impact on the natural environment since the nitrogen component included in these fertilizers leads to the release of

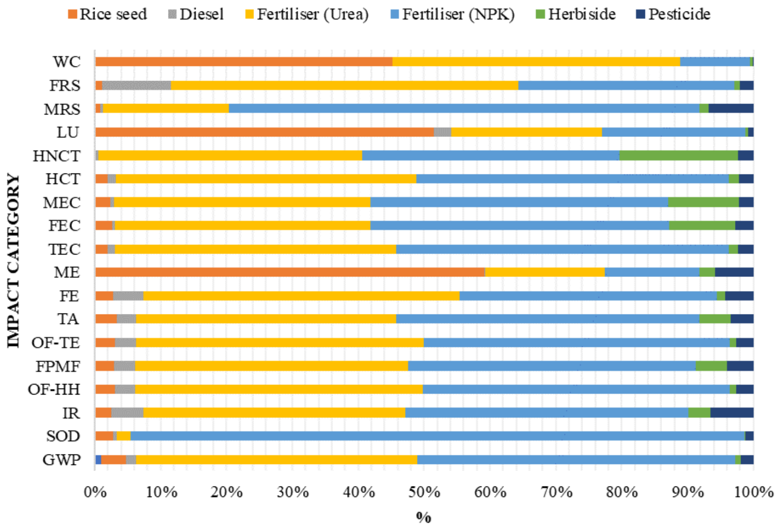
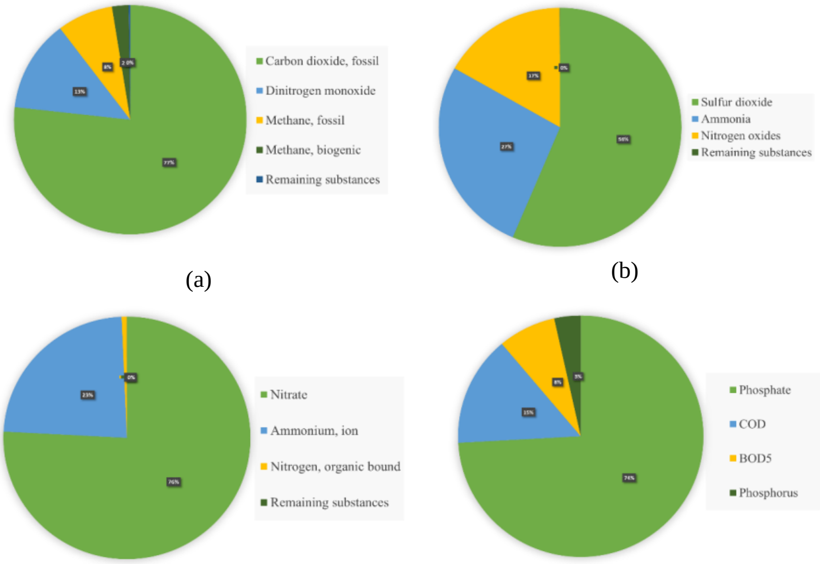


Figure 2. Hotspots in each impact category



(a) (b)

(c) (d)

Figure 3. Pollutant contributions by impact category (a) GWP; (b) TA; (c) ME; and (d) FE

nitrogen oxides (NO_x), ammonia (NH_3), and N_2O. Fertilizers facilitate the release of nitrogen gas (N_2) through a series of biological processes known as nitrification and denitrification. Soil bacteria mediate these processes under aerobic and anaerobic circumstances (Amirahmadi *et al*., 2022). The N_2O is generated through the denitrification in agricultural fields, as well as by the use of nitrogen-based fertilizers. Numerous factors have influenced the emissions of N_2O from paddy fields, including variables such as fertilizer composition, climate, and soil characteristics (Harun, Hanafiah, & Aziz, 2021).

3.4 Pollutants contribution to acidification

The rice planting process affects acidity, which can be attributed to the evaporation of NH_3 from applying fertilizers, including ammonium nitrate (Wang, Xia, Zhang, & Liu, 2010). The extensive utilization of fertilizers containing nitrogen leads to elevated levels of nitrate or nitrogen leaching, thus increasing acidification (Fusi *et al*., 2014). Furthermore, the emission of sulfur dioxide (SO_2) during the manufacturing of chemical compounds utilized in agricultural practices, including fertilizers and pesticides, plays a significant role in acidification. This analysis assessed the influences of various pollutants, including SO_2, NH_3, and nitrogen oxides (NO_x in the form NO and NO_2), measured in kg SO_2 eq. According to the data in Figure 3b, the primary contributors to acidification are SO_2, NH_3, and NO_x, accounting for 56%, 27%, and 17% of the total, respectively. The higher emission levels of these gases can be attributed to the utilization of urea and NPK fertilizers.

3.5 Pollutant contributions to eutrophication

Eutrophication is a prevalent environmental concern on a global scale, resulting from the excessive introduction of nutrients, specifically nitrogen (N) and phosphorus (P), into ecosystems. These nutrients mainly originate from many sources, with agricultural production systems being a significant contributor due to applying fertilizers. The surplus nutrients introduced to agricultural fields in the form of fertilizers can enter water bodies through several pathways, such as leaching, runoff, and precipitation. This influx of nutrients can lead to the phenomenon known as eutrophication, which affects both freshwater and marine ecosystems. It is a prevailing assumption that the eutrophication of freshwater systems is constrained mainly by phosphorus (P).

In contrast, the eutrophication of marine systems is predominantly regulated by nitrogen (N) (Huang, Xu, Ridoutt, Wang, & Ren, 2017). The findings from the study indicate that in the context of saltwater eutrophication, the primary factors contributing to this phenomenon are nitrate, ammonia, and nitrogen, accounting for 76%, 23%, and 1%, respectively, as depicted in Figure 3c. The findings presented here align with previous research on eutrophication in agricultural contexts throughout multiple provinces in Thailand (Balasuriya, Ghose, Gheewala, & Prapaspongsa, 2022). The results indicate that nitrate is the primary factor contributing to eutrophication in seawater, accounting for 92.7% of the observed effects. Ammonia and nitrogen oxides are secondary contributors, accounting for 6.7% and 0.6% of the eutrophication, respectively (Balasuriya, Ghose, Gheewala, & Prapaspongsa, 2022). In the context of eutrophication in freshwater systems (as seen in Figure 3d), it is evident that phosphorus compounds, particularly phosphate, play a predominant role, accounting for approximately 80% of the overall impact. Phosphate ions in soil exhibit a strong attraction towards aluminum and calcium, requiring the application of surplus fertilizer to enhance the P mineralization. This, in turn, leads to an increased availability of phosphate. Nevertheless, excessive use of fertilizers also amplifies the probability of eutrophication (Leon & Kohyama, 2017).

According to the findings of hotspot identification, it is established that the utilization of chemical fertilizers significantly contributes to a range of environmental impacts. One counter measure is to substitute traditional farming systems with organic farming. Organic farming is the optimal method for attaining sustainable food production and resource utilization, as well as for mitigating environmental degradation and reducing farmers' reliance on the agrochemical industry (Ashari, Sharifuddin, & Za, 2017; Rachman *et al*., 2022). Moreover, organic farming achieves a 40% reduction in energy consumption and greenhouse gas emissions compared to conventional farming (Skinner *et al*., 2019).

4. Conclusions

This study assessed the environmental impact of producing 1 ton of rice. The Global Warming Potential (GWP) is measured at 734 kg CO_2 eq. This significant result suggests a substantial impact on climate change caused by rice production. The greenhouse gases CO_2, N_2O, and CH_4 (fossil and biogenic), are the main factors responsible for global warming. CO_2 is the largest contributor, accounting for 77% of the GWP, followed by N_2O at 13% and CH_4 at 10%. The TA has a measurement of 3.13 kg SO_2 eq. This indicates a significant increase in acidity in terrestrial ecosystems, primarily caused by the application of chemical fertilizers. The FE is calculated to be 0.228 kg P eq, this value indicates a significant impact on the contamination with nutrients of freshwater systems. The ME, which stands at 0.0745 kg N eq, signifies the impact on marine ecosystems caused by nutrient runoff. Considering the substantial contribution of chemical fertilizers to GWP, the use of solutions such as precision agriculture and improved fertilizer application can effectively mitigate emissions. Farmers should consider the adoption of slow-release fertilizers or other nutrient management techniques in order to limit emissions of CO_2, N_2O, and CH_4. In addition, the implementation of organic farming can effectively decrease and eliminate the reliance on synthetic fertilizers. Policymakers need to consider implementing regulations that provide benefits for the adoption of ecologically sustainable methods and technologies in rice cultivation. This may involve providing funding for the adoption of low-emission technologies or offering backing for research on sustainable agricultural practices. Offering farmers assistance and training on sustainable farming techniques and the advantages of lowering chemical inputs can promote the adoption of measures that decrease environmental consequences. Implementing these guidelines can lead to a substantial decrease in the environmental effects of rice production within the agriculture sector. Implementing these steps will help decrease greenhouse gas emissions, land and marine pollution, and overall environmental degradation. This strategy is in line with the objective of shifting towards more sustainable agricultural methods and attaining improved environmental stewardship in rice farming.

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