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Environmental Impact of Various Rice Cultivation Methods in Northeast China through Life Cycle Assessment

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Abstract: Rice, a crucial staple in China, is cultivated through various techniques, including seedling transplanting, dry direct seeding, and film mulching. Despite its significance, rice production is a considerable environmental burden. Using a life cycle assessment (LCA) methodology, this study aimed to evaluate the environmental impacts of four rice cultivation methods (transplanting rice, dry direct-seeding rice, dry direct-seeding rice with polyethylene film (PE), and dry direct-seeding rice with biodegradable film) in Northeast China. The results indicate that the magnitude of environmental impacts among treatments was consistent across years. The potential values of all environmental impacts of the four different cultivation methods of rice in the 2021 field trial were smaller than the results of the same cultivation method of rice system in the 2022 field trial. Among the four rice cultivation methods, the consumption of energy showed inconsistency over the two years, with the highest energy consumption in the first year being for dry seeding with PE film and in the second year for dry seeding without film. Additionally, transplanting exhibited the highest impact on water resource consumption and climate change. Dry direct-seeding rice displayed the highest eutrophication and ecotoxicity. Dry direct-seeding rice with a biodegradable film had the least impact in terms of acidification. Moreover, dry direct-seeding rice with a biodegradable film minimized water consumption and greenhouse gas emissions without compromising yield.

Keywords: life cycle assessment; Northeast China; rice; dry direct-seeding; film mulching

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1. Introduction

China, with a substantial population, stands as a major global food consumer. Given the international landscape and the escalating influence of climate change, the demand for food in China is poised to rise continuously. Rice, as the primary food crop, contributes to over 40% of the total food production [1]. To meet the burgeoning needs of the growing population, there is an imperative to consistently enhance rice yields [2]. The conventional approach involves a significant input of fertilizer to augment the yield of rice per unit area. However, the excessive use of fertilizers and pesticides results in a profusion of pollutants, leading to environmental pollution [3] and instigating a cascade of environmental issues. Consequently, the environmental impacts stemming from rice production have garnered escalating attention [4].

China employs three primary rice cultivation techniques: rice transplantation, dry direct-seeding, and film-covering cultivation [5]. Rice transplantation and flooding, a practice with a history spanning thousands of years in China, is renowned for its high yields and quality. However, the soaking of rice before transplanting and the necessity for irrigation during the growth period demand significant water resources. Given today's escalating water scarcity, rice transplantation faces formidable challenges. Dry direct-seeding involves sowing rice seeds directly into the farmland after dry land preparation, akin to corn seeding. Implementing dryland irrigation during the reproductive phase of rice can yield water savings exceeding 40% [6]. Additionally, dry seeding facilitates mechanization, substantially improving production efficiency [7]. Despite its advantages, dry seeding presents challenges such as a large sowing volume, a low seedling emergence rate, susceptibility to lodging, and difficulties in ensuring yield [8]. The mulching cultivation technique, introduced from Japan in the 1980s, underwent scientific research for crops like soybean, maize, and rice in China [9–11]. Rice mulching cultivation alters environmental conditions, including temperature and air in the crop's root zone [12], and curbs water evaporation from the ground, leading to water conservation. Consequently, mulching cultivation technology finds widespread application in water-scarce, alpine-type rice fields in China and rice fields in cold areas in Northeast China [13,14]. Polyethylene (PE) mulch is usually used in agricultural production. Due to the difficulty of PE film degradation in the natural environment, which causes great pollution, biodegradable film has been researched to replace PE film and reduce the environmental pollution caused by mulching.

The Northeast region is one of the important rice-producing areas in China due to its unique geographical location and ecological conditions. With excellent rice quality and high commodity rate, this region is the largest commercial japonica rice production base in China. With the surging demand for food in recent years, the rice cultivation area has expanded to nearly 5.35×10^6 ha [15], boasting the highest production efficiency. All three rice cultivation methods are utilized in the Northeast region. These methods exhibit variations in the inputs of agricultural product, leading to diverse environmental impacts. Given this scenario, to provide a theoretical foundation for the sustainable development of rice in Northeast China, it becomes imperative to conduct a comprehensive assessment of the environmental impact associated with different rice cultivation methods. Additionally, identifying key factors influencing the environmental impact will contribute to informed decision-making in promoting sustainability.

Life cycle assessment (LCA) is a potent tool developed to systematically evaluate the potential impacts on human health and the environment throughout the life cycle of a product or production process [16]. In recent years, LCA has found widespread application in agriculture-related systems. For instance, German scholars conducted an LCA to assess the impacts on natural resources across 18 grassland farms with varying cropping intensities in southern Germany, aiming to mitigate the environmental burden of agriculture [17]. In China, researchers have delved into the agricultural LCA framework, using winter wheat in Luancheng, Hebei, as an illustrative example [18]. Additionally, scholars have integrated LCA into the entire agricultural circular economy process, proposing a technical framework to furnish reliable environmental impact assessment information for agricultural policy makers, producers, and consumers [19]. As global climate change intensifies, there is an increasing emphasis on low-carbon agriculture. Researchers have investigated the carbon footprint of agriculture, identifying the top three sources of direct carbon emissions as CH_4 produced by rice, diesel fuel, and CH_4 from livestock enteric fermentation [20]. It has been emphasized that agricultural life cycle management requires attention, including strengthened management of agricultural information inputs, enhanced utilization efficiency, accelerated promotion of agricultural technology, and the advocacy for an appropriate scale of agricultural management, among other measures for agricultural emission reduction.

In this regard, using the life cycle assessment method to study the impact of existing cultivation methods in Northeast China on the environment is aimed at achieving the following objectives: (a) quantifying and comparing the environmental impacts among different rice cultivation methods under identical climatic and soil conditions; (b) identifying the primary factors contributing to resource depletion and environmental impacts during rice production in the Northeast region; (c) establishing a scientific foundation for promoting the sustainable development of rice in the Northeast region.

2. Materials and Methods

2.1. Study Area and Data Sources

2.1.1. Study Area

Jalaid Banner is situated in the eastern part of the Inner Mongolia Autonomous Region and northeast of the Hinggan League. The terrain of Jalaid gradually descends from northwest to southeast (Figure 1). All the rivers in the city belong to the Nenjiang River system of the Songhua River Basin. With a total of 74 rivers of varying sizes, measuring a combined length of 1209 km and covering a watershed area of 21,456 km^2, these rivers create favorable conditions for rice cultivation. Jalaid Banner experiences a temperate continental monsoon climate, characterized by limited rainfall, dryness, and winds during spring. The summer is briefly warm and hot, marked by concentrated precipitation. Autumn witnesses a rapid drop in temperature, large daily temperature ranges, while winter is prolonged and cold. With distinct temperature variations across four seasons, abundant sunshine, an annual temperature of 3.6 °C, annual precipitation of 500–600 mm, and a frost-free period lasting 105–135 days, the climatic conditions are conducive to the normal growth of Jalaid rice.

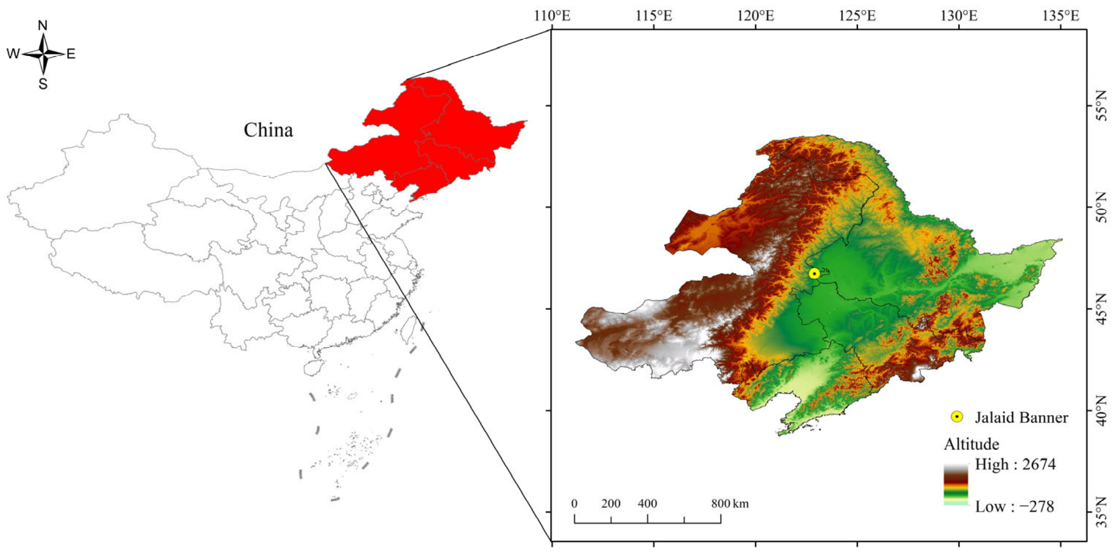


Figure 1. Location of the studied area.

2.1.2. Data Sources and Test Scheme

The study investigated the environmental effects of four distinct cultivation methods, namely, transplanting rice, dry direct-seeding rice, dry direct-seeding rice with polyethylene (PE) film, and dry direct-seeding rice with a biodegradable film. During the 2021–2022 period, field surveys and experiments were conducted in the rice cultivation area of Jalaid Banner. Data on actual rice production were collected and recorded, encompassing seed input, fertilizer consumption, pesticide usage, plastic film input, irrigation water consumption, power usage, and inputs of agricultural machinery.

The experiment was conducted from April 2021 to October 2022, featuring four treatments: (1) transplanting rice, maintaining a 1~2 cm water layer on the ground from transplanting until harvesting; (2) dry direct-seeding rice, incorporating drip irrigation tapes and irrigating based on the water demand pattern of rice; (3) dry direct-seeding rice with PE film, involving drip irrigation tapes beneath the PE film and irrigating following the water demand pattern of rice; (4) dry direct-seeding rice with a biodegradable film, mirroring the approach of dry direct-seeding rice with PE film. Three replicates of each cultivation were used with an area of 9.9 m × 10 m. Adjacent plots were separated by a 0.35 mm thick waterproof membrane buried 80 cm deep to prevent water exchange from occurring.

All four treatments involved either mechanical sowing or transplantation. The selected rice variety was Bao Nong 5, with a life cycle period of approximately 140 days. Both the PE and biodegradable films adhered to national standards, featuring a black color and a thickness of 0.01 mm. The paddy fields are transplanted in late May and harvested in late September. Dryland was sown in late April and harvested in late September. Urea (120 kg N ha^{-1}), calcium superphosphate (50 kg P_2O_5 ha^{-1}), and potassium chloride (75 kg K_2O ha^{-1}) were applied to all treatments according to the local production process. During the test period, field operations such as tillage, pest and disease control, weed control and fallow were consistent with the management practices of local farmers.

Gas collection in the static chamber was conducted 2 days before transplanting or 2 days after emergence, and subsequently every 7th day from 9:00 to 11:00. Samples of 50 mL each were collected at 0, 10, 20, and 30 min after closing the chamber. The gathered gas samples were then transferred to vacuum flasks for storage, and the concentrations of CH_4 and N_2O were determined using gas chromatography (Agilent 7890A, Santa Clara, CA, USA). Upon the rice reaching maturity, the entire crop was harvested, naturally dried, and the yield (actual moisture content of 14%) and thousand kernel weight were measured.

Excel 2022 was used to organize and calculate the raw data from the field experiment while statistical analysis was performed using SPSS 27. Significant differences in means between treatments were compared using one-way variance analysis (ANOVA) and differences between means were tested using the least significant difference (LSD) test. A significance level of $p < 0.05$ was considered significant.

2.2. Life Cycle Assessment (LCA)

In this study, an LCA approach was employed to assess energy consumption, environmental loads, potential impacts, and toxic effects on humans throughout the production, transport, distribution, use, maintenance, and recycling stages of transplanted rice, dry direct-seeding rice, dry direct-seeding rice with polyethylene film (PE), and dry direct-seeding rice with biodegradable film in Northeast China [21]. The LCA can be divided into four steps: identification of objectives and scope, inventory analysis, impact assessment, and interpretation of results.

2.2.1. System Boundary and Functional Units

Adopting the production of 1 t of rice as a functional unit, the initial boundary encompassed ore mining and fossil energy utilized in the production of agricultural products, including fertilizers and pesticide films. The concluding boundary extended to the emissions of pollutants during the rice cultivation stage. The system boundaries of the life cycle of rice production are depicted in Figure 2.

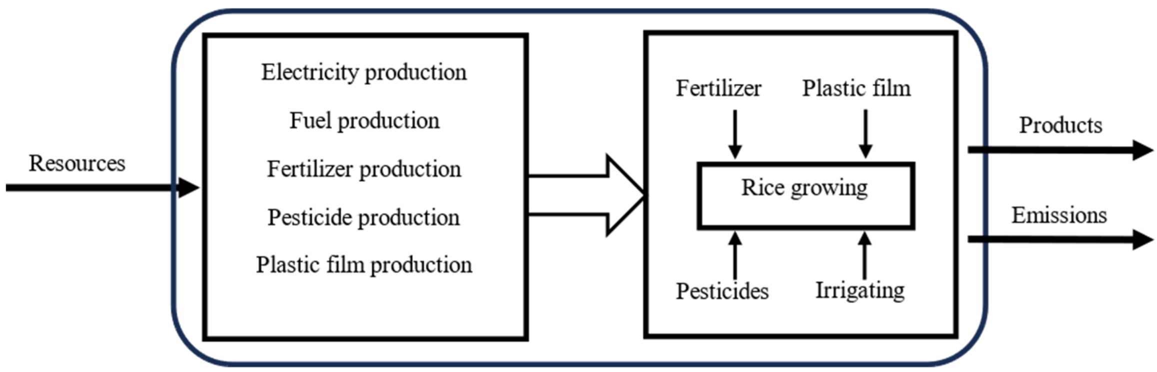


Figure 2. System boundary of rice production life cycle.

2.2.2. Inventory Analysis

The life cycle of rice production is divided into two phases: off-farm and on-farm. We considered resource consumption and pollution emissions from ore and fossil energy extraction, as well as resource consumption and pollution emissions from the production and use of fertilizers, pesticides, and mulch films. Indicators of energy, material, and water consumption in the raw material extraction and agro-crop production phases were referenced using the eFootprint system (https://www.efootprint.net/).

The China Life Cycle Assessment (LCA) Basic Database is included in the eFootprint system, which supports professional and credible research on China's product carbon footprint and is a product carbon footprint and life cycle assessment and management system. At the same time, eFootprint is a fully online LCA software system, which is much easier to use. By building a life cycle model of rice production in the eFootprint system and selecting appropriate background data sources for each material input or output, the potential environmental impacts caused by the amount of material input per hectare of rice production can be obtained. Due to a lack of information, the environmental impacts associated with the production of plant equipment, building facilities, and means of transport were not considered.

In the on-farm stage, the volatilization losses of CH_4 and N_2O in the rice fields were measured in 2021 and 2022, respectively. The volatilization loss of NH_3 accounted for 9.89% of the nitrogen input [22], and the loss of NO_3^- accounted for 4.01% of the nitrogen input [23,24]. NO_X (a generic term for nitric oxide and nitrogen dioxide) emission was 0.125% of the nitrogen input [25,26], TP (total phosphorus) loss was calculated as 1.55% of the input of phosphorus based on the first national survey of pollution sources. The active ingredients of the pesticides used was atrazine, calculated according to the ingredient list in the instructions, and the pesticide amount was calculated as 54% of the input of active components of pesticides based on information from previous studies [27]. The impact of heavy metals in the fertilizer on the environment and the heavy metals carried by the straw and grain leaving the rice field system were not considered.

The results of the rice input-output inventory for the four cultivation methods are summarized in Tables 1–3.

Table 1. Same parts of the list of input-output lists for different rice cultivation methods in a two-year field trial.

Categorization	Material (ha^{-1})	Unit	Transplanting Rice	Dry Direct-Seeding Rice	Dry Direct-Seeding Rice with PE Film	Dry Direct-Seeding Rice with Biodegradable Film
Input	Machine	kg	29.98	29.79	29.79	29.79
	Diesel oil	kg	137.00	98.75	98.75	98.75
	Gasoline	kg	46.88	43.20	43.20	43.20
	N	kg	120	120	120	120
	K_2O	kg	75	75	75	75
	P_2O_5	kg	50	50	50	50
	Pesticide	kg	2.81	6.06	1.515	1.515
	Growth regulator	kg	3	3	3	3
	Irrigation equipment	kg	37.26	192.28	247.07	247.07
	Biodegradable film	kg	0	0	0	93.495
	PE film	kg	0	0	93.495	0
	Seedling	10,000 plants	117	0	0	0
	Seed	kg	0	150	150	150
	Labor	h	243.08	201.73	169.03	154.03
Output	NH_3	kg	11.87	11.87	11.87	11.87
	NO_3^-	kg	4.81	4.81	4.81	4.81
	NO_X	kg	0.15	0.15	0.15	0.15
	TP	kg	0.78	0.78	0.78	0.78
	Pesticides (water)	kg	0.3	0.06	0.02	0.02
	Pesticides (soil)	kg	1.21	2.61	0.65	0.65

Table 2. Different parts of the list of input-output lists for different rice cultivation methods in a two-year field trial.

Categorization	Material (ha^{-1})	Unit	Transplanting Rice		Dry Direct-Seeding Rice		Dry Direct-Seeding Rice with PE Film		Dry Direct-Seeding Rice with Biodegradable Film	
			2021	2022	2021	2022	2021	2022	2021	2022
Input	Irrigation water	m^3	5721	8251	2252	4512	1641	3051	1641	3051
	Electricity	kwh	3132	4398	1126	2257	821	1526	821	1526
Output	CH_4	kg	511.87	471.83	180.68	171.64	124.16	117.95	136.31	126.29
	N_2O	kg	1.43	1.52	2.1	2.3	2.22	2.43	2.22	2.46

Table 3. Grain yield for different rice cultivation methods in a two-year field trial.

Treatment	Grain Yield (kg ha^{-1})	
	2021	2022
Transplanting rice	7988 a	8048 a
Dry direct-seeding rice	6530 c	6376 c
Dry direct-seeding rice with PE film	7514 b	7336 b
Dry direct-seeding rice with biodegradable film	7826 a	7778 a

The data in the table are the average of the yields obtained from three replicated trials. Different letters within columns are significantly different at $p < 0.05$ (LSD test).

2.2.3. Impact Assessment

The data analyzed in the above list were classified into different types of environmental impacts, a process known as impact classification. The impact types are divided into three categories: resource consumption, human health impact, and ecosystem health impact [28]. Each category contains numerous subcategories under the influence of ecosystem health, such as global warming, ozone layer destruction, acid rain, photochemical smog, and eutrophication.

Rice production necessitates significant consumption of both primary and secondary energy in the manufacturing of agricultural machinery and in the production and processing of agricultural products. Agricultural products as well as agricultural production activities heavily rely on soil and water; therefore, resource consumption needs to be taken into account when analyzing their environmental impact. Agricultural activities and agro-ecosystems in China generate large amounts of greenhouse gases, contributing to global warming. Consequently, the impact of rice production on climate change needs must be considered. The production of nitrogen fertilizer and the farming phase of the agricultural life cycle stage result in acid production; thus, the impact of rice cultivation on environmental acidification was considered. The wastewater produced in the agricultural production process and the loss of N and P in farmlands contribute to water eutrophication through various pathways. Therefore, eutrophication is used as an indicator to analyze environmental impacts. The use of pesticides in farming systems produces toxic substances, and chlorine is discharged into water bodies during agricultural production, leading to ecological pollution. Therefore, ecological toxicity should be considered when analyzing the environmental impacts of rice production. During the life cycle of rice, five main environmental impact types were considered in this study: resource consumption, climate change (GWP), environmental acidification (AP), eutrophication (EP), and ecotoxicity (ET) [29]. Resource consumption includes energy consumption (PED) and water consumption (WU), and ecotoxicity includes water toxicity and soil toxicity.

The input-output data of different rice cultivation methods were characterized, and the environmental impact potential of the production cycle was calculated. The environmental impact types and their equivalence coefficients for the main emission substances involved in this study are listed in Table 4 [30].

Table 4. Type of environmental impact and equivalent coefficient of emitted substances.

Environmental Impact Category	Emission	Equivalent Coefficient
Climate change acidification	CO_2	1
	SO_2	1
	CH_4	21
	N_2O	310
Eutrophication	PO_4^{3-}	1
	TP	3.06
	NO_X	0.13
	NO_3^-	0.42
Environmental	SO_2	1
	NH_3	1.88
	NO_X	0.7
Water toxicity	1,4-DCB	1
	Atrazine	5000
Soil toxicity	1,4-DCB	1
	Atrazine	6.6

Various environmental impact potentials can be calculated according to the following formula:

$$E_{P(X)} = \sum E_{P(x)i} = \sum Q_{(x)i} E_{F(x)i} \quad (1)$$

$E_{P(x)}$ represents the impact potential of the system on the x environmental impact; $E_{P(x)i}$ denotes the impact potential of the i emission substances on the x environmental impact; $Q_{(x)i}$ signifies the emission of the i emission substance; $E_{F(x)i}$ indicates the equivalent coefficient of the impact of the i emission substance on the x type of environment.

3. Results

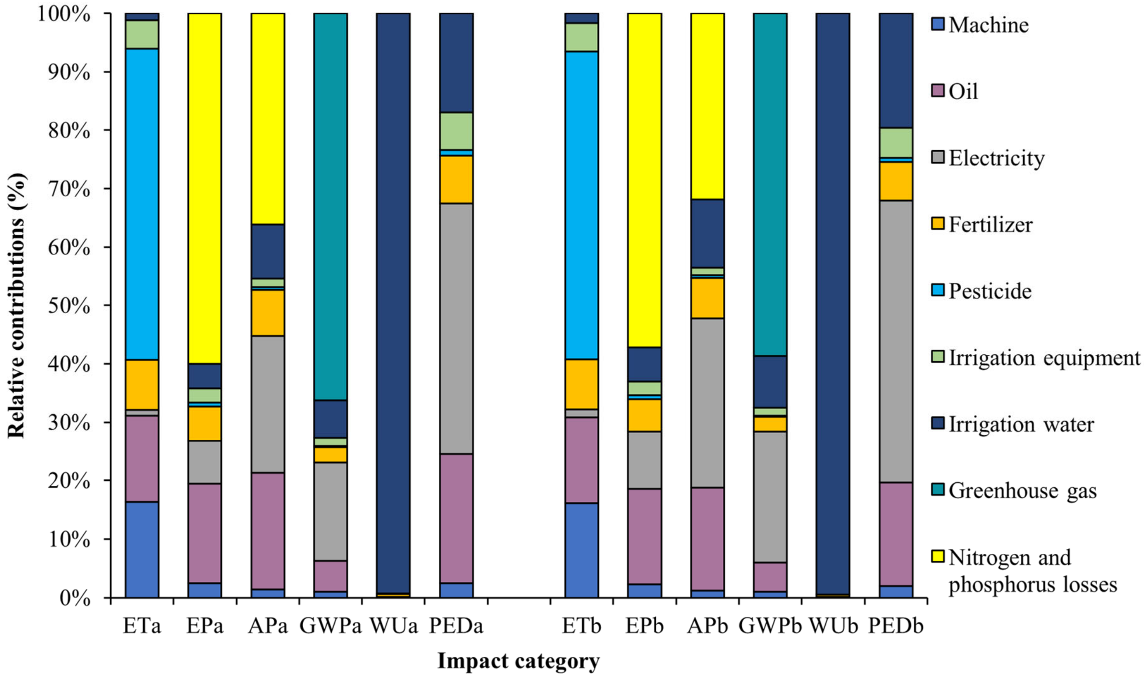
3.1. Characterization

Characterization is the process of classifying resource consumption and environmental emission inventories and calculating the environmental impact potential. Each environmental load is caused by a variety of ecological impact factors; however, the proportions of the different impact factors vary. The numerical value calculated by the corresponding impact factors representing the degree of a certain environmental load was defined as the environmental impact potential. The various inputs and outputs of the rice system were categorized according to their types. The relative contributions of different input-output types to the impact categories of rice cropping systems are shown in Figure 3.

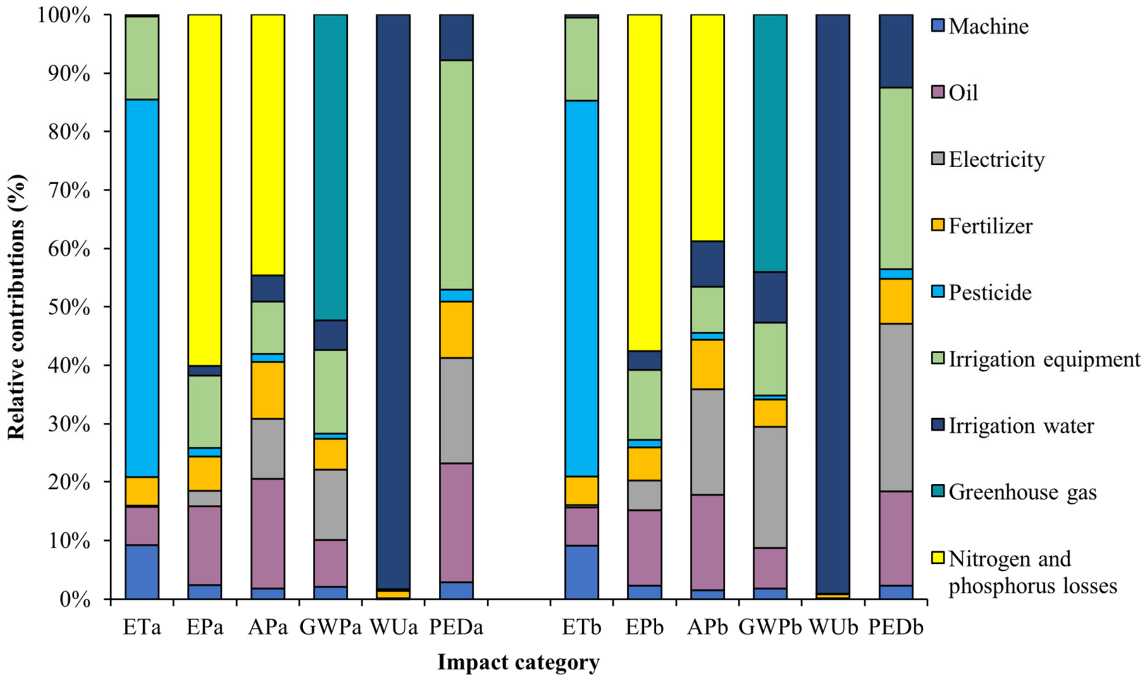
3.2. Resource Consumption

The results of the resource consumption characterization of the rice life cycle in the different cultivation methods are presented in Table 5. Based on these results, it can be concluded that energy consumption mainly occurs at the off-farm stage. This is primarily because the process consumes a large amount of energy for the mining of ores and the production of agricultural products.

The energy consumption for producing 1 t of transplanted rice, dry direct-seeded rice, dry direct-seeded rice with PE film, and dry direct-seeded rice with biodegradable film in the off-farm stage of the 2021 field trial was as high as 7712.65, 9147.13, 10,195.60, and 9288.58 MJ, respectively, accounting for more than 72.6% of the total life-cycle energy consumption, respectively. Energy consumption in the second year of the field trial increased by at least 14.7% over the first year. Water consumption mainly occurs during the on-farm stage, primarily due to the significant dependence on soil and water for crop production. Water consumption in the on-farm stage of producing 1 t of rice consumed more than 98.5% of the total life cycle consumption for all four rice cultivation methods in the two-year field trial. Water consumption in the second year was significantly higher compared to the first year. In terms of total water consumption, transplanting rice consumed the largest amount of water per 1 t of rice, at least 734.91 $m^3 \cdot t^{-1}$, followed by dry direct-seeding rice without film and dry direct-seeding rice with PE film, and the smallest amount of water consumed for the production of 1 t of rice was dry direct-seeding rice with biodegradable film, which could be as low as 218.87 $m^3 \cdot t^{-1}$.

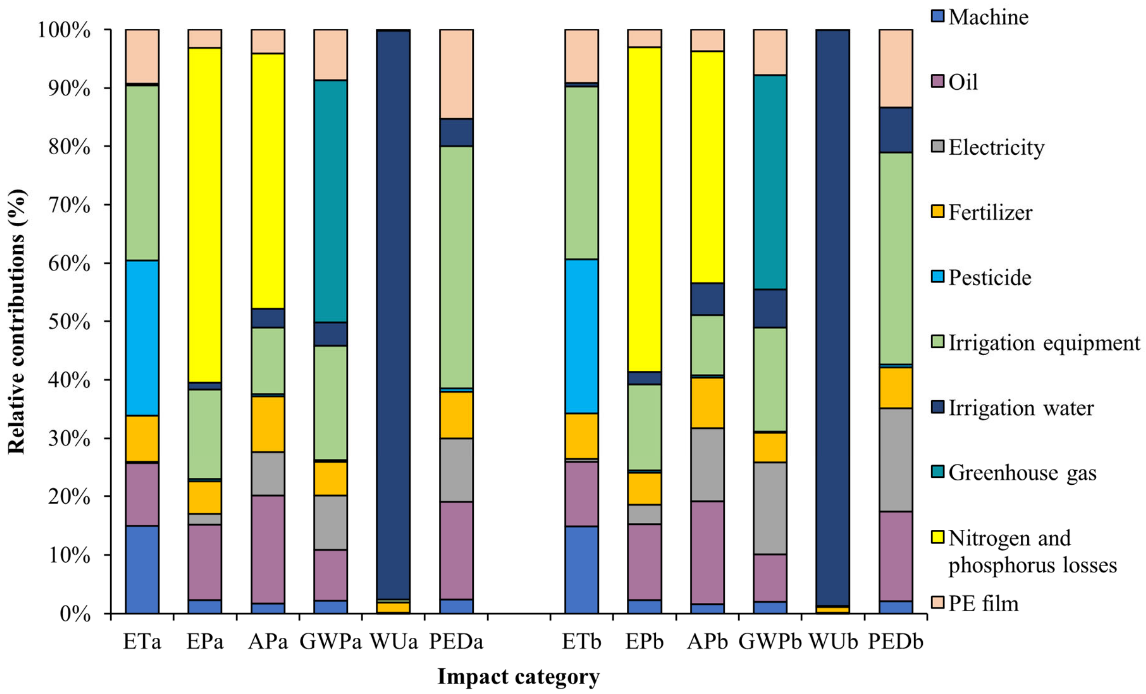


(**a**)



(**b**)

Figure 3. *Cont.*



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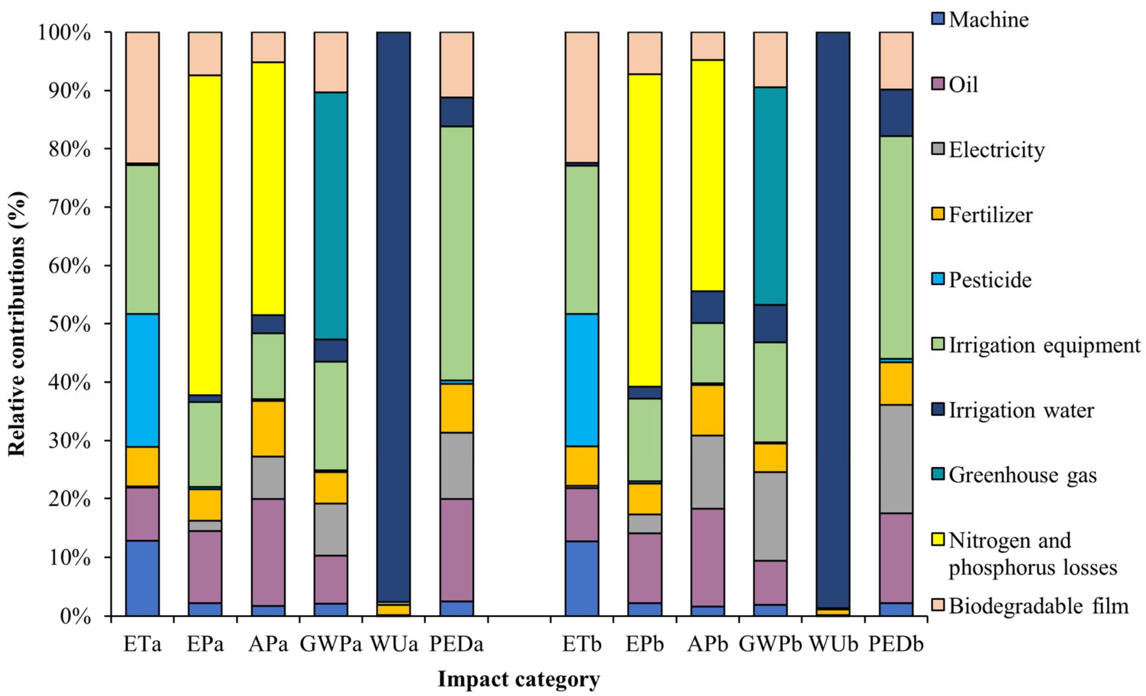

(**d**)

Figure 3. Relative contribution of different parts to each impact category. The suffixes a and b for each environmental impact represent the years 2021 and 2022, respectively. The four sub-figures (**a**–**d**) represent the relative contribution of each component to each type of impact for transplanting rice, dry direct-seeding rice, dry direct-seeding rice with polyethylene (PE) film, and dry direct-seeding rice with biodegradable film, respectively.

Table 5. Characterization results of resource consumption of four rice planting methods.

	Transplanting Rice (a)			Transplanting Rice (b)		
	Off-Farm Stage	**On-Farm Stage**	**Total**	**Off-Farm Stage**	**On-Farm Stage**	**Total**
Energy consumption (MJ·t^{-1})	7713	2908	10,620	9484	3674	13,159
Water resource consumption (m^3·t^{-1})	5.05	729.86	734.91	5.42	1044.68	1050.10
	Dry Direct-Seeding Rice (a)			**Dry Direct-Seeding Rice (b)**		
	Off-Farm Stage	**On-Farm Stage**	**Total**	**Off-Farm Stage**	**On-Farm Stage**	**Total**
Energy consumption (MJ·t^{-1})	9147	1919	11,066	11,432	2855	14,286
Water resource consumption (m^3·t^{-1})	6.06	351.53	357.59	6.67	721.23	727.91
	Dry Direct-Seeding Rice with PE Film (a)			**Dry Direct-Seeding Rice with PE Film (b)**		
	Off-Farm Stage	**On-Farm Stage**	**Total**	**Off-Farm Stage**	**On-Farm Stage**	**Total**
Energy consumption (MJ·t^{-1})	10,196	1473	11,669	11,561	1991	13,552
Water resource consumption (m^3·t^{-1})	5.76	222.59	228.35	6.15	423.82	429.97
	Dry Direct-Seeding Rice with Biodegradable Film (a)			**Dry Direct-Seeding Rice with BIODEGRADABLE Film (b)**		
	Off-Farm Stage	**On-Farm Stage**	**Total**	**Off-Farm Stage**	**On-Farm Stage**	**Total**
Energy consumption (MJ·t^{-1})	9286	1405	10,694	10,402	1869	12,271
Water resource consumption (m^3·t^{-1})	5.17	213.70	218.87	5.44	399.76	405.19

The (a) denote the results of resource consumption characterization in 2021. The (b) denote the results of resource consumption characterization in 2022.

Due to the fact that transplanting rice seedlings requires soaking prior to sowing and maintaining a 2 cm layer of water in the ground through diffuse irrigation during the reproductive period of the rice, this leads to the consumption of a large amount of irrigation water and hence, a significant amount of electricity, resulting in significant energy consumption and water resource depletion (Figure 3). In contrast, the dry direct-seeding of rice does not involve soaking the field as a process before planting. The use of drip irrigation equipment for water conservation during the rice reproductive period results in less water and electricity consumption. However, the production of irrigation equipment has become one of the major causes of energy consumption. Dry direct-seeding rice with film uses the same machinery to lay the film at the time of planting and drip irrigation belts simultaneously. Therefore, there is no extra use of agricultural machinery or fuel consumption, and other agricultural operations are essentially the same as in dry direct-seeding rice, which leads to the production of mulch as one of the main causes of energy consumption. Additionally, the large amount of water used during the on-farm stage is the most significant cause of water consumption in rice production systems. The scenario of direct water usage appears particularly severe. Dry direct-seeding rice requires a minimum of 218 m^3 of water per ton of rice produced, while transplanting rice exhibits substantial water demands, requiring at least 734 m^3 of water per ton of rice. This underscores the potential of dry direct-seeding to enhance irrigation efficiency and optimize water consumption in rice agriculture. The adoption of sprinkler irrigation systems or drip irrigation pipes as standard practices has the potential to apply extracted water more efficiently to all agricultural crops, forecasting a significant reduction in direct water demand.

3.3. Climate Change

The environmental impact potential of each pollutant was converted into a reference value using an equivalence factor. For instance, the greenhouse effect was transformed into global warming potential, expressed as CO_2 equivalents, with CO_2 as the reference. In Figure 4, the contributions of the off-farm and on-farm stages to the GWP levels of different rice cultivation methods are illustrated. The results reveal that the four rice cultivation methods targeting the production of 1 t of rice exhibited a generally consistent trend in climate change environmental impact potential in the 2021 and 2022 field trials. Transplanted rice had the highest potential climate change environmental impact, while dry direct-seeded rice with a biodegradable film had the lowest potential climate change environmental impact. The primary stage contributing to climate change induced by these rice cultivation methods was the on-farm stage. The environmental impact potential of climate change caused by the four rice-planting systems production of 1 t of rice in the off-farm stage ranges from 460 to 640 kg CO_2-eq. The climate change environmental impact potential in 2022 is 4.0–18.4% higher than in 2021. This is due to the larger contribution of irrigation water abstraction and irrigation electricity to climate change.

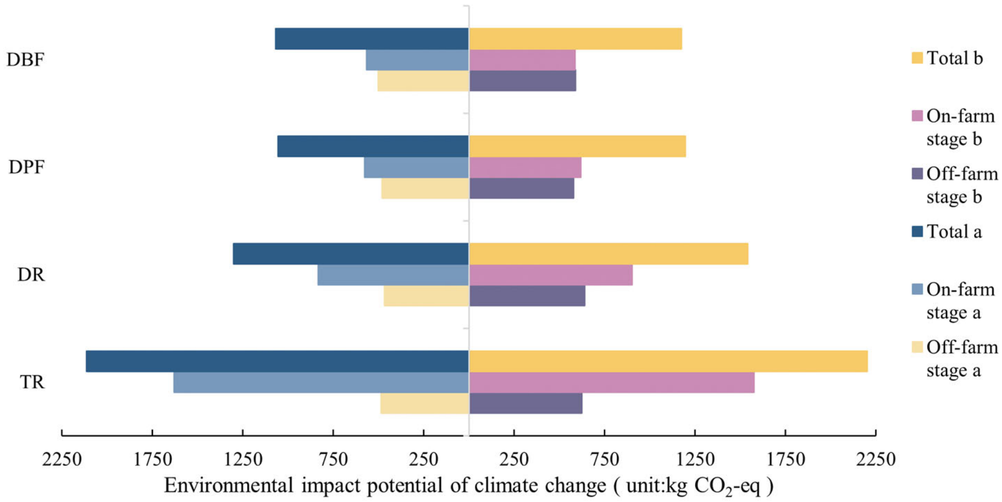

Figure 4. Climate change environmental impact potentials of four rice cultivation practices. In this figure, TR, DR, DPF, and DBF represent the transplanting rice, dry direct-seeding rice, dry direct-seeding rice with PE film, and dry direct-seeding rice with biodegradable film, respectively. The suffixes a and b for each environmental impact represent the years 2021 and 2022, respectively.

In rice production systems employing the four different cultivation methods, the primary factors influencing global climate change are the emissions of greenhouse gases from farmlands, electricity consumption, and the manufacturing of irrigation equipment. Notably, when transplanting rice, where irrigation equipment is not utilized, emissions from agricultural fields become the predominant contributors to GWP. Conversely, dry direct-seeding rice relies on irrigation equipment to supply the necessary water for rice growth, and the production of such equipment significantly contributes to the overall climate change potential (Figure 3). Rice, being a high-emission crop, releases substantial amounts of greenhouse gases, including CH_4 and N_2O, during its growth. The emissions of these gases hold significant potential for climate change impacts. Currently, greenhouse gas (GHG) emissions from agricultural activities constitute approximately 14% of the total global anthropogenic GHG emissions. Specifically, approximately 47% and 58% of the total anthropogenic emissions of CH_4 and N_2O, respectively. In China, GHG emissions from agricultural activities contribute to 11% of all GHGs produced in the country. The findings of this study indicate that for every 1 t of rice produced, the environmental impact potential of CH_4 released from transplanted rice, dry direct-seeded rice, dry direct-seeded rice with PE film, and dry direct-seeded rice with biodegradable film was approximately 78%, 63%, 55%, and 58% of that in the on-farm stage, respectively. Additionally, N_2O emissions during the on-farm stage emerge as one of the primary factors contributing to the high environmental impact potential of climate change in film-covered or non-film-covered dry direct-seeded rice, constituting more than 12%.

3.4. Environmental Acidification

Environmental acidification is a regional environmental impact, and in this study, SO_2 was used as a reference to convert the same pollutants for environmental acidification. The characterization results in Figure 5 reveal that the environmental impact potential of environmental acidification caused by the four different cultivation methods of producing 1 t of rice in 2021, from largest to smallest, are transplanting rice, dry direct-seeding rice, dry direct-seeding rice with PE film, and dry direct-seeding rice with biodegradable film. In the 2022 field trial, dry direct-seeding rice exceeded transplanting rice as having the largest environmental acidification impact potential among the four cropping methods. Notably, the on-farm stage is the primary stage of environmental acidification. For the four different rice cultivation methods, the environmental acidification potential caused by the production of 1 t of rice at the on-farm stage in 2021 and 2022 accounted for more than 61.5% and 58.3% of the total life-cycle potential, respectively. The environmental acidification potential of the four different rice cultivation methods in the 2022 field trial was greater than the results of the same cultivation method rice system in the 2021 field trial. Increased irrigation water use in the second year and water flushing enhanced the loss of salt-based ions and increased environmental acidification.

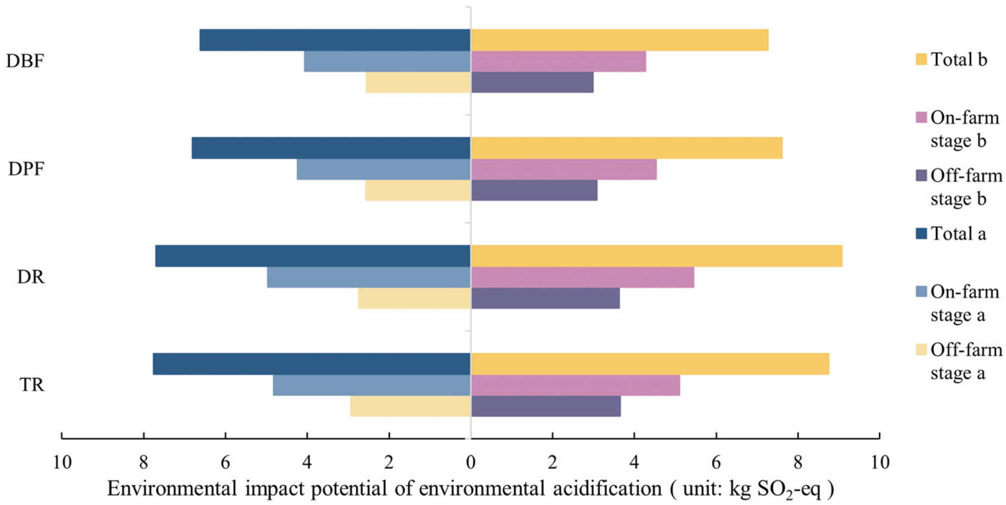

Figure 5. Environmental acidification impact potentials associated with four rice cultivation practices. In this figure, TR, DR, DPF, and DBF represent the transplanting rice, dry direct-seeding rice, dry direct-seeding rice with PE film, and dry direct-seeding rice with biodegradable film, respectively. The suffixes a and b for each environmental impact represent the years 2021 and 2022, respectively.

In terms of the contribution of each component of inputs and outputs to environmental impacts, the greatest impact on environmental acidification is the loss of nitrogen and phosphorus. Additionally, the contribution of irrigation power and extracted water to environmental acidification has increased due to the increased use of irrigation water. Throughout the entire life cycle of rice, the primary factor causing environmental acidification was the emission of NH_3, contributing more than 30% to the total environmental acidification impact potential (Figure 3). The release of NH_3 is mainly attributed to the use of nitrogen fertilizers. During their application, nitrogen fertilizers are lost to rain and groundwater, entering both groundwater and the air, thereby contributing to environmental acidification. Consequently, reducing the use of nitrogen fertilizers proves effective in mitigating the environmental acidification associated with rice production. Additionally, the production and combustion of fuel oil emerge as significant contributors to environmental acidification (Figure 3). Exhaust gases like nitrogen oxides, carbon monoxide, and hydroxides from fuel production and use not only cause serious pollution to the atmosphere but also degrade the quality of water sources and soil.

3.5. Eutrophication

In general, water bodies are considered to be in a eutrophic state when the total phosphorus and total nitrogen content exceeds 20 and 300 mg·m^3, respectively. Eutrophication in the rice production process is evaluated with PO_4 as the reference. Figure 6 indicates that the potential environmental impact of eutrophication in the production of 1 t of rice varies among the four different cultivation methods, with dry direct-seeding rice showing the highest impact and transplanting rice the lowest. The environmental impacts of eutrophication for the four rice cultivation methods in 2022 are greater than in 2021 as a whole. This impact is primarily observed during the on-farm stage, with pollutants contributing all reached more than 64% and up to 76.9% to the eutrophication potential of 1 t of rice produced by dry direct-seeding rice, dry direct-seeding rice with PE film, dry direct-seeding rice with biodegradable film, and transplanting rice, respectively. The major contributors were NH_3, NO_3^-, and TP (total phosphorus).

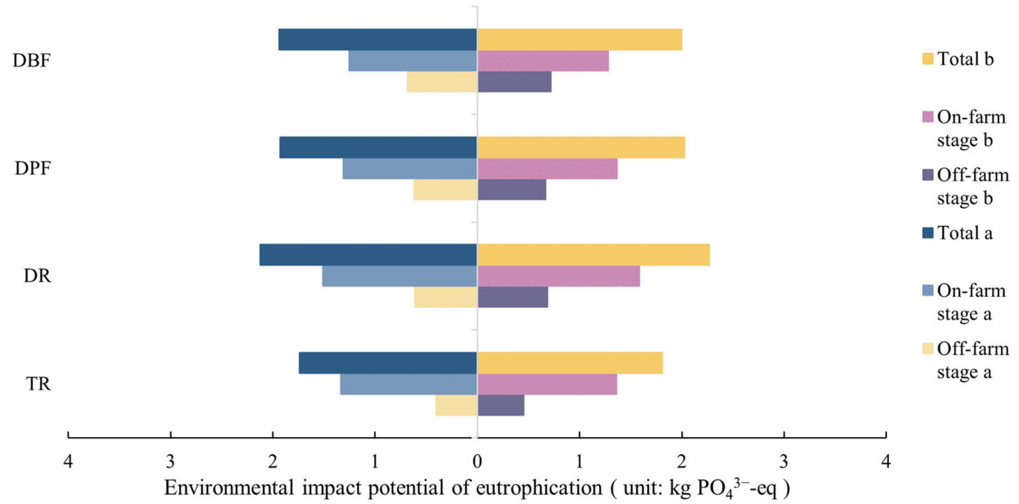

Figure 6. The eutrophication environmental impact potential of four rice planting methods. In this figure, TR, DR, DPF, and DBF represent the transplanting rice, dry direct-seeding rice, dry direct-seeding rice with PE film, and dry direct-seeding rice with biodegradable film, respectively. The suffixes a and b for each environmental impact represent the years 2021 and 2022, respectively.

The potential for eutrophication in agricultural production primarily arises from the excessive application of chemical fertilizers, leading to the entry of N and P into water bodies through various channels. The loss of nitrogen and phosphorus, caused by ammonia volatilization and nitrate-nitrogen loss in farmlands, was the primary contributor to eutrophication during the on-farm stage (Figure 3). Fertilizers are often applied in excess to maximize economic benefits, highlighting the need for scientific and rational fertilization practices to reduce the eutrophication potential of dry direct-seeding. Additionally, the contribution of irrigation equipment production to eutrophication should not be underestimated. Irrigation equipment, typically a plastic hose of variable thickness, made of polyethylene with various organic and inorganic additives, generates wastewater, waste gas, and waste residue during production, contributing to the eutrophication of water bodies.

3.6. Ecotoxicity

The ecotoxicity resulting from rice production was evaluated using 1,4-DCB as the reference. Based on Figure 7, the potential ecotoxic environmental impacts per 1 t of rice production for the four different cultivation methods of rice increased in the following order: transplanting rice, dry direct-seeding rice with PE film, dry direct-seeding rice with biodegradable film, and dry direct-seeding rice. The trends in the two-year field trials were consistent. Unlike climate change, environmental acidification, and eutrophication, the primary stage of rice production generating ecotoxic potential is the off-farm production stage. The low ecotoxicity potential in the life cycle of transplanted rice results from the use of pesticides solely for weed control and the absence of drip irrigation equipment and mulching, reducing pollutant emissions from the off-farm process. The production and use of pesticides are the main contributors to ecotoxicity in dry direct-seeding rice without films, with the potential ecotoxic environmental impacts generated by its production accounting for 64.7% of the total environmental impact potential of the life cycle in 2021 and 64.4% in 2022 (Figure 3). In the case of dry direct-seeding rice with PE film, the main cause of ecotoxicity was the production of drip irrigation equipment, owing to the lower use of pesticides, which accounted for more than 29.7% of the total life-cycle environmental impact potential. For dry direct-seeding rice with biodegradable films, the main causes of ecotoxicity were the preparation of biodegradable films and the production of drip irrigation equipment, which accounted for at least 47.9% of the total life cycle environmental impact potential.

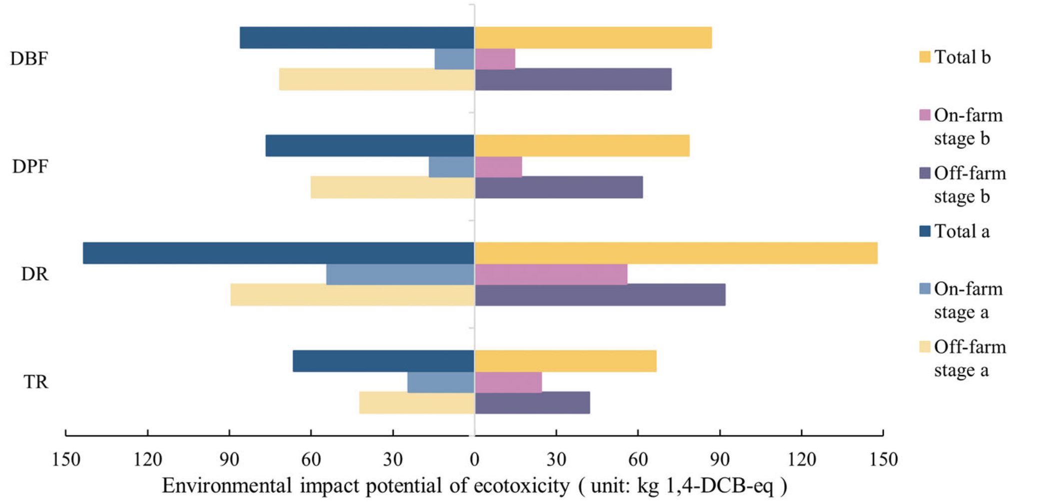

Figure 7. Environmental impact potential of ecotoxicity for four rice planting methods. In this figure, TR, DR, DPF, and DBF represent the transplanting rice, dry direct-seeding rice, dry direct-seeding rice with PE film, and dry direct-seeding rice with biodegradable film, respectively. The suffixes a and b for each environmental impact represent the years 2021 and 2022, respectively.

4. Discussion

4.1. Differences in Input-Output Lists of Different Rice Cultivation Methods

From an input perspective, rice transplanting consumes significantly more water resources compared to dry direct seeding, with the water savings of dry direct seeding cultivation technology reaching over 30.7%. Additionally, dry direct seeding without film, in comparison to dry direct seeding with film, requires more water resources, and the use of film can save at least 36.1% of water. This is because the dry seeding of rice in the production process, implementing dryland management, does not require field soaking and does not need to maintain a 1–2 cm water layer during the rice reproduction period. Moreover, mulching reduces water evaporation, and mulching for dry seeding utilizes more water-saving drip irrigation equipment, avoiding the wastage of water resources. Transplanting rice seedlings and dry seeding without mulching require more pesticides for on-farm weeding. Mulching effectively inhibits weed growth by blocking air circulation and light, which restricts the amount of carbon dioxide, oxygen, and water supplied to weeds; in turn, these cannot successfully complete photosynthesis, which can effectively inhibit their growth in farmlands, thus reducing the amount of pesticide use. Additionally, 2022 consumed 30.0% more water and up to 50.9% more water than 2021 in the field experiment. This was due to the fact that the total rice precipitation ranged from 444–451 mm and 295–327 mm during the two rice growing seasons, respectively. Among them, the precipitation during the fertility period of rice in 2021 was much larger than that of 2022, and the difference mainly occurred in July. The reduction in irrigation water resources leads to a reduction in the consumption of electricity for pumping and energy for extracting water resources. Transplanting rice seedlings during ground preparation involves more harrowing and consumes more fuel than dry direct seeding. Dry direct seeding with a film cover uses an integrated seeding-film-covering-drip-irrigation belt-spreading machine, which does not result in increased fuel consumption for farm machinery. In terms of labor, rice transplanting involves soaking, seeding, transplanting, etc., requiring substantial labor. Dry direct seeding without film reduces many planting steps, but due to its susceptibility to climate, it requires finer field management, demanding more labor. Additionally, PE films need to be recycled for dry seeding, whereas biodegradable films can naturally degrade in the field without recycling. Therefore, labor invested in PE films is higher than that of biodegradable films. For these reasons, dry seeding with biodegradable films can save significant labor and water resources and reduce pesticide input.

In terms of output, the yield of film-covered and non-film-covered dry direct-seeded rice was generally lower than that of transplanted rice. Film covering, however, can enhance the yield of dry direct-seeded rice by reducing the impact of climatic hazards on the growth and development of rice during its reproductive period. Compared to no film, using film can increase temperature, provide heat preservation, and create favorable conditions for the growth and development of rice, thereby ensuring higher yields. Additionally, the dry direct-seeding of rice can significantly reduce greenhouse gas emissions, producing more than 63.6% less methane compared to transplanting rice. Dry direct-seeding of rice with film also emitted less methane than dry direct-seeding without film. This reduction could be attributed to the film cover, which decreases water use, improves soil physicochemical properties, and influences the growth and development of rice, consequently affecting greenhouse gas emissions. However, dry direct-seeded rice increased N_2O emissions compared to transplanted rice. This is because the use of drip irrigation equipment for dry direct-seeded rice changed the alternating wet and dry changes in paddy soils, which improves the mineralization of effective soil carbon and nitrogen, enhances soil nitrification and denitrification, and increases N_2O emissions [31].

4.2. Variation in LCA Results across Different Rice Cultivation Methods

In terms of rice yield, the highest energy consumption for producing 1 t of rice in 2021 among the four rice cultivation methods was observed in dry direct-seeded rice with PE film. This result could be attributed to the energy-intensive production of drip irrigation equipment and films, whereas the highest energy consumption for dry direct-seeded rice production of 1 t of rice in 2022 could be due to the large amount of water inputs in the second year of production due to reduced precipitation, resulting in a large amount of energy consumption. However, there was still a reduction in yield, making the energy consumption of dry direct-seeded rice higher under producing a unit quality of rice. However, despite its higher energy consumption, the dry direct-seeding of rice with biodegradable film demonstrated a higher yield. Consequently, when producing the same amount of rice, this method resulted in the least energy consumption. The greatest water consumption for producing 1 t of rice occurred in transplanting rice, whereas the lowest was in dry direct-seeding rice with biodegradable film. Transplanting rice, managed in water fields, exhibited higher water usage, while dry direct seeding rice with biodegradable film, managed in dry fields with drip irrigation, saved over 30.7% of water compared to transplanting rice. Moreover, the water productivity of dry direct seeding rice with biodegradable film was the highest. In terms of the climate change impact of producing 1 t of rice, transplanting rice showed the highest impact, while dry direct-seeding rice with biodegradable film exhibited the lowest impact. CH_4 and N_2O primarily influence climate change in agriculture [32], and the dry direct-seeding technique, further aided by film covering, mitigates greenhouse gas emissions. The most significant environmental acidification and eutrophication impacts producing 1 t of rice were observed in dry direct-seeding rice without film. The main causes of eutrophication and environmental acidification are the loss of nitrogen and phosphorus. Under the conditions of the same amount of fertilizer use and the same amount of fertilizer loss, the yield of dry direct-seeding rice without film was lower, the fertilizer utilization rate per unit of yield was the lowest, the loss was the greatest, and the nitrogen and phosphorus emitted into the environment were the greatest, which had the greatest impact on eutrophication and environmental acidification. For 1 t of rice, the highest ecotoxicity impact was associated with dry direct-seeding rice without film, attributed to its lower yield and increased pesticide usage. In contrast, transplanting rice demonstrated the lowest ecotoxicity and environmental impact potential. This is primarily due to ecotoxicity impacts occurring mainly in the off-farm stage and the fact that transplanting rice involves lower pesticide use and excludes the use of drip irrigation equipment and film, consequently reducing pollutant emissions in the agricultural product production process.

4.3. Methodological Discussion

The scope of the LCA in this study extends from raw material extraction to crop maturity, covering various inputs and outputs during rice growth. However, it does not encompass the treatment of rice straw after harvest. The treatment of straw and residue is a crucial aspect of crop production. As of now, the comprehensive utilization of straw faces challenges, including unknown baseline emissions and issues related to greenhouse gas emissions at the bottom. Therefore, straw treatment is not considered within the research scope. Typically, there are six methods for handling straw: straw incorporation into the soil as fertilizer, utilization as fodder, conversion to straw fuel, use as a substrate, utilization as raw material, and two disposal methods: open burning and natural decay through stacking. According to the study, the net GHG emission reduction contribution from comprehensive straw utilization in 2020 was calculated to be 7.0×10^7 t CO_2-eq. The potential contribution to GHG emission reduction through sequestration from comprehensive straw utilization is anticipated to range between 1.52×10^8 and 1.72×10^8 t CO_2-eq by 2030 [33]. The comprehensive utilization of straw holds significant potential and space to contribute to carbon sequestration in agricultural and rural areas, necessitating in-depth exploration and full utilization.

While some studies encompass both crop production and consumption systems [34,35], this study specifically focused on crop production and agricultural input production systems. The environmental impacts associated with crop production are particularly pronounced during the crop production and consumption processes. Therefore, the scope of this study is limited to crop production systems, emphasizing the production of agricultural inputs and pollutant emissions during crop production. Transportation, agricultural product processing, household consumption, and livestock consumption processes were not considered in this study. The chosen functional unit for this study was 1 t of agricultural products, deviating from other studies that commonly use 1 ha as the functional unit [36]. Opting for the same quality as the functional unit facilitates the comparison of productivity and pollution for the same crop. This approach enables a straightforward comparison of yields and pollution levels across different crops. Consequently, the functional unit selected for this study was the production of 1 t of agricultural produce.

The agricultural production data utilized in this study were derived from diverse sources, introducing inherent variations in the degree of uncertainty. Additionally, only CH_4 and N_2O emissions were directly measured in the nitrogen and phosphorus losses from farmlands. Other losses of nitrogen and phosphorus were estimated based on fertilizer quantities and certain research calculations, potentially introducing some margin of error. In future studies, it is recommended to employ more precise methods for measuring nitrogen and phosphorus losses in the field to enhance accuracy.

The data collected in this study is from 2021–2022, and as time progresses, factors such as fertilization intensity and industrial production technology are likely to change. Therefore, the data in this study may not accurately represent other years. Additionally, the data pertaining to the crop production process in this study were based on field experiments, introducing variations compared to real-world outcomes due to differences in local farmers' fertilization practices. Consequently, this study can specifically reflect the disparities in the environmental impacts of transplanting rice, dry direct-seeding rice, dry direct-seeding rice with PE film, and dry direct-seeding rice with biodegradable film under the condition of applying the same fertilizer. To achieve a more comprehensive understanding, it is advisable to gather additional data and conduct further life cycle assessments that account for the specific conditions of local production. The time period of this study is two years, which fulfills the basic requirements for the use of life cycle assessment and field studies. However, in order to make the results of the study more reliable, the time period should be lengthened to obtain more reliable results, and therefore the study should be continued.

4.4. Similarities and Differences of LCA Results in Rice Fields in Other Areas

The energy consumption of the Vercelli transplanting rice field studied by Blengini and Busto was analyzed by LCA calculations to be about 17,800 MJ·t^{-1}, its GWP emissions were 2900 kg CO_2-eq·t^{-1}, and water consumption reached 4900 m^3·t^{-1} [37]. In this study, the energy consumption of the four cultivation methods of rice ranged from 10,621–14,286 MJ·t^{-1}, GWP from 1174–2200 kg CO_2-eq·t^{-1} and water consumption from 219 to 1050 m^3·t^{-1}. The reason for this situation is that Blengini used electricity and fuel oil to irrigate the paddy fields with a large amount of water resources during the production of transplanting rice, which resulted in high energy consumption, and the large amount of water input into the paddy field causes a large amount of greenhouse gas emissions. In this study, transplanting rice uses less water, and dryland management is practiced in dry direct-seeding rice, and mulching can save water and increase yield based on dry direct-seeding rice. Consequently, the environmental impacts in this study were lower than those in the Vercelli rice field studied by Blengini and Busto. Siti Norliyana Harun's study in Malaysia obtained results of GWP emissions of 1460 kg CO_2-eq·t^{-1}, and water consumption of 500 m^3·t^{-1} [38]. Malaysia has abundant precipitation, which is almost sufficient for rice growth. In his study, the irrigation water was extracted using a non-powered pump, which avoided additional energy consumption. Therefore, the consumption of all resources is at a low level, and the water consumption of transplanting rice in Malaysia is lower than the consumption of transplanting rice in this study. Estimation of life cycle GHG emissions from rice production was also conducted by Abdul Rahman MH in Malaysia and Brodt S in California, USA [39,40]. These studies share a common point: that the on-farm stage is the focus of rice production, and that field emissions, fertilizer application, and fossil fuel use are the main contributors to GHG emissions.

5. Conclusions

In accordance with the life cycle assessment methodology, this study delved into the differences in the environmental impacts of the production processes of transplanted rice, dry direct-seeded rice, dry direct-seeded rice with PE film, and dry direct-seeded rice with biodegradable film in Northeast China. The findings revealed that the off-farm stage incurred the highest energy consumption, constituting over 72% of the total energy consumption of the rice life cycle. This was attributed to substantial raw material extraction and the production of various agricultural products. Among the cultivation methods, the dry direct-seeding of rice with PE film exhibited the highest total energy consumption in 2021, while the dry direct-seeding of rice demonstrated the highest in 2022. The on-farm stage emerged as the stage with the highest water consumption, accounting for more than 97% of the total water consumption, given the significant reliance of rice production on soil and water. Transplanting rice consumed the most water, whereas dry direct-seeding rice with biodegradable film had the least water consumption. The on-farm stage contributed more than 36.7% of the total environmental impact potential for climate change, primarily due to substantial CH_4 and N_2O emissions during rice growth. Transplanting rice exhibited the highest environmental impact potential for climate change, while dry direct-seeding rice with biodegradable film displayed the lowest. Environmental acidification and eutrophication were primarily caused by the on-farm stage, with the field use and loss of nitrogen fertilizer accounting for over 58.3% and 64.0%, respectively. Among the cultivation methods, rice transplanting demonstrated the highest environmental impact potentials for water consumption and climate change. The greatest eutrophication and ecotoxicity were observed in dry direct-seeding rice. The least impact on acidification was observed in dry direct-seeding rice with biodegradable films. Furthermore, dry-directed rice with biodegradable films minimized water consumption and greenhouse gas emissions without compromising yield. Moreover, all the potential environmental impacts of the four different rice cultivations in the 2021 field trial were smaller than the results of the same rice cultivation system in the 2022 field trial.

Based on these findings, it is feasible to mitigate water consumption, electricity consumption, and GHG emissions through dry direct seeding. Additionally, the use of films can enhance and stabilize the yield of dry direct-seeded rice, allowing it to achieve a yield comparable to that of transplanted rice. Furthermore, reducing the impact of the crop growth stage on environmental acidification and eutrophication is achievable through rational and scientific fertilizer application, improved fertilizer utilization, and the prevention of nitrogen and phosphorus losses.

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