agriculture

MDPI

Article

Can the Integration of Water and Fertilizer Promote the Sustainable Development of Rice Production in China?

Qin Liao [1], Jiangxia Nie [1], Huilai Yin [1], Yongheng Luo [1], Chuanhai Shu [1], Qingyue Cheng [1], Hao Fu [1], Biao Li [1], Liangyu Li [2], Yongjian Sun [1,3], Zongkui Chen [1], Jun Ma [1,3], Na Li [4], Xiaoli Zhang [2,*] and Zhiyuan Yang [1,3,*]

[1] Rice Research Institute, Sichuan Agricultural University, Chengdu 611130, China; 2021311078@stu.sicau.edu.cn (Q.L.); niejiangxia@stu.sicau.edu.cn (J.N.); 2022311077@stu.sicau.edu.cn (H.Y.); 2022311071@stu.sicau.edu.cn (Y.L.); 2022111002@stu.sicau.edu.cn (C.S.); 2021211007@stu.sicau.edu.cn (Q.C.); 2021211009@stu.sicau.edu.cn (H.F.); libiao700328@163.com (B.L.); yongjians1980@163.com (Y.S.); chenzongkui@stu.sicau.edu.cn (Z.C.); majunp2002@163.com (J.M.)
[2] Chengdu Academic of Agriculture and Forestry Sciences, Chengdu 611130, China; liliangyu507@163.com
[3] Crop Ecophysiology and Cultivation Key Laboratory of Sichuan Province, Chengdu 611130, China
[4] College of Animal Science and Technology, Sichuan Agricultural University, Chengdu 611130, China; lina1409bs@163.com
[*] Correspondence: qydzhzh@163.com (X.Z.); 14236@sicau.edu.cn (Z.Y.)

Abstract: Rice production is the agricultural activity with the highest energy consumption and carbon emission intensity. Water and fertilizer management constitutes an important part of energy input for rice production and a key factor affecting greenhouse gas emissions from paddy fields. Water–fertilizer integration management (AIM) is an automated water and fertilizer management system for large-scale rice production, which can effectively save water and fertilizer resources. At present, the energy utilization and environmental impact of AIM in rice production are not clear. To clarify whether AIM is a water and fertilizer management measure that combines energy conservation and carbon emission reduction, a comparative study between the widely used farmers' enhanced water and fertilizer management (FEM) in China and AIM was conducted in this paper. Field experiments were conducted to evaluate the rice yield, carbon emission, energy utilization, and economic benefits of the two management methods. The results showed that AIM reduced water and fertilizer inputs, energy inputs, and economic costs by 12.18–28.57%, compared to FEM. The energy utilization efficiency, energy profitability, and energy productivity under AIM were improved by 11.30–12.61%. CH_4 and N_2O emissions and carbon footprint were reduced by 20.79%, 6.51%, and 16.39%, respectively. Compared with FEM, AIM can effectively improve the utilization efficiency of water and fertilizer resources and reduce carbon emissions. This study presents a mechanized water and fertilizer management approach suitable for large-scale rice production systems in China. By analyzing rice yield, resource utilization efficiency, and environmental benefits, AIM can serve as a crucial management strategy for enhancing productivity, economic returns, and environmental conservation within profitable rice production systems. In the future, further investigation into the impact of AIM on the microbial mechanisms underlying rice yield formation and greenhouse gas emissions is warranted.

Keywords: energy use efficiency; carbon footprint; greenhouse gas; economic benefits

check for updates

Citation: Liao, Q.; Nie, J.; Yin, H.; Luo, Y.; Shu, C.; Cheng, Q.; Fu, H.; Li, B.; Li, L.; Sun, Y.; et al. Can the Integration of Water and Fertilizer Promote the Sustainable Development of Rice Production in China? *Agriculture* **2024**, *14*, 585. https://doi.org/10.3390/agriculture14040585

Academic Editors: Xiaoqian Song and Jiajie Li

Received: 30 January 2024
Revised: 27 March 2024
Accepted: 2 April 2024
Published: 8 April 2024

1. Introduction

As the grain crop with the highest yield per unit area in China, rice plays a key role in ensuring food security. It is also the grain crop with the highest consumption of water and fertilizer resources and the largest agricultural source of greenhouse gas emissions [1–4]. Continuous flooding irrigation is often adopted in traditional rice production, accounting for 60% of the total agricultural water consumption, while the effective water utilization rate is below 50%, thus wasting a large amount of freshwater [5]. With per capita freshwater of only 1/4 of the world average, the promotion of water-saving irrigation technology for paddy fields in China cannot be delayed [6]. Although nitrogen fertilizer application significantly promotes rice yields, the problem of reduced nitrogen fertilizer utilization rate due to over-reliance on nitrogen fertilizer inputs for yield increase is becoming increasingly severe [7]. In China, the nitrogen fertilizer application in paddy fields accounts for 24% of the total agricultural nitrogen fertilizer consumption. In addition, a large amount of nitrogen is lost through seepage and runoff due to the special nature of paddy fields, resulting in significant non-point source pollution [8–10]. In addition to the year-after-year decline in water and fertilizer utilization efficiency, greenhouse gas emissions from paddy fields are also gaining attention. As the greenhouse gas with the highest annual growth rate, methane (CH_4) contributes up to 23% to the global warming potential. The anaerobic environment of paddy fields due to long-term continuous flooding irrigation is highly favorable for CH_4 production, making paddy fields the most important source of CH_4 emissions [11–13]. The current popular drying–wetting irrigation model can save water, but nitrous oxide (N_2O) emission increases dramatically with excessive nitrogen fertilizer inputs [14]. Therefore, the innovation in rice production technology in China requires a consideration of both efficient water and fertilizer resource utilization and greenhouse gas emission reduction, which is a very challenging task.

Water–fertilizer integration management (AIM) combines fertilizer with water and delivers them to crop roots in the appropriate quantity and timing through pipes and pressure systems according to the environmental conditions and the water requirements of the crop [15]. In this way, the nutrient uptake by the root system can be effectively promoted, thus enhancing the effectiveness of water and fertilizer [16]. A meta-analysis showed that AIM significantly enhanced the nutrient use efficiency (34.3%) and water productivity (26.4%) of the crop compared to furrow or flood irrigation [17]. Compared with conventional furrow irrigation and fertilizer application, AIM significantly reduced the amount of nitrogen fertilizer that was lost to leaching and seepage, while increasing the yield by 3.7% to 12.5% [18]. In addition, AIM significantly increased the pigment content and net photosynthetic rate of crop leaves, thus improving crop quality [19]. Currently, over 90% of crops in Israel are fertilized through AIM. About 33% of fruit trees in the US are managed using AIM [20]. It is also common for vegetable, fruit, and potato production in China [21]. However, AIM is not commonly adopted in low-profit rice production due to its high cost. Our research group has developed a water and fertilizer integration technology (methodical nitrogen water distribution management) and supporting equipment suitable for rice production (Figure 1). The equipment was used in field trials in Mianyang City in 2017 and Chengdu City in 2018. The effect of this system on the water and nitrogen use efficiency of rice was studied. The results show that water saving and fertilizer preservation were achieved using the equipment while ensuring a stable yield [22], which is significant for the efficient use of fertilizer and water in paddy fields.

Mechanization is the inevitable course of sustainable rice production. Realizing the mechanization of rice production depends in large part on the automation of the management of water and fertilizer [23]. The global implementation of large-scale mechanized rice farming relies heavily on AIM as an essential water and fertilizer management system. Most previous studies are limited to the effects of AIM on rice yield and water and nitrogen use efficiency. Studies assessing the environmental benefits of using AIM in rice production are relatively rare. However, reducing greenhouse gas emissions is necessary to achieve sustainable rice production [24]. This study quantifies and compares the annual yield, energy use efficiency (EUE), carbon footprint (CF), and economic benefits of paddy fields in southwest China using farmers' enhanced water and fertilizer management (FEM) and AIM. The novelty of the current study is to evaluate EUE, CF, and economic benefits, and integrate them with productivity to clarify the sustainability of different rice production systems. The specific objectives of this study are to (i) quantify the EUE and CF of rice under FEM and AIM, (ii) determine the primary causes of the variations in EUE and CF between FEM and AIM, (iii) choose water and fertilizer management methods that are more suitable for sustainable rice production, and put forward the improvement direction of this technology.

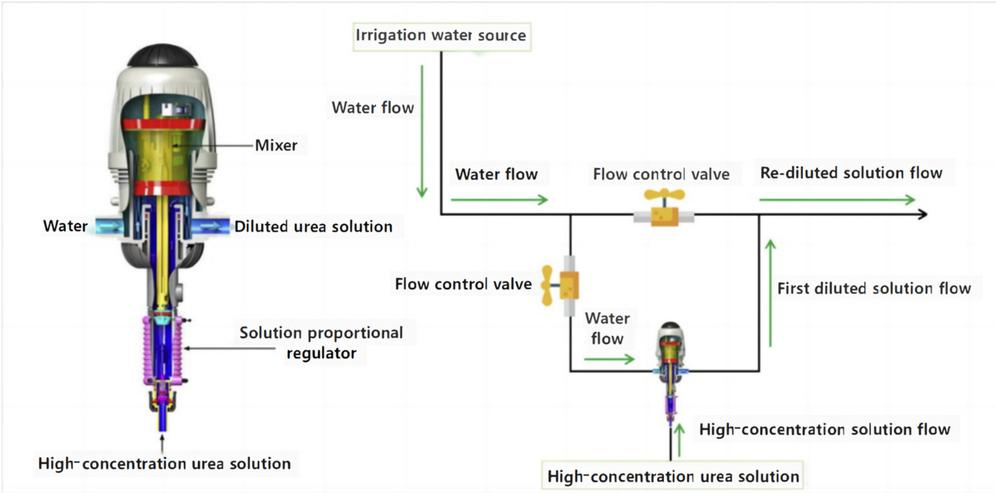

Figure 1. The structure of water and fertilizer integration equipment.

2. Materials and Methods

2.1. Test Site and Materials

The tests were conducted in 2020 and 2021, respectively, in Liandun Village and Liangshuijing Village of Yuexing Town and Simeng Town in Dongpo District of Meishan City (30°2′53.78″ N, 103°50′18.69″ E), which belong to a humid subtropical climate. Meteorological data of the rice growth stages in 2020 and 2021 at the test site were acquired from the measurements of small weather stations set up in the field (Table 1). Table 2 shows the soil's nutrient composition in the test field's 0–20 cm tillage layer. Five soil samples were collected using the five-point sampling method before the preparation of the land, and the contents of soil organic matter (potassium dichromate volumetric method), total nitrogen (Kjeldahl digestion distillation titration method), alkali-hydrolyzed nitrogen (alkali-hydrolytic diffusion method), available phosphorus (molybdenum-antimony resistance colorimetric method), and available potassium (flame photometer method) were determined after natural air drying [25].

Table 1. Meteorological conditions for the whole growth period (WGS) of the experimental rice field in Dongpo District, Meishan City, 2020–2021.

Year	Total Rainfall of WGS (mm)	Total Sunshine Hours of WGS (h)	Average Diurnal Temperature of WGS (°C)
2020	433.4	694.4	23.55
2021	585.2	630.8	23.05

Table 2. Average of selected soil characteristics for composite topsoil samples (0–20 cm) in Dongpo District, Meishan City, 2020–2021.

Year	Organic Matter ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	Available N ($mg\ kg^{-1}$)	Available P ($mg\ kg^{-1}$)	Available K ($mg\ kg^{-1}$)
2020	24.08	1.89	104.66	26.54	106.54
2021	21.38	1.57	97.33	20.88	83.76

2.2. Test Design

A two-factor split-plot design was adopted in the tests. The main plot factor was three hybrid rice cultivars, including F498, Y2115, and J534, with widely varying nitrogen efficiency. The subplot factor was the water and fertilizer management model, including FEM and AIM. Each treatment was replicated three times. The area of each split plot was 1500 m^2. The field management during the WGS of rice is shown in Table 3. The irrigation and fertilization methods of FEM and AIM are shown in Figure 2. The AIM device (Xichun Nong Smart Agricultural Technology Co., Ltd., Chengdu, China) consists of a piping system and mixing chamber, and is powered by a lithium battery. The water is first transported to the water inlet of the water–fertilizer integrator through the pipe and then transmitted to the mixing chamber, while a high-concentration fertilizer solution is fed into the mixing chamber from the fertilizer interface of the equipment. Water and fertilizer are thoroughly mixed through a mixing system and then piped to the rice fields. The equipment costs about USD 2800, has a lifespan of 20 years, and can manage 33.35 hectares of land simultaneously.

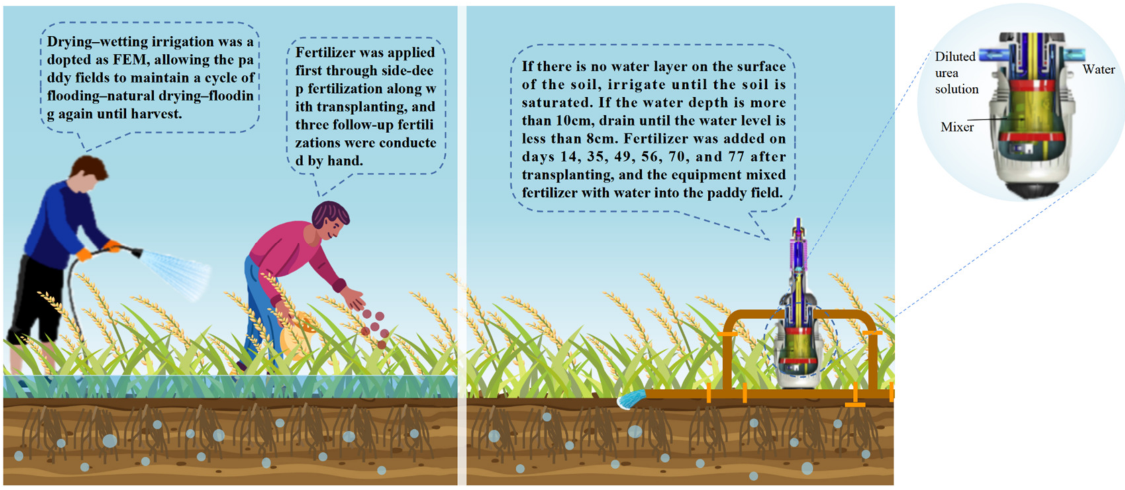

Figure 2. Irrigation and fertilization methods of farmers' enhanced water and fertilizer management (FEM) (**left**) and Water–fertilizer integration management (AIM) (**right**).

Table 3. Description of treatments and management practices performed in the experiment.

S.N.		Farmers' Enhanced Water and Fertilizer Management (FEM)	Water–Fertilizer Integration Management (AIM)
A.	Field preparation		
1.	Irrigation	The water level in the field was irrigated to 5 cm.	Same as FEM
2.	Tillage	Wheat straw from the previous crop was mixed into the plough layer after the land had been tilled twice.	Same as FEM
3.	Leveling	The soil was raked once, with a field height difference of less than 5 cm.	Same as FEM
4.	Seed preparation	After sterilization and a 36 h soaking period, the seeds were drained and placed in seedling trays.	Same as FEM
B.	Planting	Seedlings were transplanted using a tractor-driven transplanter.	Same as FEM

Table 3. *Cont.*

S.N.		Farmers' Enhanced Water and Fertilizer Management (FEM)	Water–Fertilizer Integration Management (AIM)
C.	Field management		
1.	Irrigation and drainage	Drying–wetting irrigation was adopted in FEM. The water layer was maintained at 5 cm or more in the first week after transplanting and 1 cm to 3 cm in the second to fourth week. Paddy field sun-drying was observed for weeks 5 to 6. After that, the water layer was kept at 1 cm to 3 cm during the heading period. If the water depth exceeded 10 cm before heading, the field was drained to a water layer of no more than 8 cm. After heading, a water layer of about 5 cm was formed after irrigation. Due to the natural drying of the field, cracks began to appear on the surface, and a water layer of about 5 cm was formed again after irrigation. This cycle was maintained until the mature stage. In this study, 4 irrigations and 1 drainage were conducted in 2020, while 5 irrigations and 2 drainages were conducted in 2021. The single irrigation volume ranged from 452 to 933 $m^3 \cdot ha^{-1}$.	A water layer of about 5 cm was maintained first. Then, water and fertilizer integration management was carried out after 1 week. A lithium battery–driven water–fertilizer integrator was used to inject the rated concentration of fertilizer solution into the irrigation water at regular intervals, thus mixing it into the flow toward the paddy field. The integrator was equipped with a flow sensor at the irrigation port, and the flow rate of the fertilizer solution was automatically adjusted according to the flow rate of the irrigation water. If there was a water layer in the field, it was irrigated until the water layer was raised by 1 cm; otherwise, it was irrigated until the soil was saturated. If soil cracks exceeded 2 cm due to insufficient precipitation, the field was irrigated until the soil was saturated. If the water depth exceeded 10 cm before heading due to excessive precipitation, the field was drained until the water layer fell no higher than 8 cm. In this study, 8 irrigations and 0 drainage were conducted in 2020, while 8 irrigations and 1 drainage were conducted in 2021. The single irrigation volume ranged from 108 to 551 $m^3 \cdot ha^{-1}$. Nitrogen fertilizers of 15, 15, 30, 15, 15, 15, 15, and 15 kg ha^{-1} (totaling 120 kg ha^{-1}) were applied on days 7, 14, 35, 49, 56, 70, and 77 after transplanting.
2.	Fertilization	Fertilizer was applied first through side–deep fertilization along with transplanting, and three follow–up fertilizations were conducted by hand. Then, nitrogen fertilizer was applied in the ratio of m(base fertilizer)/m(tillering fertilizer)/m(panicle fertilizer) = 3:3:4, and the total nitrogen application was 150 $kg \cdot hm^{-1}$.	
3.	Pesticide spraying	The first pesticide spraying in the field was conducted using a sprayer along with transplanting, and three more sprayings were conducted using drones.	Same as FEM
D	Harvesting and threshing	In the mature stage, the rice was harvested and threshed using a combine harvester.	Same as FEM

2.3. Measurement Items and Methods

2.3.1. Rice Yield

At the mature stage, the marginal effect was reduced by removing the rows of rice on the edges of each split plot. The remaining rice was harvested and threshed separately by hand. The yield was calculated based on the number of plants harvested.

2.3.2. Energy Analysis

The energy analysis focused on comparing the energy input, output, and utilization efficiency of the FEM and AIM. The averages of each agricultural material input in the rice growth stage in 2020 and 2021 were collected (Supplementary Table S1). The weight, service life, and efficiency of the machinery at the site were considered in the calculation of mechanical energy consumption (Supplementary Table S2). The calculation is as follows [26].

$$\text{Energy}_{\text{mach}} = \text{WH} \times \text{MTR} \times \text{WM}/\text{OL} \times \text{EFF} \quad (1)$$

where $\text{Energy}_{\text{mach}}$ is the energy input from machinery (MJ ha^{-1}). WH, MTR, WM, OL, and EFF are the working hours of machinery in the field; the energy used to manufacture, transport, and repair the machinery; the weight of the machinery; the total operational life of machinery; and the field working efficiency, respectively.

The energy input per unit area for items other than machinery was calculated on the basis of the relevant energy equivalents (Supplementary Table S3) [26–34]. The energy input for each item was calculated by multiplying the inputs by their corresponding energy equivalents. The sum of all energy inputs was the total energy input. The dry weights of rice grain (economic yield) and rice straw (biological yield) at the mature stage were multiplied by their corresponding energy equivalents to represent energy output [26].

The net energy (NE), EUE, specific energy (SE), energy productivity (EP), and energy profitability (EPF) were used to analyze the energy utilization. The calculations are as follows [26].

$$\text{NE} = \text{Energy output } (\text{MJ}\cdot\text{ha}^{-1}) - \text{Energy input } (\text{MJ}\cdot\text{ha}^{-1}) \tag{2}$$

$$\text{EUE} = \text{Energy output } (\text{MJ}\cdot\text{ha}^{-1})/\text{Energy input } (\text{MJ}\cdot\text{ha}^{-1}) \tag{3}$$

$$\text{SE} = \text{Energy input } (\text{MJ}\cdot\text{ha}^{-1})/\text{Rice yield } (\text{kg}\cdot\text{ha}^{-1}) \tag{4}$$

$$\text{EP} = \text{Rice yield } (\text{kg}\cdot\text{ha}^{-1})/\text{Energy input } (\text{MJ}\cdot\text{ha}^{-1}) \tag{5}$$

$$\text{EPF} = \text{Net energy } (\text{MJ}\cdot\text{ha}^{-1})/\text{Energy input } (\text{MJ}\cdot\text{ha}^{-1}) \tag{6}$$

2.3.3. Carbon Footprint

The CF list in this study is fully based on the system boundary from paddy cultivation to rice harvest, consisting of carbon emissions from the machinery, pesticides, diesel, fertilizers, electricity, labor, plastic film, pesticides, and seeds in production, transportation, and use, as well as greenhouse gas emissions from paddy fields all through the rice growth stage (Figure 3). Greenhouse gas emissions from paddy fields on the whole encompass carbon dioxide (CO_2), CH_4, and N_2O. However, due to the fact that the quantity of CO_2 constant through photosynthesis in rice is often greater than that of respiratory CO_2, it is generally not included or calculated in the greenhouse gas emissions from paddy fields.

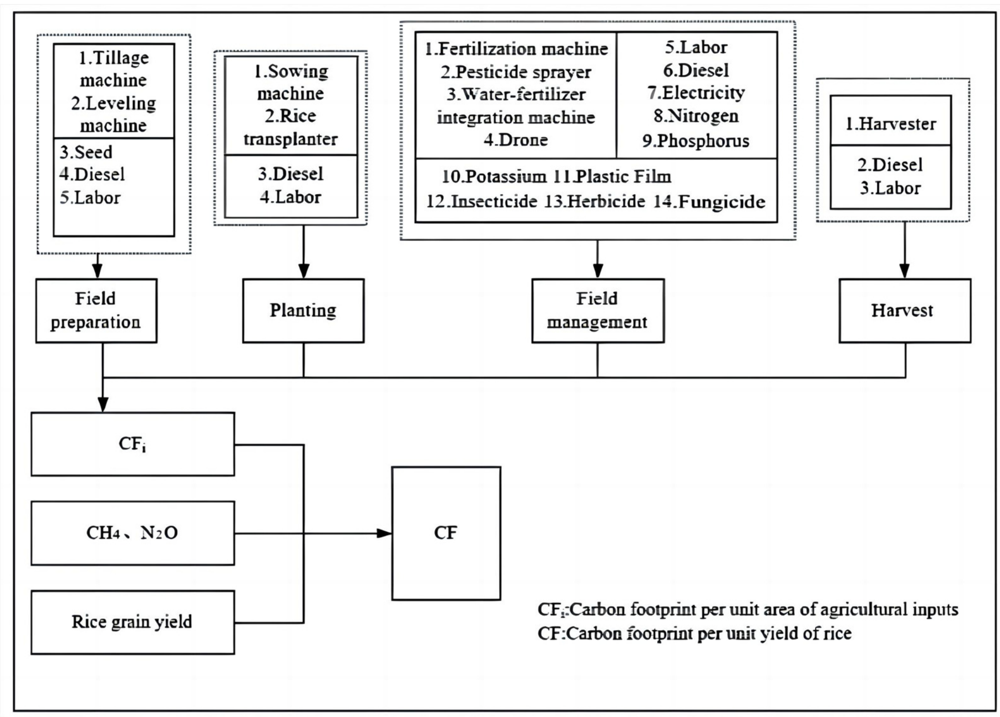

Figure 3. Carbon footprint list of rice throughout the growth stage.

The collection and determination of CH_4 and N_2O from paddy fields were conducted through the static chamber technique and gas chromatography [35]. The total rice season emissions were calculated in terms of emission fluxes. Additionally, CF per unit yield of rice from sowing to harvest was expressed by the ratio of total greenhouse gas emissions (TGHG) to rice yield over the entire growth stage (Equation (7)). Then, TGHG was obtained by multiplying the CH_4 and N_2O emissions per unit area of the paddy field by the corresponding carbon emission factors plus the carbon emissions from agricultural materials inputs (CF_i) (Equation (8)). The CF_i can be calculated with Equation (9) [36]:

$$\mathrm{CF} = \mathrm{TGHG}/\mathrm{Rice\ yield} \tag{7}$$

$$\mathrm{TGHG} = \mathrm{CF_i} + 28 \times \mathrm{F_{CH4}} + 265 \times \mathrm{F_{N2O}} \tag{8}$$

$$\mathrm{CF_i} = \sum(\delta\,\mathrm{m})_{\mathrm{i}} \tag{9}$$

where TGHG is the total greenhouse gas emissions (kg CO_2-eq ha^{-1}); CF is the carbon footprint per unit yield of rice (kg CO_2-eq kg^{-1}); CF_i is the carbon emissions from agricultural materials inputs per unit area (kg CO_2-eq ha^{-1}); F_{CH4} and F_{N2O} denote the cumulative emissions of CH_4 and N_2O from paddy fields throughout the rice season (kg·ha^{-1}); 28 and 265 are the conversion factors of CH_4 and N_2O into CO_2 emissions on a 100-year scale, respectively [37]; m is the consumption of the ith agricultural material per unit area; and δ is the carbon emission factor of the ith agricultural material (Supplementary Table S4) [38–44].

2.3.4. Economic Benefits

The complete gross profits per unit region of paddy field and the price of each input substance were calculated primarily based on the unit expenditures of rice grain and a variety of agricultural inputs (Supplementary Table S5). Total production costs were expressed as the sum of the costs of each input material. The parameters used for economic assessment included net economic return (NER), benefit-to-cost ratio (BTC), and net profitability of labor (NPL), which can be calculated as follows [26]:

$$\mathrm{NER} = \text{total gross income} - \text{total production cost} \tag{10}$$

$$\mathrm{BTC} = \text{total gross income}/\text{total production cost} \tag{11}$$

$$\mathrm{NPL} = \text{net economic return}/\text{total labor input} \tag{12}$$

All test data were collected and analyzed in SPSS23 (v.23.0; IBM Corp., Armonk, NY, USA), and the figures were plotted using Origin 2021 (OriginLab Corp., Northampton, MA, USA).

3. Results and Analysis

3.1. Comparison of Rice Yields under the Two Water and Fertilizer Management Models

The grain yield of F498 under the AIM treatment in 2020 exhibited a significant reduction of 5.6% compared to the FEM treatment, while no significant difference was observed in straw yield between the two treatments (Figure 4). Similarly, there were no notable variations in grain yield between Y2115 and J534 under either treatment; however, the straw yield indicated a significantly lower value for AIM compared to FEM. With increasing management years, rice yields increased in all varieties. In 2021, both AIM and FEM showed increased rise yields, while the differences in yield between these two treatments were small.

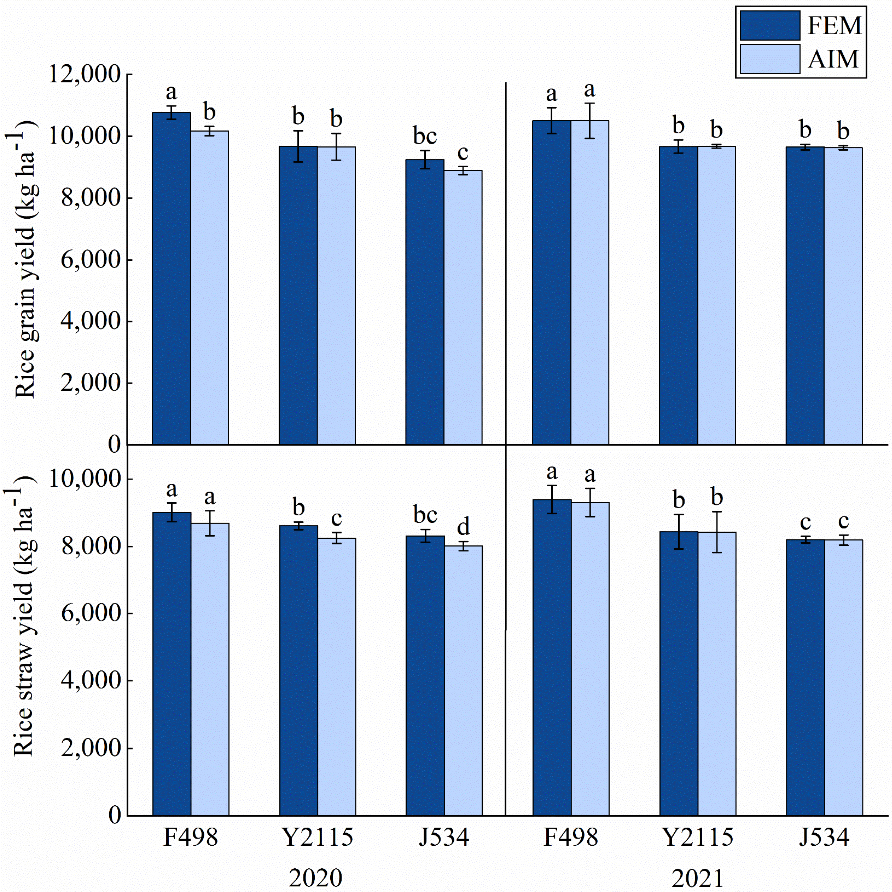

Figure 4. Rice grain yield and straw yield for F498, Y2115, and J534 under farmers' enhanced water and fertilizer management (FEM) and Water–fertilizer integration management (AIM) in 2020 and 2021. Different letters indicate statistical significance at $p < 0.05$ between treatments within a cultivar (least significant difference [LSD]).

3.2. *Energy Flow under the Two Water and Fertilizer Management Models*

The total energy input in this study ranged from 24,969.74 to 28,432.82 MJ·ha^{-1} (Table 4). AIM saved 12.18% of energy input compared to FEM. In terms of the proportion of each agricultural material in the total energy input, fertilizer always accounted for the largest proportion, followed by diesel and irrigation water, while the proportion of items such as labor, electricity, and plastic film was only 5% (Figure 5). Due to the optimization of fertilization methods, the fertilizer input of AIM was 20.80% lower than that of FEM. Compared with FEM, the water-fertilizer integrated equipment of AIM increased the mechanical input by 11.49%. However, it also saved the labor for manually applying fertilizer and diverting water for irrigation, reducing labor input by 15.00% compared to FEM. Meanwhile, AIM also reduced the input of pesticides by 24.27%.

Table 4. Input–output energy under FEM and AIM for Dongpo District from 2020 to 2021 (2-year average).

Items (MJ ha^{-1})	FEM	AIM
Machinery	1335.88	1392.58
Human labor	453.94	384.81
Diesel	9168.61	9168.61
Electricity	4.50	101.84
Nitrogen	9926.95	8137.20
Phosphorus	940.96	762.32
Potassium	1663.02	1371.67

Table 4. *Cont.*

Items (MJ ha^{-1})	FEM	AIM
Water	3932.08	2768.18
Plastic film	230.68	230.68
Insecticide	244.90	179.12
Herbicide	126.14	99.96
Fungicide	140.40	108.00
Seed	264.75	264.75
Energy input	28,432.82	24,969.74
Rice grain yield	168,627.85	164,695.00
Rice straw yield	108,257.78	105,981.31
Energy output	276,885.62	270,676.31

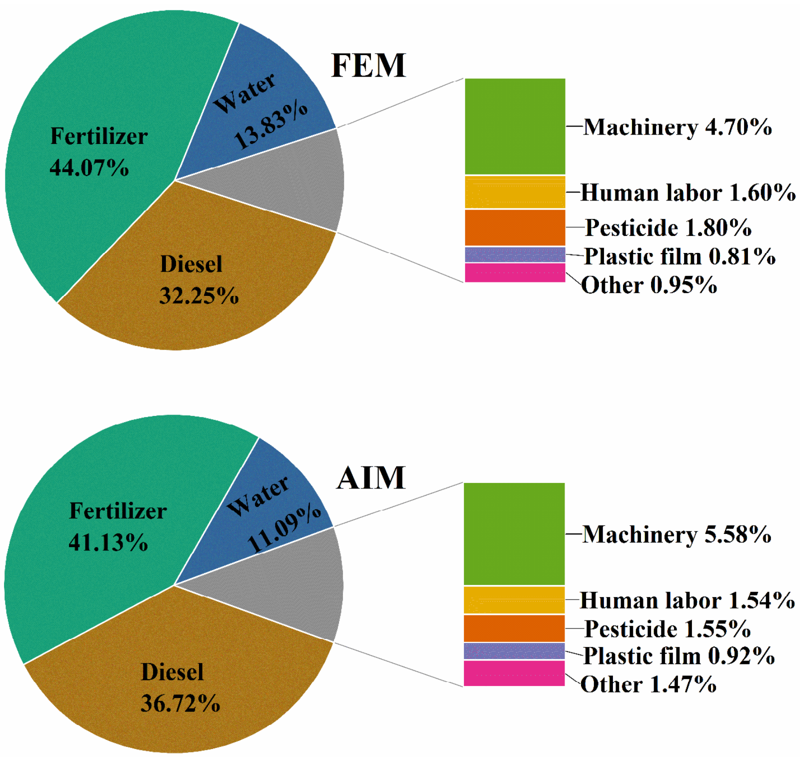

Figure 5. Composition of total energy input from different sources under FEM and AIM in 2020–2021 (two-year average).

In terms of energy utilization, the NE and SE under AIM were reduced by 1.10% and 10.10% compared with those under FEM (Figure 6). However, the EUE (10.84 MJ·ha^{-1}), EP (0.39 kg·MJ^{-1}), and EPF (9.84 MJ·MJ^{-1}) under AIM increased by 11.30%, 11.43%, and 12.61%, compared with those under FEM (9.74 MJ·ha^{-1}; 0.35 kg·MJ^{-1}; and 8.74 MJ·MJ^{-1}), indicating that more rice and NE output are produced per unit of energy input under AIM.

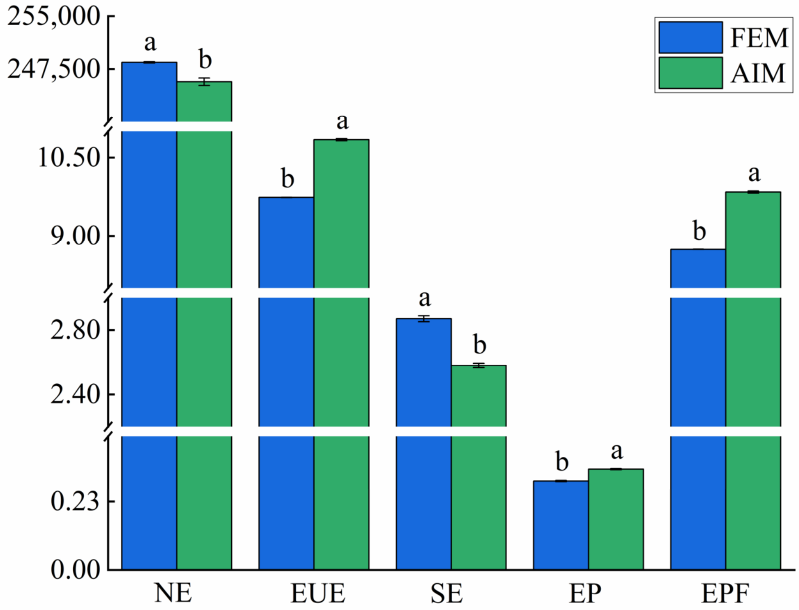

Figure 6. Comparison of energy use efficiency in rice fields under FEM and AIM in 2020–2021 (two-year average). Net energy (NE), energy utilization efficiency (EUE), specific energy (SE), energy productivity (EP), and energy profitability (EPF). Different letters indicate statistical significance at $p < 0.05$ between treatments within a cultivar (least significant difference [LSD]).

3.3. Carbon Footprint Analysis under the Two Water and Fertilizer Management Models

In this study, CF under AIM was 0.54 kg CO_2-eq kg^{-1} (Figure 7), which was 15.95% lower than that under FEM (0.64 kg CO_2-eq kg^{-1}). The TGHG of AIM was 5312.88 kg CO_2-eq ha^{-1}, which was 17.22% lower than that of FEM (6417.72 kg CO_2-eq ha^{-1}). CH_4 accounted for 73.13% to 76.50% of TGHG in this study and was the largest contributor to carbon emissions. CH_4 emissions from AIM were 20.80% lower than those from FEM (AIM, 3885.13 kg CO_2-eq ha^{-1}; FEM, 4905.42 kg CO_2-eq ha^{-1}). N_2O emissions accounted for 7.87–8.98% of TGHG, with nitrous oxide emissions from AIM being 6.51% lower those from FEM (AIM, 472.09 kg CO_2-eq ha^{-1}; FEM, 504.99 kg CO_2-eq ha^{-1}). CF_i contributed to 15.63–17.99% of TGHG. Diesel was the largest contributor to CF_i (45% to 47%), followed by fertilizers (36% to 42%). AIM reduced carbon emissions from fertilizer inputs by 18.02% while maintaining the same diesel inputs as FEM, which was the main reason for its 4.65% reduction in CF_i compared to FEM. Although the use of water and fertilizer integrators increased carbon emissions from machinery and electricity by 35.65% for AIM, it only accounted for 9.60–13.66% of the CF_i, and the advantage of AIM in reducing fertilizer input could cancel out the small amount of carbon emissions attributed to the water–fertilizer integrator. In summary, AIM is more effective in reducing carbon emissions from rice production.

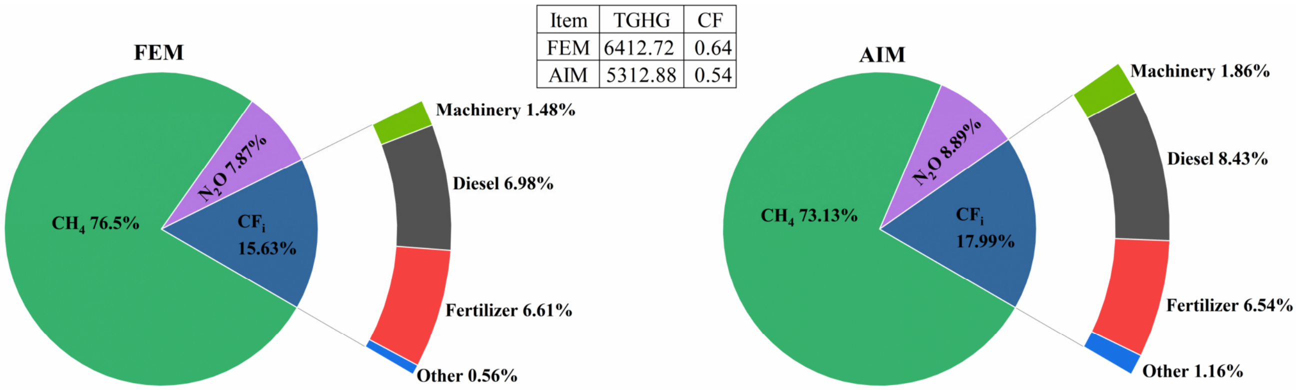

Figure 7. Composition of carbon footprint (CF) and comparison of total greenhouse gas emissions (TGHG) and CF of paddy fields under FEM and AIM from 2020 to 2021 (two-year average).

3.4. Economic Benefit Analysis under the Two Water and Fertilizer Management Models

AIM decreased agricultural materials inputs and production costs by 12.33% compared to FEM (AIM, 1592.21 USD·ha^{-1}; FEM, 1816.05 USD·ha^{-1}) (Table 5). Labor cost contributed the most to the agricultural materials input, followed by fertilizer (Figure 8). With the water–fertilizer integrator, AIM increased the cost of machinery and electricity by 4.48% but saved 17.96% on labor costs. Additionally, AIM effectively saves 18.04 to 24.23% on fertilizer and pesticide costs. With a lower cost input, AIM had higher NER, BTC, and NPL than FEM (6.10% to 21.19%), indicating greater revenues than FEM for the same cost (Figure 9).

Table 5. Economic input and output of FEM and AIM in Dongpo District in 2020 and 2021 (two-year average).

Particulars (USD·ha^{-1})	FEM	AIM
Machine	223.83	231.69
Drone	41.54	41.54
Labor	509.52	431.93
Diesel	154.68	154.68
Urea	94.62	77.56
Superphosphate	63.03	51.07
Muriate of potash	111.86	92.27
Insecticide	174.87	127.90
Herbicide	63.83	50.58
Fungicide	205.50	158.08
Rice seed	172.00	172.00
Plastic film	0.66	0.66
Electricity	0.10	2.26
Total input	1816.05	1592.21
Single-season indica rice	3967.71	3875.18

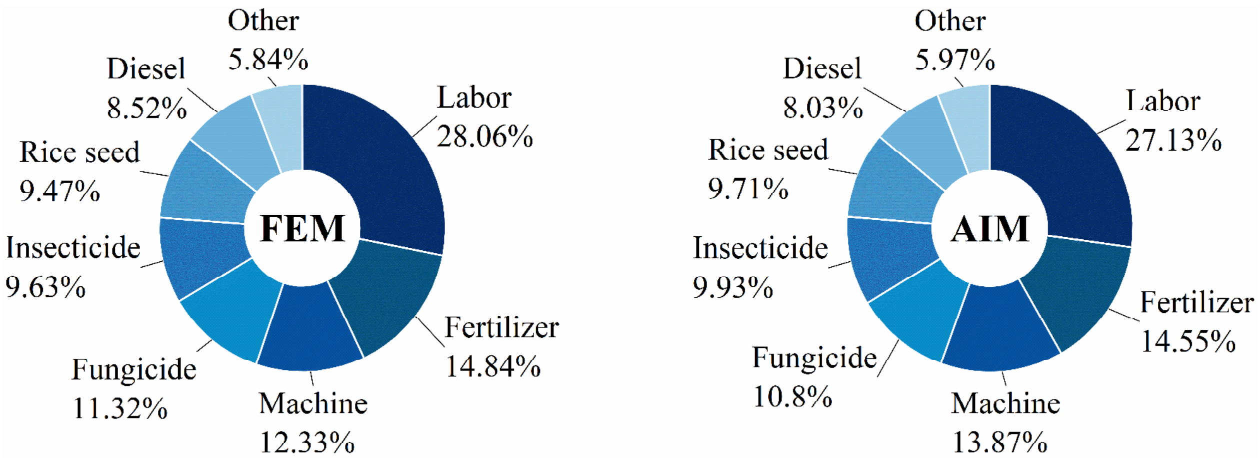

Figure 8. Composition of total capital input from different sources under FEM and AIM from 2020 to 2021 (two-year average).

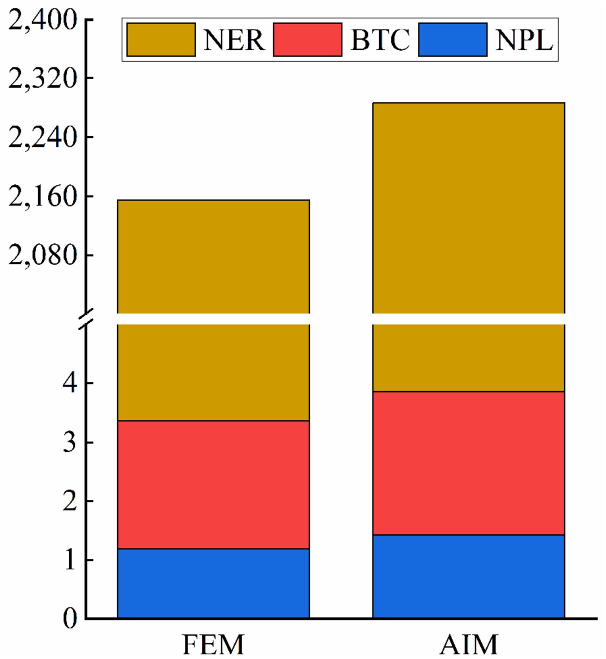

Figure 9. Comparisons of net economic return (NER), benefit-to-cost ratio (BTC), and net profitability of labor (NPL) of paddy fields under FEM and AIM from 2020 to 2021 (two-year average).

4. Discussion

4.1. Effect of Different Water and Fertilizer Management Practices on Rice Yield

Production is the basis for assessing energy output and economic returns. Although fertilizer application can rapidly increase rice yield, excessive inputs can chronically weaken the nutrient retention capacity of the soil [45,46], resulting in reduced yield-increasing effects of the fertilizer. The ability of AIM to maintain yield with less water and fertilizer input was not significantly reduced compared to FEM, mainly attributed to improved rice water productivity and nitrogen use efficiency. The feature of AIM to transport water and fertilizer to the roots of the crop through a pipe system promotes nitrogen uptake by the roots and reduces water loss from evaporation during irrigation [36,47]. These findings agree with the effects mentioned by Sidhu et al. that rice yields in Punjab, India, under AIM were not significantly different compared to those under conventional flooding irrigation, while the nitrogen fertilizer inputs were reduced by 20% [48]. Thus, through water and fertilizer integration, AIM can stimulate the yield-increasing ability of nitrogen fertilizer to a greater extent. In this study, repeated tests were conducted at different experimental sites, and the soil nutrient content in the 2020 experimental site was found to be higher than that in the 2021 experimental site. Moreover, three-line hybrid indica rice varieties Y2115 and F489, as well as two-line hybrid indica rice variety J534, were utilized. These varieties exhibited significant variations in nitrogen utilization efficiency due to their distinct breeding methods. However, the analysis of yield differences across locations and varieties between AIM and FEM indicated that AIM did not result in any substantial reduction in yield compared to FEM. This suggests that AIM is an effective management measure for consistently maintaining high rice yields.

4.2. Effect of Different Water and Fertilizer Management on Energy Utilization in Rice Production

The energy input in this study was lower than that of 37,539.50 to 64,158.78 MJ·ha^{-1} reported by Poddar and Hossein Kazemi et al. in India and Iran [49,50]; similar to the 17,799.00 to 28,373.00 MJ·ha^{-1} reported in Bangladesh [51]; but higher than that of 14,067.00 to 14,813.00 MJ·ha^{-1} for rice production in Nigeria reported by Kosemani et al. [52]. The similarity of studies in different countries was that energy consumption from fertilizers, irrigation, and diesel fuel were the main sources of total energy inputs [24,50,53]. Despite the differences in total energy inputs, the main sources of energy consumption in different countries were fertilizer, irrigation, and diesel inputs, and differences in these factors were the main contributors to the different total energy consumption.

As a country with an average annual precipitation of only 220 mm, increasing artificial irrigation has become the only way to ensure rice production in Iran. Although the current karez irrigation system in Iran can adapt to the arid geography, it is also prone to water wastage and pollution due to its inefficiency. However, as a country constrained by multiple factors such as economic difficulties, water scarcity, and social conflicts, it is difficult for Iran to innovate and maintain irrigation technology [54]. Long-term inefficient irrigation has exacerbated the salinization and desertification of agricultural land, leading to the excessive use of fertilizers to maintain soil fertility and increase yields [55]. The above factors result in more than twice the energy consumption of input irrigation water and 12.25 to 36.95% higher energy input of fertilizers (14,066.30 MJ·ha^{-1}) in the Iranian rice production system than in the present study [56]. India has also invested relatively high levels of energy in rice production, but achieved greater progress than Iran in improving and innovating irrigation technologies. However, due to inadequate power facilities, agricultural machinery and equipment in India are mainly supplied with diesel as an energy source. Coupled with the heavy government subsidization of diesel prices for farmers, diesel fuel in India is largely wasted [57]. According to a previous study, the diesel used to supply irrigation equipment in India exceeds the diesel inputs in the present study by 9.93%, and its total diesel inputs are 68.27% higher than that in this study [58], which is the main reason for the larger energy inputs in India. The lower energy inputs in Nigeria can be attributed to lower fertilizer inputs. Due to their low level of knowledge, Nigerian farmers have little motivation to buy fertilizer. Falling food prices also discourage them from investing in their crops. A series of policies formulated by the Government to promote agricultural development have also been ineffective due to insufficient financial support [59]. Sloppy management practices have inevitably contributed to the decline in rice yield in Nigeria, which is only 67.49–74.00% of that in this study [52].

Therefore, reducing energy inputs to rice production systems cannot be achieved by simply reducing the inputs of resources such as fertilizers. The key to balancing rice production and sustainable resource utilization is to improve resource utilization efficiency through rational management practices. AIM saves 12.18% of energy inputs relative to FEM in the present study due to the increased efficiency of water and fertilizer use by AIM. Firstly, AIM increases nitrogen availability by delivering fertilizer in small doses and frequently to align with the law of plant nutrient absorption [8,60], thus saving fertilizer inputs on the basis of stable yield. Secondly, this beneficial effect further alters the soil environment by reducing the nutrients available for weed and pathogen growth, thus saving inputs of different chemicals [61].

4.3. Effects of Different Water and Fertilizer Management on the CF of Rice Paddies

The CF of rice production in this study was lower than the 2.35 to 2.42 kg CO_2-eq kg^{-1} of continuous flood irrigation in central China reported by Du et al. [62]. Due to favorable climatic conditions, double-cropped rice is one of the main types of production in central China. Farmland is waterlogged during most of the year, leading to changes in soil structure, which in turn accelerates nutrient loss and encourages farmers to develop the habit of over-fertilizing [63,64]. For example, the 1215 kg CO_2-eq ha^{-1} nitrogen fertilizer input reported by Li et al. in rice production in central China is three times higher than the one in this study [36]. This is an important reason why central China has a high CF for rice production. In contrast, the AIM in this study builds almost no water layer and has the effect of improving soil quality and reducing nutrient loss, thereby decreasing the CF. Excessive CF for rice production in central China is also a key factor contributing to the high average CF levels in China (0.89 kg CO_2-eq kg^{-1}) [65]. All these results demonstrate the importance of AIM for mitigating CF in rice production in China.

Numerous studies have shown that methane is a major contributor to CF, which is consistent with the results of this study [62]. The reduction of methane emission from paddy fields under AIM treatment in this study is mainly attributed to the fact that AIM creates an aerobic environment on the surface of the soil as little water layer is built up. Therefore, it is challenging to release large amounts of CH_4 into the atmosphere because methanotrophic bacteria on the soil surface oxidize it [12].

Nitrous oxide emissions in the present study were similar to the average rice field N_2O emissions in China reported by other scholars [66,67]. Compared with AIM, alternate irrigation and more nitrogen were applied in FEM, thus providing favorable conditions for N_2O production. Under the alternating irrigation mode, the rice was mostly in a flooded environment during the effective tillering stage. Thus, NO^{3-} in soil was reduced to N_2O through denitrification. Due to the mineralization of organic nitrogen, a substantial quantity of NH_4^+ was accumulated in the soil. The sun-drying during the inefficient tillering stage dramatically increased soil oxygen levels, leading to dramatic nitrification with NH_4^+ as the substrate and a peak in N_2O emissions [68]. AIM reduces the amount of nitrogen applied, consequently lowering the amount of active nitrogen in the soil and reducing the nitrogen source for N_2O production. Meanwhile, AIM can also keep the soil water content in a saturated state, so that most of the N_2O is further reduced to N_2. This results in a low peak and low frequency of N_2O emissions [61,69].

After analyzing the CF composition of rice production in southwest China from 2004 to 2016, Lyu et al. concluded that reducing fertilizer inputs by improving fertilizer utilization was a major method to reduce CF from rice production, which was similar to the conclusions of Sidhu et al. [48,70]. Huang et al. concluded that fertilizer contributed the most to CF_i in rice production by studying the CF of rice under different crop rotation techniques in central China [71]. In this study, the contribution of fertilizer to CF_i was also close to 40%, indicating the great potential of reduced fertilizer inputs in reducing CF_i in rice production. Therefore, AIM with reduced water and fertilizer inputs can reduce methane and nitrous oxide emissions by altering the soil environment, and it is also an important water and fertilizer management tool to reduce CF_i in rice.

4.4. Impact of Different Water and Fertilizer Management on Economic Efficiency of Rice Production

Economic benefits are the main parameter that determines whether agricultural measures can be promoted on a large scale [72]. The rice production cost in this study was lower than the 3087.33–3245.55 USD·ha^{-1} reported in Iran with a lower mechanization level, but it is higher than the 659.79 to 862.27 USD·ha^{-1} reported in Myanmar with lower labor costs [49,73]. Through water and fertilizer utilization efficiency improvement, AIM reduced water and fertilizer inputs and achieved more substantial production benefits than FEM, which was more in line with China's requirements for intensive development [74]. With the increasing scarcity of freshwater resources, irrigation water charges will gradually become popular. Thus, the excellent water-saving features of AIM will make its cost-saving advantages even more prominent.

5. Conclusions

In this study, the performance of AIM and FEM in rice production differed frequently in the water and fertilizer inputs. By optimizing the water and fertilizer supply mode of paddy fields, AIM not only achieves a lower energy input, higher energy utilization efficiency, lower production cost, and higher benefit-to-cost ratio without significantly reducing output, but also reduces N_2O emissions and CF_i, and significantly reduces CH_4 emissions. Therefore, AIM is a management system that effectively enhances both crop yield and agricultural resource utilization efficiency, while also playing a pivotal role in mitigating carbon emissions associated with intensive rice production and alleviating the economic burden on farmers. This measure holds significant implications for large-scale global rice production systems in terms of energy conservation and emission reduction. In the future, further investigation into the impact of AIM on the microbial mechanisms underlying rice yield formation and greenhouse gas emissions is warranted. However, AIM relies on integrated water and fertilizer equipment. Although the investment in this equipment is worthwhile in the longer term, the larger one-time investment is a difficult choice for farmers. Especially for low-profit rice, the investment recovery cycle is longer under the premise that the production scale is not too large.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture14040585/s1, Table S1: Resource consumption for drying-wetting water and fertilizer management (FEM) and the water and fertilizer integration (AIM) in Dongpo District from 2020 and 2021 (2-year average); Table S2: Description of parameters needed for estimating energy inputs with machinery; Table S3: Energy equivalents of agricultural inputs and outputs; Table S4: Emission factors are used for estimating greenhouse gas emissions from manufacturing, packaging, and transportation of agricultural inputs; Table S5: Unit prices of rice grain and the various inputs. Data were retrieved from National Development and Reform Commission.

Author Contributions: Conceptualization: Q.L., X.Z., L.L. and Z.Y.; Methodology: H.Y., Y.L. and X.Z.; Writing—review and editing: Q.L. and Q.C.; Formal analysis: X.Z., H.F. and C.S.; Investigation: Q.L., X.Z., Q.C., H.F., J.N., H.Y., Y.L., C.S., N.L., Y.S., Z.C., J.M., B.L. and L.L.; Software: J.N.; Visualization: N.L., Y.S. and Z.C.; Supervision: Z.Y.; Resources: Z.Y.; Project administration: Z.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the National Key Research and Development Program of China (Nos. 2023YFD2301901); the Research Program Foundation of Key Laboratory of Sichuan Province (2022ZDZX0012); and the Key Research and Development program of Chengdu City (2022-YF09-00040-SN).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors have no conflicts of interest to declare that are relevant to the content of this article.

Abbreviations

FEM: farmers' enhanced water and fertilizer management; AIM, water–fertilizer integration management; WH, working hours of machinery in the field; MTR, energy used to manufacture, transport, and repair the machinery; WM, weight of machinery; OL, total service life of the machine; EFF, field working efficiency; NE, net energy; EUE, energy utilization efficiency; SE, specific energy; EP, energy productivity; EPF, energy profitability; TGHG, total greenhouse gas emissions; CF, carbon footprint per unit yield of rice; CF_i, carbon emissions from agricultural materials inputs per unit area; NER, net economic return; BTC, benefit-to-cost ratio; NPL, net profitability of labor.

References

1. Balaine, N.; Carrijo, D.R.; Adviento-Borbe, M.A.; Linquist, B. Greenhouse Gases from Irrigated Rice Systems under Varying Severity of Alternate-Wetting and Drying Irrigation. *Soil Sci. Soc. Am. J.* **2019**, *9*, 1533–1541. [CrossRef]
2. Novoa, V.; Rojas, O.; Ahumada-Rudolph, R.; Arumí, J.L.; Munizaga, J.; de la Barrera, F.; Cabrera-Pardo, J.R.; Rojas, C. Water footprint and virtual water flows from the Global South: Foundations for sustainable agriculture in periods of drought. *Sci. Total Environ.* **2023**, *869*, 161526. [CrossRef]
3. Tian, S.; Xu, Y.; Wang, Q.; Zhang, Y.; Yuan, X.; Ma, Q.; Feng, X.; Ma, H.; Liu, J.; Liu, C.; et al. The effect of optimizing chemical fertilizers consumption structure to promote environmental protection, crop yield and reduce greenhouse gases emission in China. *Sci. Total Environ.* **2023**, *857*, 159349. [CrossRef] [PubMed]
4. Rogelj, J.; Shindell, D.; Jiang, K.; Forster, P.; Ginzburg, V. Mitigation Pathways Compatible with 1.5 °C in the Context of Sustainable Development 2019. In *Global Warming of 1.5 °C*; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2018.
5. He, A.; Yuan, B.; Jin, Z.; Man, J.; Peng, S.; Zhang, L.; Liu, H.; Nie, L. Comparative study on annual yield, water consumption, irrigation water use efficiency and economic benefits of different rice-oilseed rape rotation systems in Central China. *Agric. Water Manag.* **2021**, *247*, 106741. [CrossRef]
6. An, Y.; Li, Q.; Zhang, L. Managing Agricultural Water Use in a Changing Climate in China. *Sustain. Prod. Consum.* **2022**, *33*, 978–990. [CrossRef]
7. Zheng, W.; Luo, B.; Hu, X. The determinants of farmers' fertilizers and pesticides use behavior in China: An explanation based on label effect. *J. Clean. Prod.* **2020**, *272*, 123054. [CrossRef]
8. Fang, N.; Yu, L.; Lu, Z. Application Effects of Stabilized Fertilizer with Reduced Amount and Frequency on Rice. *Asian Agric. Res.* **2019**, *11*, 67–69+80. [CrossRef]
9. Hu, L.; Zhang, X.; Zhou, Y. Farm size and fertilizer sustainable use: An empirical study in Jiangsu, China. *J. Integr. Agric.* **2019**, *18*, 2898–2909. [CrossRef]
10. Gao, Y.; Sun, C.; Ramos, T.B.; Huo, Z.; Huang, G.; Xu, X. Modeling nitrogen dynamics and biomass production in rice paddy fields of cold regions with the ORYZA-N model. *Ecol. Model.* **2023**, *475*, 110184. [CrossRef]
11. Khalil, M. NON-CO_2 greenhouse gases in the atmosphere. *Energy Environ.* **1999**, *24*, 645–661. [CrossRef]
12. Tang, J.; Wang, J.; Li, Z.; Wang, S.; Qu, Y. Effects of Irrigation Regime and Nitrogen Fertilizer Management on CH_4, N_2O and CO_2 Emissions from Saline–Alkaline Paddy Fields in Northeast China. *Sustainability* **2018**, *10*, 475. [CrossRef]
13. Li, Q.; Chen, Q.; Lv, R.; Liu, W.; Zhao, L.; Zhang, J.; Guo, Q.; Qiu, X.; You, H. Spring soil CO_2 and CH_4 emissions in the Yellow River Delta wetland, China. *J. Sea Res.* **2022**, *190*, 102280. [CrossRef]
14. Zhong, Y.; Wang, X.; Yang, J.; Zhao, X.; Ye, X. Exploring a suitable nitrogen fertilizer rate to reduce greenhouse gas emissions and ensure rice yields in paddy fields. *Sci. Total Environ.* **2016**, *565*, 420–426. [CrossRef] [PubMed]
15. Chuan, L.; Zheng, H.; Zhao, J.; Sun, S.; Zhang, J. The development of integrated management of water and fertilizer. In Proceedings of the 2nd International Conference on Energy, Environment and Materials Science(EEMS 2016), Singapore, 29–31 July 2016.
16. Wang, J.; Du, G.; Tian, J.; Jiang, C.; Zhang, Y.; Zhang, W. Mulched drip irrigation increases cotton yield and water use efficiency via improving fine root plasticity. *Agric. Water Manag.* **2021**, *255*, 106992. [CrossRef]
17. Li, H.; Mei, X.; Wang, J.; Huang, F.; Hao, W.; Li, B. Drip fertigation significantly increased crop yield, water productivity and nitrogen use efficiency with respect to traditional irrigation and fertilization practices: A meta-analysis in China. *Agric. Water Manag.* **2021**, *244*, 106534. [CrossRef]
18. Singandhupe, R.B.; Rao, G.G.S.N.; Patil, N.G.; Brahmanand, P.S. Fertigation studies and irrigation scheduling in drip irrigation system in tomato crop (*Lycopersicon esculentum* L.). *Eur. J. Agron.* **2003**, *19*, 327–340. [CrossRef]
19. Zong, R.; Wang, Z.; Zhang, J.; Li, W. The response of photosynthetic capacity and yield of cotton to various mulching practices under drip irrigation in Northwest China. *Agric. Water Manag.* **2021**, *249*, 106814. [CrossRef]
20. Yasuor, H.; Yermiyahu, U.; Ben-Gal, A. Consequences of irrigation and fertigation of vegetable crops with variable quality water: Israel as a case study. *Agric. Water Manag.* **2020**, *242*, 106362. [CrossRef]
21. Zheng, H.; Chuan, L.; Zhao, J.; Sun, S.; Zhang, J. Overview of Water and Fertilizer Integration Development. In Proceedings of the 2016 International Conference on Advances in Energy, Environment and Chemical Science (AEECS 2016), Changsha, China, 23–24 April 2016. [CrossRef]
22. Yang, Z.; Li, N.; Ma, P.; Li, Y.; Zhang, R.; Song, Q.; Guo, X.; Sun, Y.; Xu, H.; Ma, J. Improving nitrogen and water use efficiencies of hybrid rice through methodical nitrogen–water distribution management. *Field Crops Res.* **2020**, *246*, 107698. [CrossRef]
23. Franco, W.; Barbera, F.; Bartolucci, L.; Felizia, T.; Focanti, F. Developing intermediate machines for high-land agriculture. *Dev. Eng.* **2020**, *5*, 100050. [CrossRef]
24. Yadav, G.S.; Babu, S.; Das, A.; Mohapatra, K.P.; Singh, R.; Avasthe, R.K.; Roy, S. No-till and mulching enhance energy use efficiency and reduce carbon footprint of a direct-seeded upland rice production system. *J. Clean. Prod.* **2020**, *271*, 122700. [CrossRef]
25. Guo, C.; Yang, C.; Fu, J.; Song, Y.; Chen, S.; Li, H.; Ma, C. Effects of crop rotation on sugar beet growth through improving soil physicochemical properties and microbiome. *Ind. Crops Prod.* **2024**, *212*, 118331. [CrossRef]
26. Yuan, S.; Cassman, K.G.; Huang, J.; Peng, S.; Grassini, P. Can ratoon cropping improve resource use efficiencies and profitability of rice in central China? *Field Crops Res.* **2019**, *234*, 66–72. [CrossRef] [PubMed]

27. Erdal, G.; Esengün, K.; Erdal, H.; Gündüz, O. Energy use and economical analysis of sugar beet production in Tokat province of Turkey. *Energy* **2007**, *32*, 35–41. [CrossRef]
28. Yilmaz, I.; Akcaoz, H.; Ozkan, B. An analysis of energy use and input costs for cotton production in Turkey. *Renew. Energy* **2005**, *30*, 145–155. [CrossRef]
29. Sayin, C.; Mencet, M.N.; Ozkan, B. Assessing of energy policies based on Turkish agriculture: Current status and some implications. *Energy Policy* **2005**, *33*, 2361–2373. [CrossRef]
30. Esengun, K.; Guenduez, O.; Erdal, G. Input–output energy analysis in dry apricot production of Turkey. *Energy Convers. Manag.* **2007**, *48*, 592–598. [CrossRef]
31. Karkacier, O.; Goktolga, Z.G. Input–output analysis of energy use in agriculture. *Energy Convers. Manag.* **2005**, *46*, 1513–1521. [CrossRef]
32. Ozkan, B.; Fert, C.; Karadeniz, C.F. Energy and cost analysis for greenhouse and open-field grape production. *Energy* **2007**, *32*, 1500–1504. [CrossRef]
33. Pathak, B.S.; Bining, A.S. Energy use pattern and potential for energy saving in rice-wheat cultivation. *Energy Agric.* **1985**, *4*, 271–278. [CrossRef]
34. Ozkan, B.; Akcaoz, H.; Pert, C. Energy input–output analysis in Turkish agriculture. *Renew. Energy* **2004**, *29*, 39–51. [CrossRef]
35. Karki, S.; Adviento-Borbe, M.A.A.; Massey, J.H.; Reba, M.L. Assessing Seasonal Methane and Nitrous Oxide Emissions from Furrow-Irrigated Rice with Cover Crops. *Agriculture* **2021**, *11*, 261. [CrossRef]
36. Li, S.; Guo, L.; Cao, C.; Li, C. Integrated assessment of carbon footprint, energy budget and net ecosystem economic efficiency from rice fields under different tillage modes in central China. *J. Clean. Prod.* **2021**, *295*, 126398. [CrossRef]
37. Field, C.B.; Barros, V.R.; Intergovernmental Panel on Climate Change. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Guangdong Agricultural Sciences*; Cambridge University: Cambridge, UK, 2014.
38. Dyer, J.A.; Desjardins, R.L. Carbon Dioxide Emissions Associated with the Manufacturing of Tractors and Farm Machinery in Canada. *Biosyst. Eng.* **2006**, *93*, 107–118. [CrossRef]
39. Cheng, K.; Pan, G.; Smith, P.; Luo, T.; Ming, Y. Carbon footprint of China's crop production—An estimation using agro-statistics data over 1993–2007. *Agric. Ecosyst. Environ.* **2011**, *142*, 231–237. [CrossRef]
40. Brentrup, F.; Hoxha, A.; Christensen, B. Carbon footprint analysis of mineral fertilizer production in Europe and other world regions. In Proceedings of the 10th International Conference on Life Cycle Assessment of Food (LCA Food 2016), Dublin, Ireland, 19–21 October 2016.
41. Lal, R. Carbon emission from farm operations. *Environ. Int.* **2004**, *30*, 981–990. [CrossRef] [PubMed]
42. Guo, J.; Song, Z.; Zhu, Y.; Wei, W.; Li, S.; Yu, Y. The characteristics of yield-scaled methane emission from paddy field in recent 35-year in China: A meta-analysis. *J. Clean. Prod.* **2017**, *161*, 1044–1050. [CrossRef]
43. Narita, N.; Sagisaka, M.; Inaba, A. Life cycle inventory analysis of CO_2 emissions—Manufacturing commodity plastics in Japan. *Int. J. Life Cycle Assess.* **2002**, *7*, 277–282. [CrossRef]
44. Zhang, W.-F.; Dou, Z.-X.; He, P.; Ju, X.-T.; Powlson, D.; Chadwick, D.; Norse, D.; Lu, Y.-L.; Zhang, Y.; Wu, L.; et al. New technologies reduce greenhouse gas emissions from nitrogenous fertilizer in China. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 8375–8380. [CrossRef]
45. Samoy-Pascual, K.; Lampayan, R.M.; Remocal, A.T.; Orge, R.F.; Tokida, T.; Mizoguchi, M. Optimizing the lateral dripline spacing of drip-irrigated aerobic rice to increase water productivity and profitability under the water-limited condition. *Field Crops Res.* **2022**, *287*, 108669. [CrossRef]
46. Hou, Q.; Ni, Y.; Huang, S.; Zuo, T.; Wang, J.; Ni, W. Effects of manure substitution for chemical fertilizers on rice yield and soil labile nitrogen in paddy fields of China: A meta-analysis. *Pedosphere* **2022**, *33*, 172–184. [CrossRef]
47. Liao, R.; Wu, W.; Hu, Y.; Xu, D.; Huang, Q.; Wang, S. Micro-irrigation strategies to improve water-use efficiency of cherry trees in Northern China. *Agric. Water Manag.* **2019**, *221*, 388–396. [CrossRef]
48. Sidhu, H.S.; Jat, M.L.; Singh, Y.; Sidhu, R.K.; Gupta, N.; Singh, P.; Singh, P.; Jat, H.S.; Gerard, B. Sub-surface drip fertigation with conservation agriculture in a rice-wheat system: A breakthrough for addressing water and nitrogen use efficiency. *Agric. Water Manag.* **2019**, *216*, 273–283. [CrossRef]
49. Kazemi, H.; Kamkar, B.; Lakzaei, S.; Badsar, M.; Shahbyki, M. Energy flow analysis for rice production in different geographical regions of Iran. *Energy* **2015**, *84*, 390–396. [CrossRef]
50. Poddar, R.; Acharjee, P.U.; Bhattacharyya, K.; Patra, S.K. Effect of irrigation regime and varietal selection on the yield, water productivity, energy indices and economics of rice production in the lower Gangetic Plains of Eastern India. *Agric. Water Manag.* **2022**, *262*, 107327. [CrossRef]
51. Rahman, S.; Barmon, B.K.; Rahman, S. Energy productivity and efficiency of the 'gher' (prawn-fish-rice) farming system in Bangladesh. *Energy* **2012**, *43*, 293–300. [CrossRef]
52. Kosemani, B.S.; Bamgboye, A.I. Energy input-output analysis of rice production in Nigeria. *Energy* **2020**, *207*, 118258. [CrossRef]
53. Yang, Z.; Cheng, Q.; Liao, Q.; Fu, H.; Zhang, J.; Zhu, Y.; Lv, T.; Sun, Y.; Ma, J.; Li, N. Can reduced-input direct seeding improve resource use efficiencies and profitability of hybrid rice in China? *Sci. Total Environ.* **2022**, *833*, 155186. [CrossRef] [PubMed]
54. Abadi, B.; Sadeghfam, S.; Ehsanitabar, A.; Nadiri, A.A. Investigating socio-economic and hydrological sustainability of ancient Qanat water systems in arid regions of central Iran. *Groundw. Sustain. Dev.* **2023**, *23*, 100988. [CrossRef]

55. Faryadi, M. Soil security under salt attack: Protection of the soil against the salinization caused by drying up of Lake Urmia. *Soil Secur.* **2023**, *13*, 100113. [CrossRef]
56. Pishgar-Komleh, S.H.; Sefeedpari, P.; Rafiee, S. Energy and economic analysis of rice production under different farm levels in Guilan province of Iran. *Energy* **2011**, *36*, 5824–5831. [CrossRef]
57. Chatterjee, R. How state governance can offer a new paradigm to energy transition in Indian agriculture? *Energy Policy* **2024**, *185*, 113965. [CrossRef]
58. Chaudhary, V.P.; Gangwar, B.; Pandey, D.K.; Gangwar, K.S. Energy auditing of diversified rice-wheat cropping systems in Indo-gangetic plains. *Energy* **2009**, *34*, 1091–1096. [CrossRef]
59. Abubakar, A.; Gambo, J.; Umar, S. An Overview of the Effects of Some Agricultural Policies in Nigeria-1960–2020. *Niger. Agric. J.* **2021**, *52*, 151–162.
60. Farneselli, M.; Benincasa, P.; Tosti, G.; Simonne, E.; Guiducci, M.; Tei, F. High fertigation frequency improves nitrogen uptake and crop performance in processing tomato grown with high nitrogen and water supply. *Agric. Water Manag.* **2015**, *154*, 52–58. [CrossRef]
61. Zheng, J.; Zhou, M.; Zhu, B.; Fan, J.; Lin, H.; Ren, B.; Zhang, F. Drip fertigation sustains crop productivity while mitigating reactive nitrogen losses in Chinese agricultural systems: Evidence from a meta-analysis. *Sci. Total Environ.* **2023**, *886*, 163804. [CrossRef] [PubMed]
62. Du, X.; Hao, M.; Guo, L.; Li, S.; Hu, W.; Sheng, F.; Li, C.F. Integrated assessment of carbon footprint and economic profit from paddy fields under microbial decaying agents with diverse water regimes in central China. *Agric. Water Manag.* **2022**, *262*, 107403. [CrossRef]
63. Zhou, Y.; Liu, K.; Harrison, M.T.; Fahad, S.; Gong, S.; Zhu, B.; Liu, Z. Shifting Rice Cropping Systems Mitigates Ecological Footprints and Enhances Grain Yield in Central China. *Front. Plant Sci.* **2022**, *13*, 895402. [CrossRef]
64. Xu, Y.; Su, B.; Wang, H.; He, J.; Yang, Y. Analysis of the water balance and the nitrogen and phosphorus runoff pollution of a paddy field in situ in the Taihu Lake basin. *Paddy Water Environ.* **2020**, *18*, 385–398. [CrossRef]
65. Xu, C.; Chen, Z.; Ji, L.; Lu, J. Carbon and Nitrogen Footprints of Major Cereal Crop Production in China: A Study Based on Farm Management Surveys. *Rice Sci.* **2022**, *29*, 288–299. [CrossRef]
66. Zeng, Y.; Li, F. Impacts of Nitrogen Fertilizer Substitution on Greenhouse Gas Emission in a Paddy Field of South China Under Ridge Irrigation. *J. Soil Sci. Plant Nutr.* **2022**, *22*, 837–847. [CrossRef]
67. Zhao, Z.; Yue, Y.; Sha, Z.; Li, C.; Deng, J.; Zhang, H.; Gao, M.; Cao, L. Assessing impacts of alternative fertilizer management practices on both nitrogen loading and greenhouse gas emissions in rice cultivation. *Atmos. Environ.* **2015**, *119*, 393–401. [CrossRef]
68. Wu, B.; Mu, C.C.; Liu, H.; Xu, Y.K.; Zhang, Y.; Yang, J.S.; Xu, W.N. Quantifying soil nitrous oxide emissions in spring freezing-thawing period over different vegetation types in Northeast China. *J. Mt. Sci.* **2022**, *19*, 1919–1930. [CrossRef]
69. Song, X.; Ju, X.; Topp, C.F.E.; Rees, R.M. Oxygen Regulates Nitrous Oxide Production Directly in Agricultural Soils. *Environ. Sci. Technol.* **2019**, *53*, 12539–12547. [CrossRef] [PubMed]
70. Lyu, Y.; Zhang, X.; Yang, X.; Wu, J.; Lin, L.; Zhang, Y.; Wang, G.; Xiao, Y.; Peng, H.; Zhu, X.; et al. Performance assessment of rice production based on yield, economic output, energy consumption, and carbon emissions in Southwest China during 2004–2016. *Ecol. Indic.* **2020**, *117*, 106667. [CrossRef]
71. Huang, J.; Yu, X.; Zhang, Z.; Peng, S.; Liu, B.; Tao, X.; He, A.; Deng, N.; Zhou, Y.; Cui, K.; et al. Exploration of feasible rice-based crop rotation systems to coordinate productivity, resource use efficiency and carbon footprint in central China. *Eur. J. Agron.* **2022**, *141*, 126633. [CrossRef]
72. Liu, T.Q.; Li, S.H.; Guo, L.G.; Cao, C.G.; Li, C.F.; Zhai, Z.B.; Zhou, J.Y.; Mei, Y.M.; Ke, H.J. Advantages of nitrogen fertilizer deep placement in greenhouse gas emissions and net ecosystem economic benefits from no-tillage paddy fields. *J. Clean. Prod.* **2020**, *263*, 121322. [CrossRef]
73. Htwe, T.; Sinutok, S.; Chotikarn, P.; Amin, N.; Akhtaruzzaman, M.; Techato, K.; Hossain, T. Energy use efficiency and cost-benefits analysis of rice cultivation: A study on conventional and alternative methods in Myanmar. *Energy* **2021**, *214*, 119104. [CrossRef]
74. He, X.; Kang, H.; Gu, Y.; Song, Y. Optioning Water Rights:A Potential Alternative to the Hanjiang-Weihe River Water Transfer Project, China. *Chin. Geogr. Sci.* **2020**, *30*, 1039–1051. [CrossRef]