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Optimizing Nutrient and Energy Efficiency in a Direct-Seeded Rice Production System: A Northwestern Punjab Case Study

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Abstract: This study was carried out in Amritsar, Punjab, to find out how efficiently nutrients were used and how much energy was employed in direct-seeded rice (DSR) production. In this study, four levels of nitrogen (0, 40, 50, and 60 kg N ha^{-1}) and three levels of phosphorus (0, 37.5, and 45 kg P_2O_5 ha^{-1}) were tested. In a rice production system, the energy indices of various inputs and outputs were evaluated through the application of energy equivalency. The nutrient-use efficiencies in rice were assessed using different efficiency indices. The maximum grain yields of 38.9 q ha^{-1} and 36.9 q ha $^{-1}$ were recorded at 50 kg N ha^{-1} and 45 kg P_2O_5 ha^{-1}, respectively. On the other hand, application of nitrogen at 60 kg N ha^{-1} and phosphorus at 45 kg P_2O_5 ha^{-1} resulted in maximum straw yield of 57.1 q ha^{-1} and 51.1 q ha^{-1}, respectively. In comparison with the control, application of 60 and 50 kg N ha^{-1} resulted in 161.9% and 151.0% higher grain yield, respectively. On the other hand, with applications of 45 kg P_2O_5 ha^{-1} and 37.5 kg P_2O_5 ha^{-1}, an increase in the grain yield of 17.3 and 28.6%, respectively, over the control was recorded. Moving further towards nutrient-use efficiencies (NUEs), the highest values of partial factor productivity of nitrogen (PFP_N), agronomic efficiency of nitrogen (AE_N), partial nutrient balance of nitrogen (PNB_N), and recovery efficiency of nitrogen (RE_N) were 89.1, 50.4, 1.78 and 0.72, respectively, which were obtained at 40 kg N ha^{-1}, after which the values started decreasing steadily. In the case of phosphorus, the partial factor productivity (PFP_P) of 88.6 was the maximum at 37.5 kg P_2O_5 ha^{-1}, but partial nutrient balance (PNB_P) of 0.36 and recovery efficiency (RE_P) of 0.08 were highest at 45 kg P_2O_5 ha^{-1}. The main results revealed that the farmer field had an excessive amount of non-renewable energy inputs. The experimental field depicted greater energy-usage efficiency (EUE) of 4.5, energy productivity (EP) of 0.14, and energy profitability (EP_1) of 3.5. These results were primarily ascribed to a significant drop in energy inputs under direct-seeded rice (DSR). In the case of non-renewable energy inputs, fertilizer made the maximum contribution to energy input (47.9%) in the farmer's field. We conclude that nutrient-use efficiencies and energy-use efficiency were highest at 50 kg N and 45 kg P_2O_5 ha^{-1}. This recommendation is beneficial for farmers because lower inputs and higher outputs are the main objective of every farmer.

Keywords: direct-seeded rice; nutrient-use efficiencies; energy efficiencies; partial factorproductivity; agronomic efficiency; partial nutrient balance; recovery efficiency; energy productivity; energy profitability

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1. Introduction

The agricultural sector has a significant role in both energy production and consumption [1]. Sustainable agricultural production is dependent upon the efficient utilization of energy in agriculture [2]. The main byproducts and end products of the agricultural system provide a significant amount of nutritional energy for human and animal populations. Indirect energy is present in socioeconomic fields, farming situations, and other areas, but it can be challenging to quantify. The energy used in the manufacture of numerous agricultural components, such as machinery, seeds, chemical fertilizers, crop protection, and animal production factors, is generally included in indirect energy [3]. This study was mainly conducted to provide insights into the optimization of fertilizer, which increases the energy-use efficiency of farmers field in DSR. In particular, chemical fertilizers and oil are the main causes of the indirect use of energy. Use of fertilizer, which makes up a significant portion of the energy in farms, contributes to between 70% and 75% of the energy used in agriculture [4]. Farmers use a large amount of energy on fertilizer and other inputs. However, the first question to be answered is whether the energy is used efficiently. To achieve the highest yield possible in the rice cultivation system, farmers apply large amounts of fertilizers. When the rice plant's root system is still developing in the early growth stages, they apply N fertilizer. The plant uses only 20–50% of the applied nitrogen for metabolic processes. Nevertheless, the global average partial factor productivity N (PFP_N) of the application of roughly 40 kg grain kg^{-1} N results in low N-use efficiency [5–7]. Uncertainty in calculating the appropriate amount of fertilizer to apply to the field is one of the factors that impacts nutrient-use efficiency [8]. Fertilizer applications that include both phosphorus and nitrogen improve soil quality and crop yields in rice fields [9].

Excessive amounts of nitrogen, potassium, and phosphate from synthetic fertilizers raise the risk of terrestrial ecotoxicity in rice grown in conventional systems and reduce the nutrient-use efficiency [10]. The main purpose of this research is to maintain crop production with the minimum use of fertilizer, which improves the agronomic efficiency of rice. Agronomic efficiency (AE_N) of nitrogen increases by increasing the nutrient uptake in the above-ground part and by decreasing various N losses (leaching, denitrification, and volatilization) from the field [11]. On the other hand, the average recovery efficiency for N (RE_N) and P (RE_P) is less than 50% and 20%, respectively. Fertilizer usage for rice has increased faster than rice's yield growth. The highest energy is invested in the application of fertilizer in all cropping systems (rice wheat, rice-mustard greengram, rice-vegetable pea-wheat greengram, maize-vegetable pea wheat, pigeonpea wheat, and soybean wheat) which varied from 12,526 to 18,364 MJ ha^{-1} [12–14]. Excessive use of nutrients, such as nitrogen (N), beyond the requirements of crops, leads to environmental losses [15] and has consequently resulted in greenhouse gas emissions, which have an adverse effect on the environment. The global agricultural CH_4 and N_2O emissions from rice fields are around 30% and 11%, respectively [16]. Direct-seeded rice (DSR) is one of the methods available in this case to lower CH_4 emissions because it conserves 15–30% of water during initial cropping and emits less CH_4 (2.13 $mg/m^2/day$) than other rice varieties [17], but it can also have unintended consequences such as increasing N_2O emissions. It is very difficult to limit gas generation in rice soils because of the trade-off between N_2O and CH_4 production [18]. For many years, scientists have been trying to identify the patterns and mechanisms for controlling the emissions of CH_4 from paddy fields [19,20]. Farmers often apply huge quantities of N fertilizer because of the government's substantial urea fertilizer subsidies, but these quantities are more than what plants require [21].

Particularly in the last few decades, Punjabi farmers overuse of chemical fertilizers has resulted in a number of issues with soil health, nutrient flow, and environmental pollution. In order to increase crop output and lower crop cultivation costs, farmers should be encouraged to utilize chemical fertilizers in a balanced manner. Soil testing is crucial for replenishing the soil with necessary nutrients, which will boost crop productivity and ultimately production, and increase farmers' revenue. This is why recognizing the significance of soil testing is overdue [22]. During the past ten years, the European farming sector has increased its usage of nitrogen fertilizer by approximately 2%, with 10.2 million tonnes used in 2018. The statistics for phosphorus are less impressive, coming in at 1.1 million tonnes, and its use has dropped by about 1% over the past ten years. The main aim of this research is to measure the direct influence of fertilizer use on agricultural costs, as well as the indirect effect of fertilizer use on overall energy consumption. This experiment increases rice's efficiency in using N and P in small regions with similar climates and topographies, while also increasing our understanding of how to evaluate nutrient management. Farmers may address the worldwide difficulties of increasing rice yield while decreasing energy inputs by carrying out the suggestions presented in this research [23].

2. Materials and Methods

2.1. Survey Detail

A survey of 30 farmers was carried out in the Amritsar district in 2020. The input and output data were obtained from the farmer through an administered questionnaire. The average land area was 5 ha^{-1}, and the land had a loamy sand soil texture. Farmers were regularly addressed by agriculture officers and extension agents, who verified and validated the data. All farming operations in this area are being closely observed by them. Selected farmers had ten years of experience of farming with one hectare of land.

2.2. Experimental Location

In the *kharif* season of 2021, a field experiment was carried out at Khalsa College in Amritsar. The experiment site was located at 31.63° N latitude and 74.87° E longitude, representing the Indo-Gangetic alluvial plains, in the Trans-Gangetic Agro-Climatic zone. The soil was loamy sand, moderaltely saline in nature, low in organic carbon, available nitrogen and available phosphorus; and high in available potassium (Table 1). The elevation above mean sea level was 234 m. The rice cultivar '*Pusa Basmati 1718*' was sown in the last week of June in 2021. The twelve fertilizer treatments included were N_0 (control), N_{40} (40 kg N ha^{-1}), N_{50} (50 kg N ha^{-1}), and N_{60} (60 kg N ha^{-1}), and P_0 (control), $P_{37.5}$ (37.5 kg P_2O_5 ha^{-1}), and P_{45} (45 kg P_2O_5 ha^{-1}), with four replications. Phosphorus was applied through DAP as a basal dose and nitrogen through urea at 3, 6, and 9 weeks after sowing. The plot size was 7.0 m × 5.50 m. The crop was manually harvested during the first week of November. The data on yield attributes and grain yield were recorded at crop harvest.

Table 1. Physical and Chemical properties of experimental field.

Soil Characteristic	Soil Depth (0–15 cm)
Textural Class	Loamy sand
pH	8.85
Electrical conductivity (dS m^{-1}) at 25 °C	0.42
Organic carbon	0.56%
Available nitrogen (kg ha^{-1})	199
Available phosphorus (kg ha^{-1})	18
Available potassium (kg ha^{-1})	305

2.3. Nutrient-Use Efficiencies

Partial factor productivity (PFP) [11], physiological efficiency (PE) [24], agronomic efficiency (AE) [25], internal recovery efficiency (IE) [26], and partial nutrient balance (PNB) [27] of added N and P fertilizer were calculated:

$$\mathrm{PFP}\left(\frac{\mathrm{kg}}{\mathrm{ha}}\right) = \frac{\text{Grainyield}}{\text{quantity of nutrient applied inplots}} \tag{1}$$

$$\text{AE kg grain/kg N or P applied} = \frac{(\text{grain yield in N fertilized plot} - \text{grain yield in no N plot})}{(\text{quanitity of N fertilizer applied in N fertilized plot})} \tag{2}$$

$$\mathrm{PE}(\mathrm{kg}\frac{\text{grain}}{\mathrm{kg}}\text{N or P uptake}) = \frac{(\text{grain yield in N fertilized plot} - \text{grain yield in no N plot})}{(\text{total N uptake in N fertilized plot} - \text{total N uptake in no N plot})} \tag{3}$$

$$\text{RE}(\%) = \frac{\text{Grainyield}}{\text{total nutrient uptake in above ground cropbiomass with nutrient applied}} \quad (4)$$

$$\text{PNB kg}\frac{\text{grain}}{\text{kg}}\text{N or P} = \frac{\text{nutrient content of harvested portion of the crop}}{\text{amount of nutrient applied}} \quad (5)$$

2.4. Energy Analysis

For the various input data, energy consumption was calculated using the energy equivalent coefficients of various energy sources, as mentioed in Table 2. Labor, machinery, diesel, fertilizers, seeds, and pesticides were used as inputs. The production was measured in terms of grain yield and straw yield. To determine various energy indices, like Net energy [28], Energy profitability [28], Energy use efficeincy [29], Energy productivity [30], and Specific energy [31]; following formulae were used:

$$\text{Net energy} = \text{Output energy} - \text{Input energy} \quad (6)$$

$$\text{Energy profitability} = \frac{\text{Net energy}\left(\frac{\text{MJ}}{\text{ha}}\right)}{\text{Input energy}\left(\frac{\text{MJ}}{\text{ha}}\right)} \quad (7)$$

$$\text{Energy-use efficiency} = \frac{\text{Output energy}\left(\frac{\text{MJ}}{\text{ha}}\right)}{\text{Input energy}\left(\frac{\text{MJ}}{\text{ha}}\right)} \quad (8)$$

$$\text{Energy productivity} = \frac{\text{Grain yield}\left(\frac{\text{kg}}{\text{ha}}\right)}{\text{Input energy}\left(\frac{\text{MJ}}{\text{ha}}\right)} \quad (9)$$

$$\text{Specific energy} = \frac{\text{Input energy}\left(\frac{\text{MJ}}{\text{ha}}\right)}{\text{Grain yield}\left(\frac{\text{kg}}{\text{ha}}\right)} \quad (10)$$

Table 2. Energy equivalent coefficient of various energy sources used in DSR production system.

Component (Es)	Unit	Energy Equivalent Coefficient (MJ Unit^{-1})	Source
Rice seed	kg	14.7	[32]
Man (h)	Man-h	1.96	[33]
Tractor	Tractor-h	62.7	[33]
Nitrogen	kg	60.6	[11]
Phosphorus	kg	11.1	[34]
Zinc Sulfate	kg	20.9	[35]
Ferrous Sulfate	kg	151.8	[36]
Herbicide	kg	120	[37]
Fuel	L	56.31	[33]
Irrigation	ha^{-1} cm	1.02	[38]

2.5. Statistical Analysis

There were two approaches used in the data analysis: descriptive and qualitative. The descriptive data were analyzed through Microsoft Excel (2010) and the qualitative data were analyzed through SAS Institute Inc., Cary, NC, USA, using JMP 12.0. An analysis of variance (ANOVA) was used to compare the different energy indicators among the experimental field and the farmer field. A post hoc analysis (using the *t*-test) was then conducted. Quantile plots were used to verify the normality of the data before mean comparison using ANOVA. A 5% level of significance was used for the statistical analysis.

3. Results and Discussion

3.1. Effect of Nitrogen and Phosphorus on Yield Attributes

The different levels of fertilizer showed a remarkable effect on grain yield attributes (Table 3, Figure 1). The highest grain yield i.e., 38.9 q ha^{-1} was recorded at 50 kg N ha^{-1}, which was statistically at par with 60 kg N ha^{-1}. The increase in grain yield might be due to the optimum absorption of N and P fertilizer. On the other hand, other nutrients increase the source–sink relationship in plants [39,40]. The lowest grain yield was observed in the unfertilized treatment. There was a significant increase of 9.3 percent in grain yield with the application of 50 kg N ha^{-1} compared to 40 kg N ha^{-1}. The highest straw yield was observed at 60 kg N ha^{-1}, i.e., 57.1 q ha^{-1}, which significantly differed from results of 50 kg N ha^{-1} (53.8 q ha^{-1}), 40 kg N ha^{-1} (50 q ha^{-1}), and the control (33 q ha^{-1}). This might be due to the continued application of N fertilizer, which increases the greenness in the plant and increases the photosynthetic rate in the plant, resulting in greater dry matter accumulation because photosynthates translocate from the source to the sink.

Table 3. Effect of nitrogen and phosphorus on grain yield and straw yield (q ha^{-1}).

Treatments	**Grain Yield (q ha^{-1})**	**Straw Yield (q ha^{-1})**
Nitrogen treatments (kg ha^{-1})		
N_0	15.5 ^{c}	33.0 ^{c}
N_{40}	35.6 ^{b}	50.0 ^{b}
N_{50}	38.9 ^{a}	53.8 ^{ab}
N_{60}	40.6 ^{a}	57.1 ^{a}
SE (m)±	5.81	5.35
Phosphorus treatments (kg ha^{-1})		
P_0	28.3 ^{c}	46.4 ^{b}
$P_{37.5}$	33.2 ^{b}	47.9 ^{b}
P_{45}	36.4 ^{a}	51.1 ^{a}
SE (m)±	2.35	1.38

Data with different letters in the same column are significantly different at LSR 0.05 using Duncan's multiple range test (DMRT).

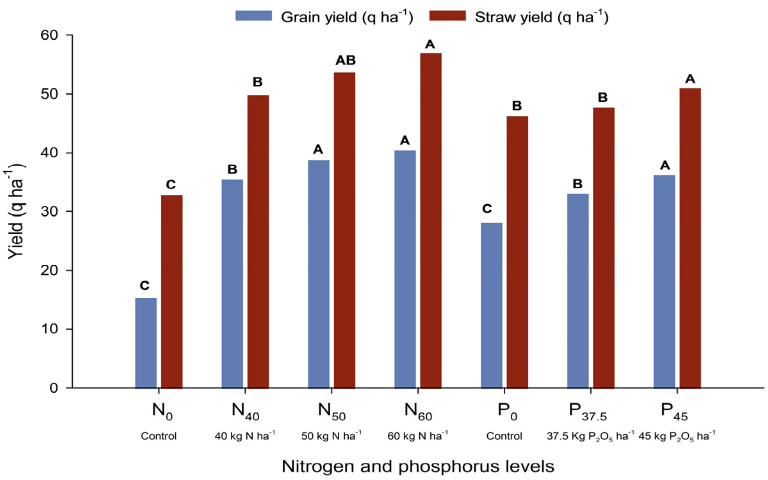

Figure 1. Effect of nitrogen and phosphorus on grain and straw yield. A—Maximum value; AB—Statistically at par; B and C—Significantly differ.

Moving further, higher grain yield (36.4 q ha^{-1}) and straw yield (51.1 q ha^{-1}) were observed when the crop was fertilized with 45 kg P_2O_5 ha^{-1} of customized fertilizer (CF), which was significantly different from the treatment of 37.5 kg P_2O_5 ha^{-1} and the control. According to Panhawar et al. (2011), applying phosphorus fertilizer has been found to enhance upland rice productivity [40]. The lower grain yield and straw yield were observed in an unfertilized plot. The grain yield increased significantly by 8.7% and 22.2% with the application of 45 kg P_2O_5 ha^{-1} and 37.5 kg P_2O_5 ha^{-1}, respectively, over the control. On the other hand, there was significant increase in straw yield at 45 kg P_2O_5 ha^{-1}, which was 6.2% and 9.1% higher than that at 37.5 kg P_2O_5 ha^{-1} and the control, respectively.

3.2. Nutrient-Use Efficiencies

One of the most important issues in agriculture is fertilizer optimization, i.e., increasing input-use efficiency without compromising economic yield. Several N-usage efficiency metrics were used to evaluate the level of crop utilization of applied N. Nutrient use effiecincies are calaculated for different levels of nitrogen and phosphorus describe in Table 4. The three N-usage efficiency indices that are frequently employed in agronomy research—agronomy efficiency, recovery efficiency, and partial factor productivity—were reviewed by Dobermann (2007) [41].

Table 4. Nutrient-use efficiencies of different treatments.

Treatments	PFP_N	PFP_P	AE_N	PNB_N	PNB_P	RE_N	RE_P
N_0	0	39.9 ^{c}	0	0	0.17 ^{c}	0	0.08 ^{a}
N_{40}	89.1 ^{a}	93.5 ^{b}	50.4 ^{a}	1.78 ^{a}	0.39 ^{b}	0.72 ^{a}	0.07 ^{a}
N_{50}	77.8 ^{b}	100.7 ^{ab}	46.8 ^{ab}	1.56 ^{b}	0.44 ^{a}	0.69 ^{a}	0.06 ^{a}
N_{60}	67.7 ^{c}	104.6 ^{a}	41.9 ^{b}	1.20 ^{c}	0.45 ^{a}	0.65 ^{a}	0.03 ^{a}
SE (m)±	20.3	15.1	11.7	0.39	0.06	0.17	0.01
P_0	67.6 ^{c}	0	39.9 ^{b}	1.26 ^{c}	0	0.64 ^{b}	0
$P_{37.5}$	79.9 ^{b}	88.6 ^{a}	49.1 ^{a}	1.52 ^{b}	0.36 ^{a}	0.70 ^{ab}	0.05 ^{b}
P_{45}	87.1 ^{a}	80.9 ^{b}	50.1 ^{a}	1.76 ^{a}	0.36 ^{a}	0.73 ^{a}	0.08 ^{a}
SE (m)±	5.69	28.3	3.24	0.14	0.12	0.02	0.02

PEP—partial factor productivity; AE—agronomic efficiency; PNB—partial nutrient balance; RE—recovery fertilizer. Data with different letters in the same column are significantly different at LSR 0.05 using Duncan's multiple range test (DMRT).

A measure of production efficiency calculated in terms of crop output per unit of applied nutrient is called partial factor productivity, or PFP. It shows how productive a rice cropping system is in relation to the amount of nutrients it absorbs. PFP_N was high with 40 kg N ha^{-1} (89.1 kg ha^{-1}) applied, but PFP_P was highest at 45 kg P_2O_5 ha^{-1}. A decrease in native soil N supply, nutrient imbalances, subsurface compaction, a reduction in root volume, and a rise in insect and disease incidence can all be reasons for the partial productivity decline for N (Karim and Ramsamy, 2000) [42]. In the case of phosphorus, the highest PFP_P was observed at 45 kg P_2O_5 ha^{-1} but PFP_N was highest at 60 kg N ha^{-1}. A similar result was found by Basavarajappa et al., 2021, who concluded that PFP for phosphorus decreased progressively as CF levels increased [21]. According to the previous research result, they concluded that N absorption showed a positive impact with P fertilizer application [43].

Nitrogen application levels caused the AE_N to range from 50.4 kg grain yield per kg of N at 40 kg ha^{-1} to 41.9 kg grain yield per kg of N at 60 kg ha^{-1}. According to Saleque et al., the most severe adverse events were noted at low doses of N application [44]. The average annual grain yield (AEG) ranged between 39.9 kg/ha^{-1} of P_2O_5 applied to the control and 50.1 kg/ha^{-1} of P_2O_5 applied at 45 kg ha^{-1} of P_2O_5. When nitrogen is present, plants are able to absorb more phosphorus. The next step was to determine the nitrogen uptake in the plant's above-ground portions from fertilized and unfertilized plots using RE_N. Compared to other amounts of fertilizer treatment, the results showed that RE_N was greatest at 40 kg N ha^{-1}. Afterwards, the RE_N in rice decreased as the dose of N increased. From 37.5 kg P_2O_5 ha^{-1} to 45 kg P_2O_5 ha^{-1}, RE_P ranged from 0.05 percent to 0.08 percent. Due to low phosphorus fertilizer efficiency and the law of diminishing returns, the agronomic efficiency and recovery efficiency of phosphorus cannot rise with increases in the dose of fertilizer applied, leading to lower partial factor production [45].

Increasing the nutrition level starts the deterioration in the partial nitrogen balance. From 40 to 60 kg ha^{-1} of nitrogen, PNB_N ranged from 1.78 to 1.20 kg grain yield per kg of nitrogen applied, but PNB_P was constant between 37.5 and 45 kg P_2O_5 ha^{-1}, or 0.36 (Table 4).

3.3. Energy Balance Comparison between Farmers' Fields and Experimental Field

The demand for energy in agriculture increases continuously in order to feed the world's growing population [35,46]. The energy inputs comprised rice seed, man, tractor, nitrogen, phosphorus, zinc sulfate, ferrous sulfate, herbicide, fuel, and irrigation. The predicted energy inputs and outputs for experimental and farmers' fields are depicted in Table 5. The amount of rice seed used in the farmers' and experimental fields was same. In both the farmers' and experimental fields, mechanization accounted for a sizeable portion of the input, contributing 6.13% (experimental field) and 3.41% (farmers' fields) to total input energy. For farmers' fields, the use of human labor was significantly higher than that in the experimental field, contributing 1.44% of the total energy input, while the experimental field shares 2.5% of the total input energy. Fertilizer (24%) was the highest contributor among the energy input sources in rainfed rice [47]. The use of chemical fertilizer also increased the energy inputs [48]. The utilization of chemical fertilizers was found to be highest in the farmers' fields. The nitrogen fertilizer accounted for 8.2% and 47.9% of energy input in the experimental and farmers' fields, respectively. The consumption of phosphorus in the experimental field was 1.1% of the total energy input. On the other hand, the consumption of phosphorus in farmers' fields was 0.3% of the total energy input. The use of zinc sulfate, ferrous sulfate, and herbicide was found to be higher in the farmers' fields.

Table 5. Energy consumption pattern of experimental and farmers' fields.

Input (Unit)	Experimental Field		Farmer Field	
	Quantity per Unit Area (ha^{-1})	Total Energy Equivalent (MJ ha^{-1})	Quantity per Unit Area (ha^{-1})	Total Energy Equivalent (MJ ha^{-1})
Input				
Rice seed	20	294	20	294
Man (h)	365	715.4	365.1	715.5
Tractor (h)	27	1695.6	27	1695.6
Nitrogen	37.5	2272.5	393.1	23,821.8
Phosphorus	27.5	305.25	13.55	149.8
Zinc sulfate	40	836	52.5	1097.2
Ferrous sulfate	2.37	349.1	2.5	379.5
Herbicide	2.87	344.4	5.127	612
Fuel	30	1689	31	1745.3
Irrigation (m^3)	18,750	19,125	18,767.7	19,143.05
Total energy input (MJ/ha)		27,626.5		49,654

This finding shows that weed growth was comparatively higher under the conditions of the farmers' fields than those of the experimental field because farmers were intensively using herbicide to manage weeds in the DSR production system. The use of zinc sulfate and ferrous sulfate accounted for 2.2% and 0.7% of total energy input in the farmers field, which was higher than that in the experimental field. The farmers' fields used a higher amount of diesel for the land preparation than the experimental field, which was 3.5% higher than the total energy input. The higher amount of irrigation as water energy in the farmers' fields was the result of the maintenance of the hard-pan due to rainfall. In farmers' fields, irrigation water energy accounted for around 38.5% of the overall energy, but in the experimental field it was 69.2% of the total input energy. According to Bautista and Miniwa's (2010) analysis of the energy balance for various rice production systems in the Philippines, the energy output–input ratios for systems with canals and pump facilities were 9.0 and 7.5, respectively [49].

The energy input and output were 29,020 and 131,238 MJ ha^{-1} for the experimental field and 49,587 and 123,487 MJ ha^{-1} for the farmers' fields, respectively (Table 6). Bockari-Gevao et al. concluded that chemical fertilizer is a major contributor to energy input, i.e., 12,400 MJ ha^{-1} in rice crops [50]. According to the study, irrigation and fertilizer show the maximum energy percentage in rice production. The EUE was 4.5 in the experimental field and 2.4 in the farmers' fields. This indicates that a maximum amount of input energy is required to produce the output energy in the farmers' fields, or that they used the maximum input resource. On the other hand, the experimental field used efficient input resources, while the highest energy inputs were due to maximum fertilizer application in the farmers' fields. From a review of the literature, Ghosh et al. (2021) concluded that the EUE increased by 0.95–1.6% in rice [51].

Table 6. Energy indices in rice production system.

Items	Units	Experimental Field	Farmers Data
Energy input	J ha^{-1}	29,020	49,587
Energy output	MJ ha^{-1}	131,238	123,487
Net energy	MJ ha^{-1}	102,218	73,900
Energy profitability	-	3.52	1.5
Energy-use efficiency	-	4.52	2.5
Energy productivity	kg MJ^{-1}	0.14	0.1
Direct energy	MJ ha^{-1}	2404.4 (8.7%)	2460.8 (4.9%)
Indirect energy Direct + Indirect energy	MJ ha^{-1}	25,221 (91.2%)	47,192 (95%)
Renewable energy	MJ ha^{-1}	715.4 (2.5%)	715.5 (1.4%)
Non-renewable energy Renewable + Non-renewable energy	MJ ha^{-1}	26,910.8 (97.4%)	48,938.2 (98.5%)

The highest EP1 and EP were recorded in the experimental field rather than the farmers' fields. The lower energy productivity in farmers' fields was due to the maximum use of fertilizer. On the other hand, EP1 was also a maximum in the experimental field (3.5) rather than the farmer field (3.4). The EUE, EP, and EP1 were highest in the experimental field, which led to a larger decrease in energy inputs (i.e., fertilizers, human labor, and irrigation). On the other hand, greater output energy is responsible for the higher mean net energy in the experimental field (102,218 MJ ha^{-1}), and this increase is proportional to the increase in energy output. According to a report from Iran's Gulian Province, 36,928 MJ ha^{-1} of net energy was produced from paddy production [52]. The share of renewable and non-renewable energy was 2.5% and 97.4% in the experimental field, respectively (Figure 2). The external inputs (fertilizer and zinc sulfate) increased the non-renewable energy sources in the farmers' fields. Consistent with previous results, it was indicated that about 25–30% of energy was used for crop establishment and field preparation [53].

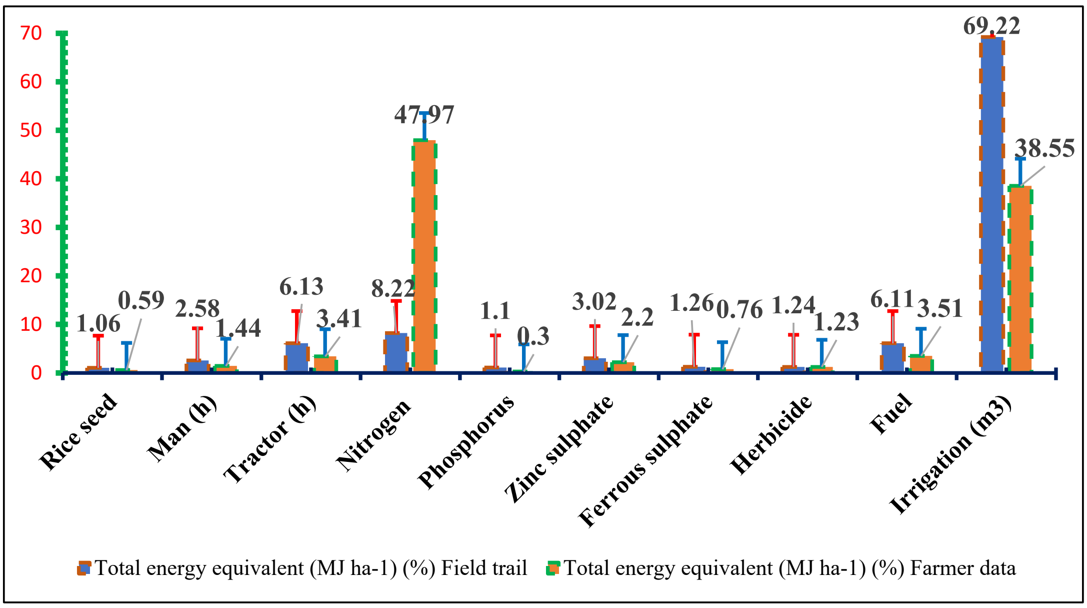

Figure 2. Different agricultural inputs' energy shares (%) in the experimental field and the farmers' fields.

3.4. Comparison of Energy Indicators between Treatments

The predominant energy input source and management technique used in each of the rice activities is based on fertilizer, as shown in Table 7. The results showed that fertilizer use was the greatest input energy in the system. Consistent with several research conclusions, it is clear that fertilizer application increases crop growth and development in this region, while decreasing resource use efficiency and showing a negative effect on the environment. Thus, it is necessary to reduce energy input in the form of fertilizer application to prevent environmental degradation. Nitrogen was the largest contributor of the fertilizer input, followed by phosphorus [48].

Table 7. Comparison of energy indicators between treatments.

Treatments	Total Energy Input	Energy Output	Net Energy	Energy Profitability	Energy-Use Efficiency	Energy Productivity (kg/MJ)
Nitrogen level (kg/ha)						
N_0	25,384	64,035 ^{d}	38,651 ^{c}	1.521 ^{c}	2.521 ^{c}	0.061 ^{c}
N_{40}	27,808	114,930 ^{c}	87,122 ^{b}	3.130 ^{b}	4.130 ^{b}	0.128 ^{b}
N_{50}	28,414	124,499 ^{b}	96,085 ^{ab}	3.380 ^{ab}	4.380 ^{ab}	0.137 ^{ab}
N_{60}	29,020	131,238 ^{a}	10,2218 ^{a}	3.521 ^{a}	4.521 ^{a}	0.140 ^{a}
SE (m)±	796.8	15,251.6	14,458.7	0.46	0.46	0.01
Phosphorus level (kg/ha)						
P_0	27,351	99,758 ^{c}	72,407 ^{c}	2.607 ^{c}	3.607 ^{c}	0.102 ^{c}
$P_{37.5}$	27,768	108,799 ^{b}	81,032 ^{b}	2.878 ^{b}	3.878 ^{b}	0.118 ^{b}
P_{45}	27,851	117,469 ^{a}	89,618 ^{a}	3.179 ^{a}	4.179 ^{a}	0.129 ^{a}
SE (m)±	154.7	5113	4968.3	0.16	0.16	0.007

Data with different letters in the same column are significantly different at LSR 0.05 using Duncan's multiple range test (DMRT).

These findings reflect the viewpoint of the farmers, who have no concerns about the impact of fertilizer use on the environment and believe that yield correlates precisely to the quantity of fertilizer used. The magnitude of energy input ranged from 25,384 MJ ha^{-1} to 29,020 MJ ha^{-1}.The highest total energy input i.e., 29,020 MJ ha^{-1}, was reported from 60 kg N ha^{-1}. Rice consumes more indirect energy, of which 25% is attributed to N fertilizer only [54]. Moving further, when we used phosphorus fertilizer as a form of indirect energy, the maximum input was observed at P_{45}. i.e., 27,851 MJ ha^{-1}, which was 1.7% higher than the control. Despite the fact that the DSR system is the main subject of this study, more fertilizer is used, which results in higher input energy consumption. Findings from previous studies' findings demonstrated that, in the production of rice, direct energy used in various rice growing techniques ranged from 57 to 63%, while indirect energy accounted for 37 to 43% of total energy consumed.

The average crop biomass production, which includes grains and straw for the yield of paddy rice, is responsible for the system's energy output. Table 4 displays the energy output from the production of crop biomass. In the rice system, the lowest energy was measured for the control, while the highest production energy (131,238 MJ ha^{-1}) was obtained at 60 kg N ha^{-1}. The various types of yield are responsible for the highest production energy when there are variations in fertilizer levels. In some ways, the increased rice yield made up for the system's lower energy output [55]. In the case of phosphorus, the highest output was observed at 45 kg P_2O_5 ha^{-1} (27,851 MJ ha^{-1}), which was significantly different from others.

The current study evaluated Four energy indicators: EP_1, EUE, EP and NE. The results showed that the cropping system had a significant difference in each of the energy indicators. An indicator of how much energy is effectively used in various agricultural operations is called energy-use efficiency. The EUE was maximum at 50 kg N ha^{-1}, but equal to that at 60 kg N ha^{-1}, which means 50 kg N ha^{-1} is efficient for farmers from an economical point of view. A similar result was found by Venkatesh et al., 2017, who concluded that energy-use efficiency of rice is 4.9 [54]. In phosphorus, the highest EUE was recorded at 45 kg P_2O_5 ha^{-1}, which differed significantly from that of other treatments. The main products were considered to be grains with straw as a byproduct. While moving towards EP_1, the maximum value (3.52) was recorded at 60 kg N ha^{-1}, and was equivalent to that at 50 kg N ha^{-1} but was significantly different from that of others. In phosphorus, a similar trend was followed by EP_1, which was followed by EUE. The environmental impacts of agricultural production can be assessed with the EP indices. Maximum EP (0.140 kg MJ ha^{-1}) was observed at 60 kg N ha^{-1}, and was comparable with that at 50 kg N ha^{-1} but differed from that of others. This indicates that 0.14 kg of output was produced for each unit of energy. A similar result was provided by Troung et al. (2017), who found from their research on EP that, for every MJ of energy used, 0.15–0.16 kg of rice is produced using the traditional approach [56].

4. Conclusions

The study depicted the nutrient-use efficiency and energy consumption of direct-sown rice in experimental and farmers' fields. The study focused on the diverse use of nitrogen fertilizer in DSR production. The mean input and output energies observed for the experimental field were 29,020 and 131,238 MJ ha^{-1}, and for the farmers' fields they were 49,587 and 123,487 MJ ha^{-1}. The non-renewable energy consumption was maximized for the farmers' fields (98.5%) rather than the experimental field (97.4%). The average EUE recorded was 2.5 for the farmer field and 4.5 for the experimental field. The higher EUE and EP in the experimental field were due to the use of lower energy inputs (i.e., fertilizer, irrigation, and human labor). The nutrient-use efficiency, partial factor productivity, agronomic efficiency, recovery efficiency, and partial nutrient balance of nitrogen were highest at 40 kg N ha^{-1}. On the other hand, the partial factor productivity and partial nutrient balance of phosphorus were highest at 37.5 kg P_2O_5 ha^{-1}, while recovery efficiency reached a maximum at 45 kg P_2O_5 ha^{-1}.

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