Partial Substitution of Mineral fertilizers with organic fertilizers to Increase Yield and Profitability of Irrigated Lowland Rice Cultivation

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Abstract

Uganda has the world's lowest fertilizer use rate at just 1-1.5 kg per hectare. This limited use is a key factor hindering rice productivity in the country. Farmers can use affordable organic fertilizers to partially replace expensive mineral fertilizers, increasing the profitability of rice cultivation. This study focused on identifying the optimal combinations and application rates of inorganic fertilizers and organic inputs to enhance the yield and profitability of irrigated rice, particularly by varying nitrogen levels, the most limiting nutrient. Using a combination of organic and inorganic fertilizers improved paddy yields by enhancing nitrogen efficiency and increasing profitability, as demonstrated by the cost-benefit ratio. In contrast, mineral fertilizers produced the lowest yields and profits. The optimal fertilizer option identified was a combination of mineral and organic fertilizers, using a low nitrogen rate of 30 kg/ha. This approach yielded the highest cost-benefit ratio of 4.7, resulting in a net benefit of UGX 11.4 million per hectare. The second-best option was the organic fertilizers providing 90 kg N/ha, which achieved a cost-benefit ratio of 4.3 and a net benefit of UGX 9.7 million per hectare.

Introduction

Limited use of fertilizers is often cited as one of the important constraints limiting productivity of rice in Uganda, as in other Sub-Saharan countries [1, 2]. Although fertilizers can increase yields, many farmers either do not use them at all or use only the small quantities they can afford due to financial constraints and prohibitive costs of purchasing [3, 4]. Farmers in Uganda use only 1-1.5 kg of fertilizer per hectare, making Uganda the lowest in fertilizer use in the world [5]. This rate is below the Sub-Saharan Africa average of 8 kilograms per hectare. Additionally, some farmers lack the knowledge of how to use fertilizers effectively. Inappropriate application of fertilizers can become an inefficient and unprofitable practice [6]. Other farmers may have abandoned the use of fertilizers because it made no economic sense in terms of return on investment. The most commonly cited reason (50%) by farmers for not using inorganic fertilizers is that they are too expensive. Other reasons for not using inorganic fertilizers include a lack of knowledge about them (25%), limited access (14.1%), and a perception that inorganic fertilizers are ineffective (9.5%). Similar trends are seen in the non-use of organic fertilizers, where a lack of knowledge about on-farm compost preparation and the high cost of purchasing compost manure, primarily from urban areas, are significant factors [7]. A recent study on irrigated rice in Eastern Uganda showed that when farmers followed the recommended agronomic practices (RAP), even without the use of fertilizers, they were able to significantly boost their yields and income and reduced the yield gap [8]. The study observed that while adding inorganic NPK fertilizer along with recommended farming practices resulted in yield gains, it was not profitable for rice farmers. This was primarily due to the high cost of local mineral fertilizers and the low prices that farmers received for their paddy. This suggests that to achieve increased rice production through fertilization at current market prices, the government must subsidize fertilizers to boost usage [9, 10]. Enhancing access to output markets can contribute to raising the profitability of fertilizer use by improving the prices received by farmers for their crops [6]. This can be pursued through deliberate interventions aimed at increasing the competitiveness of the farmer's output [11]. Strategies may include maximizing farm productivity (total factor productivity), minimizing production and marketing costs, and improving the quality of paddy and milled rice [12], in addition to enforcing quality standards and grades, as well as implementing branding initiatives. In Uganda, the adoption of improved modern rice varieties, which have higher yield potential compared to traditional varieties, has been slow [13]. These modern varieties also demonstrate a better response to fertilizer application. However, many farmers continue to cultivate traditional landraces that yield less and show limited responsiveness to inputs, which can result in reduced fertilizer use. Combining fertilizer application with unimproved rice cultivars leads to a negative return on investment [14].

The national fertilizer policy of Uganda aims to have a fertilizer industry that provides farmers with affordable and accessible fertilizers to increase and sustain agricultural productivity and improve agricultural incomes. The strategies for implementing the National Fertilizer Policy include 1) strengthening the capacity of farmers to use fertilizers in a safe, profitable, and sustainable way; and 2) developing and sharing knowledge and information on fertilizer use and soil fertility management with extension staff and farmers [5].

Organic fertilizers present an affordable and effective alternative to more costly mineral fertilizers [15, 16]. Partial substitution of mineral fertilizers with organic fertilizers can indeed help reduce overall fertilizer costs by maximizing nutrient use efficiency [17, 18] and potentially lowering the amount of mineral fertilizer needed. Research indicates that adjusting the rates of organic fertilizers in combination with inorganic fertilizers can enhance soil properties, improve water use efficiency, and increase the availability and utilization of soil nutrients [19, 20]. This practice has the potential to result in higher crop yields and economic benefits when compared to the exclusive use of chemical fertilizers. While organic fertilizers can be more cost-effective in the long run due to their slow-release nature and ability to improve soil health, they may not always provide the immediate, concentrated nutrient boost that some crops require. Integrating both types of fertilizers can optimize nutrient availability, potentially leading to higher yields and reduced reliance on costly mineral inputs.

The objective of this study was to determine the optimal combination and application rates of inorganic fertilizers and organic inputs to enhance the yield and profitability of irrigated rice. Recognizing that Nitrogen (N) is the most limiting nutrient for rice production in the area, the study specifically focused on varying nitrogen levels of 30 kg/ha, 60 kg/ha, and 90 kg/ha. The treatments included the application of inorganic fertilizers, organic fertilizers, a combination of both, and a control group that did not receive any fertilizer (see treatment details in tables 1 and 2). This study aimed to 1) quantify the increase in paddy yield associated with varying nitrogen (N) levels, 2) compare the effects of organic manure applications versus mineral fertilizers, as well as their combinations, on paddy yield, and 3) analyze the profitability of each type of fertilizer and their combinations. [5]. This rate is below the Sub-Saharan Africa average of 8 kilograms per hectare. Additionally, some farmers lack the knowledge of how to use fertilizers effectively. Inappropriate application of fertilizers can become an inefficient and unprofitable practice [6]. Other farmers may have abandoned the use of fertilizers because it made no economic sense in terms of return on investment. The most commonly cited reason (50%) by farmers for not using inorganic fertilizers is that they are too expensive. Other reasons for not using inorganic fertilizers include a lack of knowledge about them (25%), limited access (14.1%), and a perception that inorganic fertilizers are ineffective (9.5%). Similar trends are seen in the non-use of organic fertilizers, where a lack of knowledge about on-farm compost preparation and the high cost of purchasing compost manure, primarily from urban areas, are significant factors [7]. A recent study on irrigated rice in Eastern Uganda showed that when farmers followed the recommended agronomic practices (RAP), even without the use of fertilizers, they were able to significantly boost their yields and income and reduced the yield gap [21]. The study observed that while adding inorganic NPK fertilizer along with recommended farming practices resulted in yield gains, it was not profitable for rice farmers. This was primarily due to the high cost of local mineral fertilizers and the low prices that farmers received for their paddy. This suggests that to achieve increased rice production through fertilization at current market prices, the government must subsidize fertilizers to boost usage [9, 10]. Enhancing access to output markets can contribute to raising the profitability of fertilizer use by improving the prices received by farmers for their crops [6]. This can be pursued through deliberate interventions aimed at increasing the competitiveness of the farmer's output (Twine et al., 2023b). Strategies may include maximizing farm productivity (total factor productivity), minimizing production and marketing costs, and improving the quality of paddy and milled rice [12], in addition to enforcing quality standards and grades, as well as implementing branding initiatives. In Uganda, the adoption of improved modern rice varieties, which have higher yield potential compared to traditional varieties, has been slow [22]. These modern varieties also demonstrate a better response to fertilizer application. However, many farmers continue to cultivate traditional landraces that yield less and show limited responsiveness to inputs, which can result in reduced fertilizer use. Combining fertilizer application with unimproved rice cultivars leads to a negative return on investment [14].

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Methodology

Experimental Location

The experiment was conducted at the Doho Rice Irrigation Scheme in Butaleja District, east of Uganda. It is the largest public irrigation scheme for rice in Uganda [23] situated at 34.02 degrees E and 0.56 degrees N, 1100 m above sea level. Doho gets its irrigation water from the Manafwa River, a natural fresh water river originating from Mount Elgon. The soils of the Doha region are silky clay loam soils with an average PH (H_2O) of 6.8, C.E.C. of 32.4 meq per 100g, organic carbon content of 4.4, and total nitrogen content of 0.08% [24]. The area has an annual average rainfall of 1186 mm, spread bi-modally over two rainy seasons, from March to May and from August to October. The average annual temperature is 22.7 degrees Celsius, with an average daily temperature range of 15.4 degrees Celsius to 30.7 degrees Celsius [25].

Experimental Design

The experiment was conducted using a two-factor Randomized Complete Block (RCB) design. This design included ten fertilizer treatments as the main plot factor and four rice varieties as the subplot factor, with each treatment replicated three times. All fertilizer treatments were randomized within each replicate, while the rice varieties were not randomized. Each main treatment plot was assigned an area of 25 m² (5 × 5 m) and was surrounded by a 0.5 m bunded buffer zone (without rice) to prevent the lateral movement of dissolved fertilizers between plots. In each main treatment plot, four rice varieties—NARORICE-1, UKAFACI-39, WITA-9, and a popular farmers' variety, K-98 —were grown, each having five rows planted continuously with no separation between varieties. Three seedlings of each rice variety were transplanted per hill at a spacing of 30 cm between rows and 15 cm between hills in a row. The seedlings were grown in a wet bed nursery for three weeks before transplanting.

The fertilizer treatments consisted of four different N rates: control with 0 kg N per hectare, 30 kg N per hectare, 60 kg N per hectare, and 90 kg N per hectare, and three fertilizers: mineral fertilizer, organic fertilizer, and a combination of mineral and organic fertilizers. Composted cow manure was used as an organic fertilizer. A detailed treatment description is provided in Table 1.

Table 1. Details of application rates of fertilizer for the various experimental treatments

Treatment Code	Treatment Description	Simple Description
Control	without fertilization	No application of fertilizer
M1	100% Mineral fertilizer, N:P:K rate (30:14.4:20) kg/ha	Only mineral fertilizer applied at low N level (30 kg/ha)
M2	100% Mineral fertilizer, N:P:K rate (60:19.2:26.6) kg/ha	Only mineral fertilizer applied at medium N level (60 kg/ha)
M3	100% Mineral fertilizer, N:P:K rate (90:24:33.3) kg/ha	Only mineral fertilizer applied at high N level (90 kg/ha)
O1	100% Organic fertilizer, N:P:K rate (30:8.7:45.6) kg/ha	Only organic fertilizer applied at high N level (90 kg/ha)
O2	100% Organic fertilizer, N:P:K rate (60:17.3:91.1) kg/ha	Only organic fertilizer applied at medium N level (60 kg/ha)
O3	100% Organic fertilizer, N:P:K rate (90:26:136.7) kg/ha	Only organic fertilizer applied at high N level (90 kg/ha)
MO1	50% Mineral fertilizer+50% Organic fertilizer, N:P:K rate (30:12:33.4) kg/ha	combination of mineral and organic fertilizer at low N level (30 kg/ha)
MO2	50% Mineral fertilizer+50% Organic fertilizer, N:P:K rate (60:18.3:58.9) kg/ha	combination of mineral and organic fertilizer at medium N level (60 kg/ha)
MO3	50% Mineral fertilizer+50% Organic fertilizer, N:P:K rate (90:24.5:84.3) kg/ha	combination of mineral and organic fertilizer at high N level (90 kg/ha)

Note: The treatment codes M, O, and MO refer to different types of fertilizers: M stands for mineral fertilizer, O denotes organic fertilizer, and MO represents a combination of both mineral and organic fertilizers. These treatments are applied at three different levels of nitrogen: 30 kg per hectare (level 1), 60 kg per hectare (level 2), and 90 kg per hectare (level 3).

The fertilizer application was divided into three stages. The basal application was done at the time of transplanting. The first top-dressing was applied three weeks after transplanting, which corresponds to the active tillering stage of rice. The second top-dressing was done six weeks after transplanting, corresponding with the maximum tillering stage of rice. For the treatments involving organic fertilizer, all of it was applied as a basal fertilizer at the time of transplanting. Similarly, all mineral phosphate and potash fertilizers were also applied as basal fertilizers at transplanting. However, mineral nitrogen fertiliz-

Table 2. Details of the timing and application rates of N, P, and K in kg/ha for each treatment, specifying the nutrient amounts applied from each source.

N Rate	Timing of Application	Mineral Fertilizer			Organic Fertilizer			Mineral + Organic Fertilizer					
		N	P	K	N	P	K	N_io	N_o	P_io	P_o	K_io	K_o
30 kg N/ha	Basal	16.5	14.4	20.0	30.0	8.7	45.6	8.8	15.0	7.7	4.3	10.6	22.8
	1st Top-dressing	6.7	0.0	0.0	0.0	0.0	0.0	6.2	0.0	0.0	0.0	0.0	0.0
	2nd Top-dressing	6.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Total N, P K Kg/ha applied	30.0	14.4	20.0	30.0	8.7	45.6	15.0	15.0	7.7	4.3	10.6	22.8
60 kg N/ha	Basal	22.0	19.2	26.6	60.0	17.3	91.1	11.0	30.0	9.6	8.7	13.3	45.6
	1st Top-dressing	19.0	0.0	0.0	0.0	0.0	0.0	9.5	0.0	0.0	0.0	0.0	0.0
	2nd Top-dressing	19.0	0.0	0.0	0.0	0.0	0.0	9.5	0.0	0.0	0.0	0.0	0.0
	Total N, P K Kg/ha applied	60.0	19.2	26.6	60.0	17.3	91.1	30.0	30.0	9.6	8.7	13.3	45.6

90 kg N/ha	Basal	27.5	24.0	33.3	90.0	26.0	136.7	13.2	45.0	11.5	13.0	16.0	68.4
	1st Top-dressing	31.2	0.0	0.0	0.0	0.0	0.0	15.9	0.0	0.0	0.0	0.0	0.0
	2nd Top-dressing	31.2	0.0	0.0	0.0	0.0	0.0	15.9	0.0	0.0	0.0	0.0	0.0
	Total N, P K Kg/ha	90.0	24.0	33.3	90.0	26.0	136.7	45.0	45.0	11.5	13.0	16.0	68.4

Note: N_io, N_o, P_io, P_o, K_io, and K_o are treatment codes that indicate the amounts of N, P, and K kg/ha that are applied from both organic (o) and inorganic (io) sources.

ers were divided into three applications: one as basal fertilizer and the others at three and six weeks after transplanting, as indicated in Table 2.

Data Collection and Analysis

Growth measurements and yield sampling were conducted on plants excluding the border rows and those adjacent to missing hills. For yield-related characteristics such as plant height and tiller count, data were collected from 20 hills, with 10 samples taken from each of two diagonal sections of the plot. A harvest area of 9 m² within the treatment zone was designated for yield determination. Each harvest was placed in separate plastic bags, transported to the cutting floor, and then individually threshed, sun-dried, and cleaned. The grain from each treatment was weighed, and its moisture content was measured using a moisture meter at the time of weighing. The weight and moisture content were used to calculate the yield for each treatment, which is reported in kilograms per hectare at 14% moisture content.

Agronomic N use efficiency (ANUE), which is the amount of crop yield increase achieved per unit of nitrogen fertilizer applied [26, 27, 28] was computed using the formula below;

$$ANUE = \frac{\text{Grain yield in fertilized plot} - \text{Grain yield in N control plot}}{\text{Applied N in N fertilized plot}}$$

A cost-benefit analysis (CBA) assessed the profitability of various fertilizer treatments and rice varieties to identify the most lucrative fertilizer options for different rice varieties, offering farmers recommendations on the best combinations to enhance profits. A survey of 71 randomly selected farmers was conducted in June 2025 to gather accurate data on the cost of production and the selling price of rice for computing the CBA. Using a standardized spreadsheet, farmers provided cost figures for 1 acre, which were then converted to costs per hectare for precise analysis and benchmarking. Out of 71 surveyed farmers, 70 (98.6%) indicated that they sell their rice after milling. Therefore, the benefits in the CBA were based on the selling price of milled rice. The farm gate price for milled rice by variety was UGX 3700 for NARORICE-1, 3,600 for UKAFACI-39, 3000 for K-98 and 3000 for WITA-9. The milling charge is determined by multiplying the milled rice output in kilograms by the milling rate, which is UGX 130, regardless of the rice variety. The rice milling output, the finished milled rice produced from a specific quantity of paddy, varies by variety: 68% for NARORICE-1, 60% for UKAFACI-39, and 58% for K-98 and WITA-9. Cow manure for the experiment was procured locally from farms near the experimental site at UGX 200,000 for 1.5 tons. Additionally, 50 kg each of NPK and urea fertilizers were purchased from local dealers at UGX 185,000 and 150,000, respectively [29].

All data collected were collated in Microsoft Excel and subjected to a two-way analysis of variance (ANOVA) in randomized blocks using the Statistical Tool for Agricultural Research (STAR) developed by the International Rice Research Institute [30]. Means between treatments were separated by the Tukey's honestly significant difference (HSD) test.

Results

Yield and Yield Attributes

We discovered that the average yields in the second season, at 5,963 kg/ha, were significantly higher than the first season's yields of 3,904 kg/ha across all experimental treatments (see Figure 1). All fertilizer treatments resulted in higher yields compared to the control group. However, only those treatments that combined mineral and organic fertilizers at all levels (MO1, MO2, and MO3), as well as the treatment with the highest level of organic fertilizer (O3), exhibited significantly greater yields than the control.

The highest yields were achieved with the combinations of inorganic and organic inputs (MO1, MO2, and MO3) and the highest level of organic input (O3). Overall, inorganic inputs yielded the lowest among the three nitrogen sources. While increasing the levels of mineral, organic, and the combination of mineral and organic fertilizers led to increased yields, the differences were not statistically significant within the various fertilizer groups or sources.

By combining the yields from both seasons, we ranked the performance of the various fertilizer treatments based on paddy yield productivity, from lowest to highest, as follows: Control (no fertilizer), M1, M3, M2, O2, O1, MO2, MO1, MO3, and O3. These results indicate that the highest yields of irrigated rice in Doho, Butaleja, can be achieved by applying a combination of mineral and organic fertilizers. Moreover, if access to mineral fertilizers is limited, utilizing the highest level of organic fertilizers can yield similarly high yield levels as the combination of mineral and organic fertilizers.

During the first cropping season, the four varieties demonstrated significant differences in paddy yields; however, no notable interaction was observed between the varieties and the fertilizer treatments. In the second cropping season, the yield performance of the varieties varied based on the type of fertilizer applied. The yield response of the varieties to fertilizers was recorded as lowest with mineral fertilizers (r = 0.6), moderate with a combination of mineral and organic fertilizers (r = 0.7), and strong with organic fertilizers (r = 0.9) (Figure 2). Among the varieties, WITA-9 and UKAFACI-39 showed a moderate yield response to fertilizers, both with an average correlation coefficient r = 0.7. NARORICE

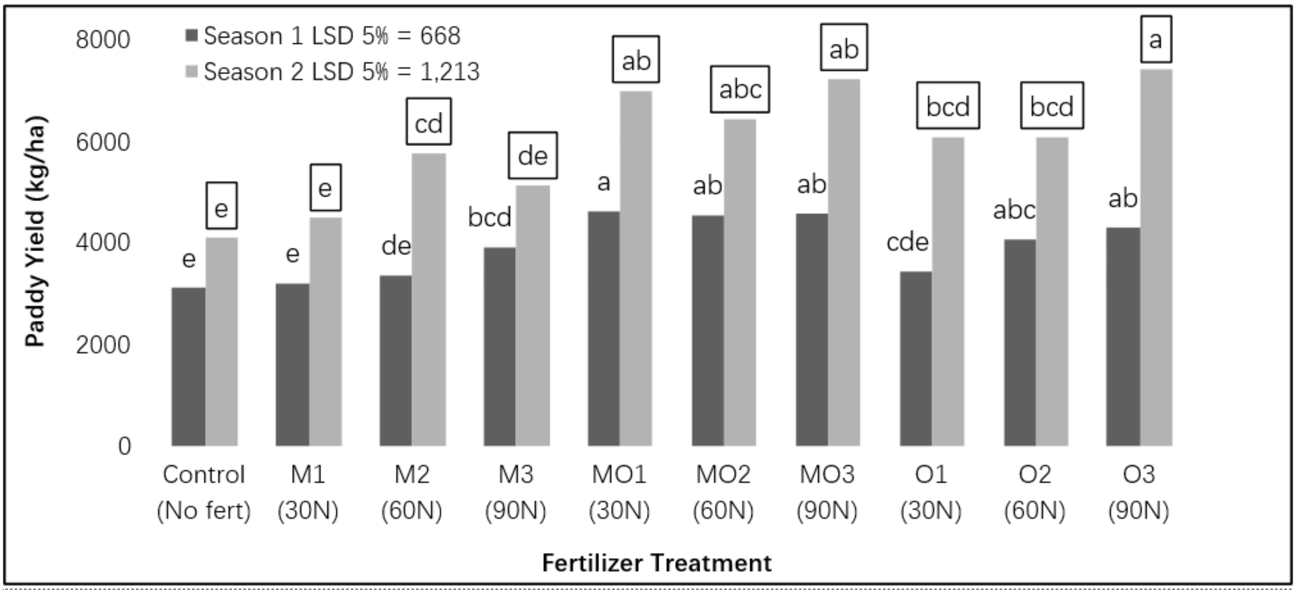

Figure 1. Paddy yield of irrigated rice treated with different levels of mineral (M1, M2, and M3), organic (O1, O2, and O3), and combined mineral and organic fertilizers (MO1, MO2, and MO3), compared to an unfertilized control.

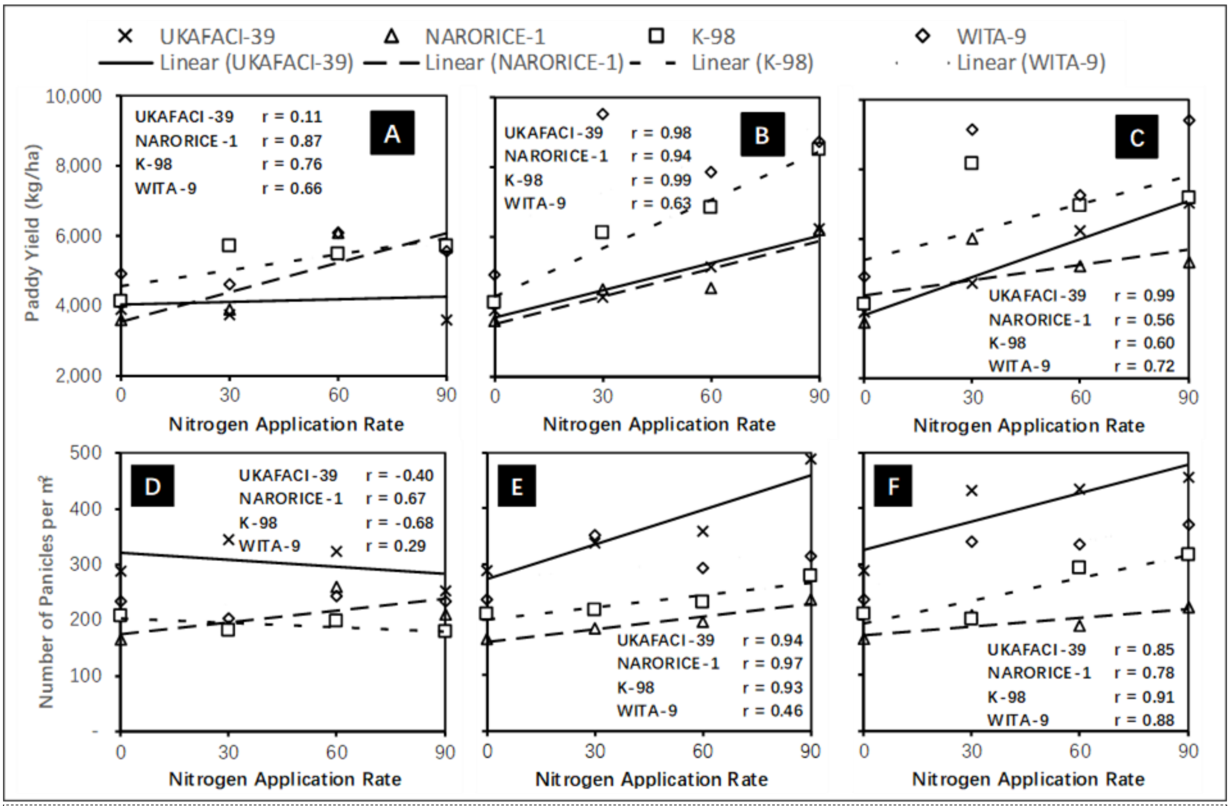

Figure 2. Response of irrigated lowland rice varieties to different N levels from three sources: mineral fertilizers (A), organic fertilizers (B), and a combination of both mineral and organic fertilizers (C).

-1 and K-98 showed a strong response (0.8), with similar overall responses to fertilizer application, both with an average correlation r = 0.8. Figures 2A, 2B, and 2C illustrate the differing yield responses of the varieties to nitrogen from three sources: mineral fertilizers, organic fertilizers, and a combination of both. About the panicle density of varieties per square meter, we observed a similar response pattern to varying N levels as that for the paddy yield, with a general weak response to mineral fertilizers and strong positive response to organic fertilizers alone or in combination with mineral fertilizers. Using organic fertilizers alone or in combination with mineral fertilizers enhanced the varietal response to fertilizers, with UKAFACI-39 exhibiting the highest yield response rate.

Agronomic Nitrogen Use Efficiency (ANUE)

We found that the ANUE was significantly higher in the second growing season, with an average yield of 39.3 kg paddy per kg nitrogen applied. By contrast, the first season yielded only 16.0 kg paddy for every kg N, which may be explained by the residual effects of the inputs of fertilizers applied in that first season.

When comparing the ANUE of different fertilizer sources, we observed the lowest ANUE with mineral fertilizers, producing only 5 kg of paddy for each kg of N in the first season and 17 kg in the second. The highest ANUE was achieved, on the other hand, by combining mineral and organic fertilizers (MO), yielding 30 kg of paddy per kg of N in the first season and 56 kg in the second. Organic fertilizers came second, with an ANUE of 13 kg and 45 kg paddy yield per kg nitrogen in the first and second growing seasons, respectively. It is important to highlight that the highest overall ANUE was observed in the treatment MO1, which had the lowest nitrogen application rate of 30 kg/ha.

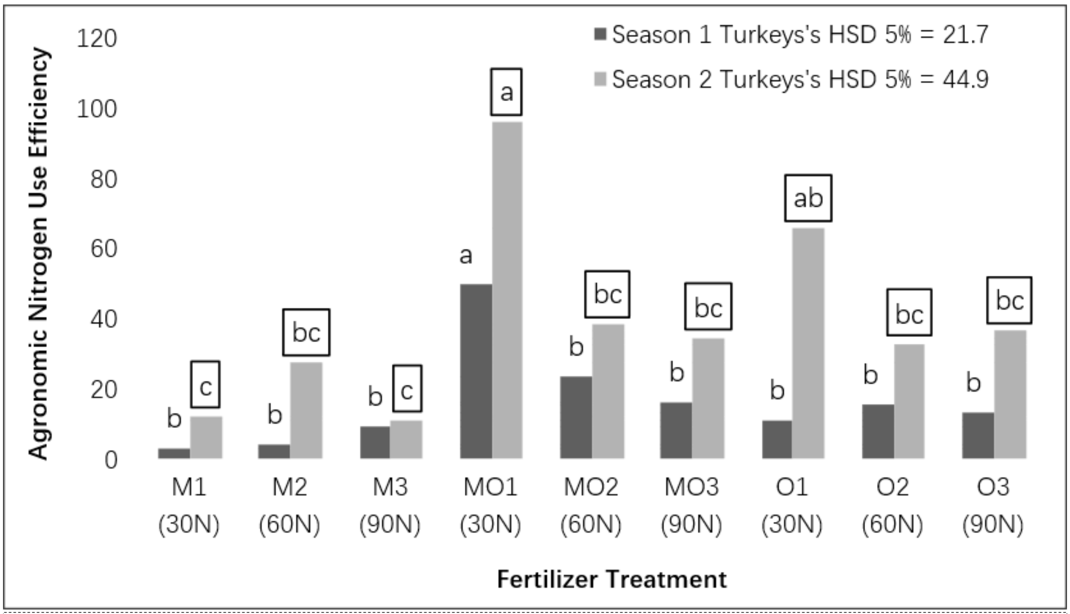

Figure 3. Comparison of the ANUE of irrigated rice grown with varying levels of N fertilizers from three sources: mineral (M), organic (O), and a combination of both mineral and organic (MO) fertilizers

Among the lowland rice varieties tested, we did not observe any significant differences in ANUE during the first season. However, in the second season, we found that the ANUE of WITA-9, which yielded 54.5 kg of paddy per kg of N, and K-98, which yielded 52.2 kg of paddy per kg of N, were significantly higher than that of NARORICE-1, with ANUE of 30.7 kg, and UKAFACI-39, which had an ANUE of only 19.8 kg of paddy yield per kg of nitrogen. This indicates that the popular farmer varieties WITA-9 and K-98, when grown with fertilizers, can not only compete favorably but can even outperform the improved varieties NARORICE-1 and UKAFACI-39 in terms of yield.

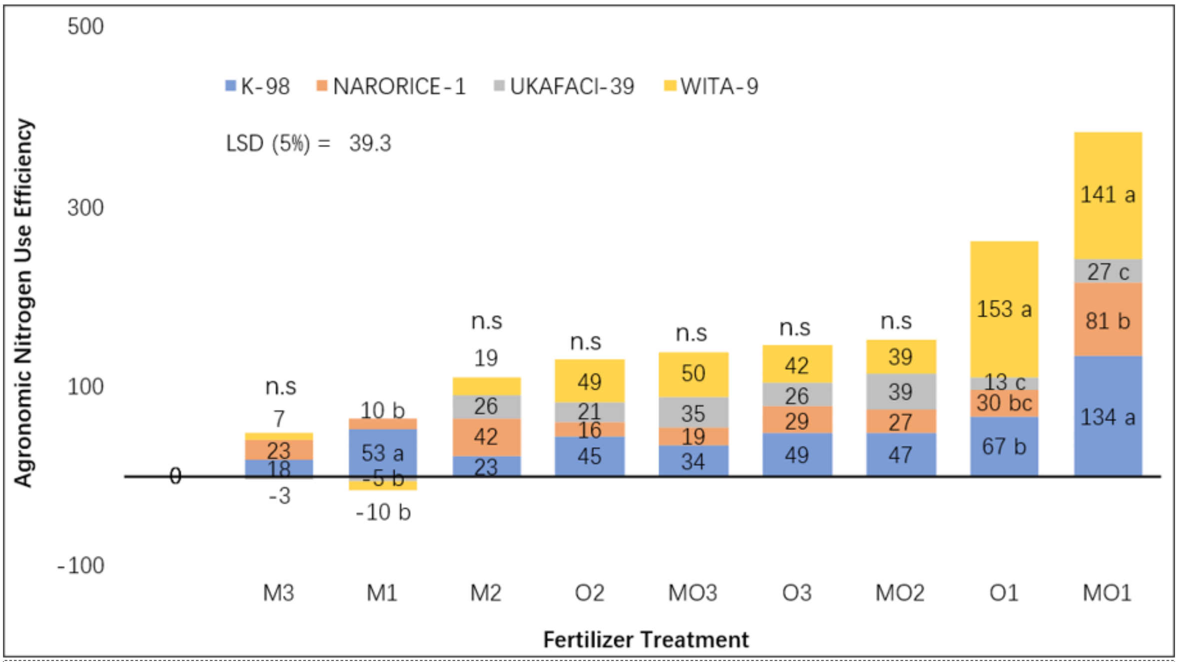

Figure 4. Comparison aNUE of four irrigated lowland rice varieties grown with varying levels of N fertilizers from three sources: mineral (M), organic (O), and a combination of both mineral and organic (MO) fertilizers.

During the first season, we did not observe any statistically significant differences in ANUE due to the interaction between rice varieties and fertilizer treatments. However, in the second season, we found a significant interactive effect between the varieties and fertilizers on ANUE. This was particularly evident under the MO1 fertilizer treatment, which registered the highest ANUE.

Cost-Benefit Analysis (CBA)

The analysis showed that the combination of mineral and organic fertilizer (MO1) with a low nitrogen rate of 30 kg/ha yielded the highest cost-benefit ratio of 4.7, resulting in a net benefit of UGX 11.4 million per hectare (Figure 3). The second-best treatment, O1, had a cost-benefit ratio of 4.3 and a net benefit of UGX 9.7 million per hectare. For the rice varieties analyzed, treatment MO1 consistently produced the highest cost-benefit ratio for K-98 and NARORICE-1. However, for UKAFACI-39 and WITA-9, the top cost-benefit ratios varied among treatments MO2, MO3, and O1, but these differences were not significant (Figure 4). Additional details on the cost-benefit analysis and net benefits are available in the appendix.

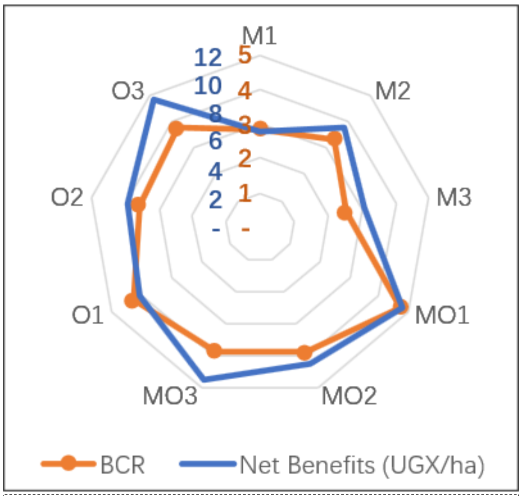

Figure 5. Comparison of the cost-benefit ratio and net benefits (UGX/ha) of cultivating lowland rice with different levels of nitrogen fertilizers from three sources: mineral (M), organic (O), and a combination of both mineral and organic (MO) fertilizers.

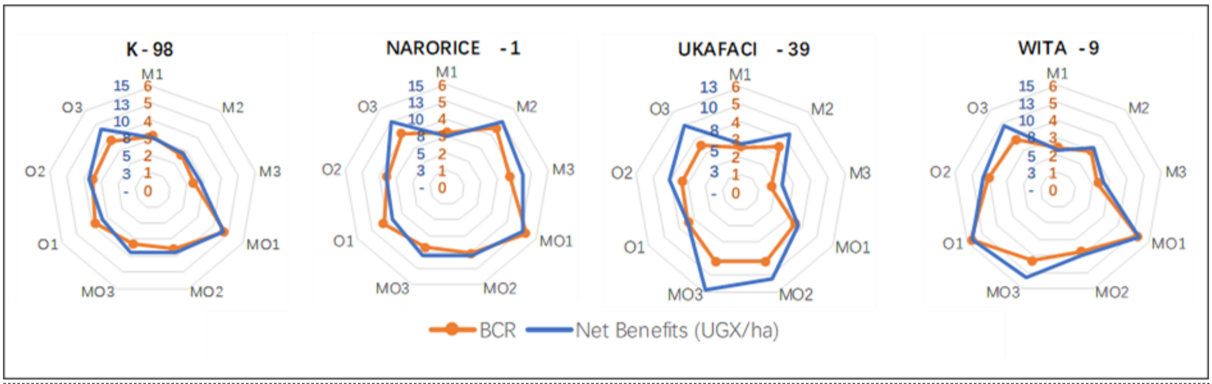

Figure 6. Comparison of the net benefits (UGX/ha) and the cost-benefit ratio of growing four irrigated lowland rice varieties with varying levels of N fertilizers from three sources: mineral (M), organic (O), and a combination of both mineral and organic (MO) fertilizers. The chart has two scales: the blue scale shows net benefits in UGX per hectare, and the amber scale displays cost-benefit ratios

Discussion

Fertilizers play a crucial role in improving irrigated lowland rice productivity in Uganda. However, a significant number of farmers either do not utilize fertilizers or apply them at rates lower than the recommended levels. This situation is largely attributed to the high costs associated with fertilizers and the limited understanding among farmers regarding appropriate fertilizer application techniques. Organic fertilizers that are easily accessible provide an affordable alternative to more expensive mineral fertilizers. Partially substituting mineral fertilizers with organic options can help lower overall fertilizer costs. This study aimed to determine the best combination and application rates of inorganic fertilizers and organic inputs to improve the yield and profitability of irrigated rice, with a specific focus on varying nitrogen levels, as it is the most limiting nutrient. This study, conducted in Doho, Butaleja, demonstrated that fertilizers can enhance the yields of irrigated lowland rice; all fertilizer treatments resulted in higher yields compared to the unfertilized control treatment. Notably, only the treatments that combined mineral and organic fertilizers at all levels (30, 60, and 90 kg/ha), along with the highest level of organic fertilizer (90 kg/ha), led to a significant increase in yields compared to the control treatment. In the treatments MO1, MO2, MO3, and O3, paddy yields increased by 1,487, 1,413, 1,464, and 1,172 kg/ha in the first season, and by 2,874, 2,292, 3,108, and 3,278 kg/ha in the second season, respectively. Moreover, among the three sources of nitrogen fertilizers—mineral, organic, and a combination of mineral and organic—we found that the blend of inorganic and organic fertilizers produced the highest yields, while the mineral fertilizers resulted in the lowest yields. In the first season, mineral fertilizers yielded an average of 3,485 kg/ha, organic fertilizers 3,924 kg/ha, and the combination of both produced the highest yield at 4,568 kg/ha. In the second season, yields increased: mineral fertilizers averaged 5,115 kg/ha, organic fertilizers yielded 6,517 kg/ha, and the combination resulted in 6,873 kg/ha. Our findings align with another study showing that organic fertilizers produce higher rice yield gains than mineral fertilizers [14]. The study indicated that organic fertilizers can yield gains of up to 90.4%, with an average gain of 1,424 kg/ha and a maximum of 2,830 kg/ha. In contrast, mineral fertilizers achieved a 51.9% yield gain, averaging 948 kg/ha and reaching a maximum of 2,931 kg/ha. Another study on maize showed that applying a high rate of organic fertilizers (120 kg N/ha) can achieve grain yields similar to those produced by a high rate of mineral N fertilizers (120 kg N/ha), provided that soil moisture is not limiting [17]. Our findings also mirror the results of similar studies that showed the most significant increases in grain yield came from applying farmyard manure together with mineral fertilizer [31], leading to substantial cost savings [32]. These findings indicate that locally sourced organic fertilizers may serve as a more affordable option or partial substitute for mineral fertilizers, assisting farmers in improving their irrigated rice yields.

We assessed the Agronomic Nitrogen Use Efficiency (ANUE) of various fertilizer treatments to ensure our yield recommendations are agronomically optimized, rather than just yield-focused. ANUE measures the additional grain yield gained per kilogram of nitrogen fertilizer used, highlighting how effectively crops convert nitrogen into harvestable products. This efficiency is vital for sustainable agriculture as it enhances fertilizer use, mitigates environmental impact, and boosts crop productivity [27]. Our results showed that a combination of mineral and organic fertilizers achieved the highest ANUE. We observed an ANUE of 30 kg of paddy yield per kg of nitrogen in the first season and 56 kg in the second season. In comparison, mineral fertilizers only yielded 5 kg and 17 kg per kg of nitrogen in the respective seasons, while organic fertilizers yielded 13 kg and 45 kg. Notably, treatment MO1, which had the highest overall production, also attained the highest ANUE, followed by treatment O1, which ranked second in yield. A study examining the agronomic efficiency of organic versus inorganic nitrogen sources found that mineral fertilizers produced the highest grain yields and ANUE. This result is likely because the organic sources used in this study, mainly fresh rice straw and Sesbania, required time to decompose before their nutrients became available to the rice crop. The researchers noted that nitrogen uptake during the vegetative phase was consistently lower with fresh organic fertilizers compared to mineral fertilizers. However, when fresh rice straw was combined with mineral urea, the resulting yields and ANUE were comparable to those achieved with mineral fertilizers alone [33]. A recent study found that combining 50% inorganic fertilizer (75 kg N per hectare) with poultry manure (5 tons per hectare) improved nitrogen uptake and the nitrogen use efficiencies of hybrid rice. Additionally, using cow manure (5 tons per hectare) along with 75% inorganic fertilizer (112.5 kg N per hectare) proved to be an effective alternative for reducing the use of chemical fertilizers [34]. These observations, which align with our findings, demonstrate that the combined application of organic and inorganic fertilizers is a practical approach for enhancing irrigated lowland rice yields, and this study shows that the combination of mineral and organic fertilizer at a low N level (30 kg/ha) is most effective. This study further revealed that the widely used farmers' varieties, WITA-9 and K-98, demonstrated significantly higher ANUE at over 50 kg of paddy per kg of nitrogen. In contrast, the improved aromatic rice varieties NARORICE-1 and UKAFACI-39 had average ANUE values of only 30.7 kg and 9.8 kg of paddy per kg of nitrogen, respectively. This indicates that these local cultivars have the potential to outperform the improved varieties when they receive adequate fertilization. This result challenges the common belief that improved rice varieties generally have a higher ANUE compared to local or farmer varieties [35]. However, it is important to note that most nitrogen applied to rice beyond 125 kg N per hectare is not fully utilized by the plants, unless there is an integration of inorganic and organic nitrogen inputs [36].

Increasing rice yields is not beneficial for farmers unless it also results in higher profits. Higher yields can only lead to increased profits if the costs do not exceed the gains and if market prices for rice are favorable. Farmers often consider expenses such as seeds, fertilizers, labor, and the potential income from selling rice. By doing so, they can ensure that adopting yield-enhancing practices—such as using new varieties, managing soil fertility, and optimizing water use—will lead to better financial outcomes [37]. In this study, we performed a cost-benefit analysis (CBA) on different fertilizer treatments and rice varieties to find the most profitable options. Our goal is to recommend the best combinations that will maximize farmers' profits. The results of the CBA revealed that the combination of mineral and organic fertilizer (MO1), utilizing a low nitrogen rate of 30 kg/ha, yielded the highest cost-benefit ratio of 4.7. This resulted in a net benefit of UGX 11.4 million per hectare. The next best option was O1, which achieved a cost-benefit ratio of 4.3 and a net benefit of UGX 9.7 million per hectare. These findings align with the analysis of the ANUE, confirming that these options are the most effective and profitable. Our findings align with another study that aimed to identify the best combination of farm manure and inorganic fertilizer for sustainable wheat production. The study showed that a combination of 75% the recommended urea rate of 150kg N/ha and 25% farm manure was the most effective, yielding a benefit-cost ratio (BCR) of 1.45 and a nitrogen use efficiency (NUE) of 50.4. This was followed by a 50:50 combination of urea and farm manure, which had a BCR of 1.22 and an NUE of 33.7. In contrast, a treatment using 100% urea yielded a BCR of 1.1 and an NUE of 16.4. They concluded that the option of having a 75:25 urea and farm manure combination was the most profitable option for farmers [38]. Therefore, these observations indicate that using a combination of mineral and organic fertilizers is the most effective and profitable strategy for farmers, with application rates differing based on the cropping context and available organic resources.

Conclusion

Fertilizers play a vital role in enhancing the productivity of irrigated lowland rice in Uganda. Farmers can utilize organic fertilizers, which are generally more affordable, to partially replace costly mineral fertilizers, thereby increasing their profitability in rice cultivation. Our research indicates that a combination of inorganic and organic fertilizers yields the best results. This blend allows for the most efficient use of nitrogen fertilizers and generates the highest profits, as demonstrated by the cost-benefit ratio. In contrast, mineral fertilizers produced the lowest yields and profits. The optimal fertilizer option identified in this study is a combination of mineral and organic fertilizers, using a low nitrogen rate of 30 kg/ha. This approach yielded the highest cost-benefit ratio of 4.7, resulting in a net benefit of UGX 11.4 million per hectare. The second-best option was the organic fertilizers providing 90 kg N/ha, which achieved a cost-benefit ratio of 4.3 and a net benefit of UGX 9.7 million per hectare.

Author contributions

Conceptualization and Design: SA and AW, Data Acquisition, Analysis, and Interpretation: SA, AW, JE, SE and KM, Writing and Revision: SA, AW and PD, Resources and Tools: CI, TA and SA, Supervision and Oversight: CI, TA and PD, Validation: AW, SA. All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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