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Minimizing Chemical Fertilizer Usage and Improve Soil Nutrient and Microbial Activity Through Organic Strategies in Rice Production

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Abstract

This study explores the potential of minimizing chemical fertilizer use in rice production by incorporating organic fertilization strategies. Ten treatments were tested, combining varying proportions of Recommended Dose of Fertilizer (RDF), poultry manure (PM), and vermicompost (VC), to assess their effects on plant growth, grain yield, and soil health. The treatments are T_1 = Control (No fertilizer), T_2 = 100% RDF, T_3 = 75% RDF, T_4 = 100% PM, T_5 = 100% VC, T_6 = 50% PM+50% VC, T_7 = 25% RDF+75% PM, T_8 = 25% RDF+75% VC, T_9 = 50% RDF+50% PM, T_{10} = 50% RDF+50% VC. The results indicated significant improvements in plant height, panicle length, effective grain panicle^{-1}, and grain yield with organic treatments compared to the control. Notably, in T_9 and T_{10}, the combined use of organic amendments with reduced RDF (50% RDF + 50% PM/VC) showed promising results, improving soil fertility indicators such as nitrogen, potassium, organic carbon, and bulk density. The study highlights the potential of organic strategies to reduce chemical fertilizer dependency while maintaining or enhancing agricultural productivity and supporting sustainable farming practices. These findings align with recent research emphasizing the role of organic amendments in improving soil structure, fertility, and crop yields in rice production.

Keywords: Plant Growth, Vermicompost, Soil Nutrient, Organic Carbon, Poultry Manure

Abbreviations: RDF: Recommended Dose of Fertilizer; PM: Poultry Manure; VC: Vermicompost; INM: Integrated Nutrient Management; SRDI: Soil Resources and Development Institute; BRRI: Bangladesh Rice Research Institute; LSD: Least Significant Difference; OC: Organic Carbon; OM: Organic Matter; NS: Non-Significant

Introduction

Agriculture plays a pivotal role in the global economy and food security, with rice being one of the most important staple crops for over 2.5 billion people worldwide [1]. As the global population continues to grow, so does the demand for rice, necessitating increased productivity. However, this surge in crop yields has often been driven by the excessive use of chemical fertilizers, which have raised significant concerns regarding environmental sustainability, soil health, and water quality [2]. The over-application of chemical fertilizers in rice farming has been linked to soil acidification, nutrient imbalances, and contamination of aquatic ecosystems through runoff, leading to long-term ecological degradation and reduced biodiversity [3,4]. These issues have called for alternative practices that can maintain high yields while minimizing the negative impact on the environment.

In response to these concerns, using organic fertilizers, such as poultry manure (PM) and vermicompost (VC), has gained attention as a viable strategy to reduce reliance on chemical fertilizers. Organic fertilizers improve soil quality by enhancing soil structure, increasing microbial activity, and boosting the availability of essential nutrients. Studies have shown that poultry manure is rich in nitrogen, phosphorus, and potassium, which are vital for plant growth, while vermicompost is known for its high levels of micronutrients and beneficial soil organisms that enhance soil fertility and structure [5]. These organic amendments not only replenish soil nutrients but also improve water retention and contribute to long-term soil health [6].

Although organic fertilizers offer several advantages, their adoption in rice farming remains limited due to their lower nutrient concentration compared to chemical fertilizers and the labor-intensive process of application. As a result, many rice farmers continue to rely on synthetic fertilizers for their higher nutrient content and ease of application. However, integrating organic fertilizers with reduced chemical inputs, as part of a balanced fertilization strategy, may provide an effective solution. Research has suggested that such combined approaches can significantly reduce the environmental footprint of rice cultivation while maintaining or even enhancing rice yields, thereby promoting sustainable agricultural practices [7,8].

Recent studies have emphasized the importance of reducing chemical fertilizer use while still maintaining rice productivity. Integrated nutrient management (INM) practices, which combine both organic and inorganic fertilizers, are seen as a promising approach to achieve this balance. By reducing the use of synthetic fertilizers and supplementing them with organic amendments, farmers can enhance soil fertility, increase nutrient use efficiency, and minimize the risk of environmental contamination [9,10]. Moreover, INM practices have been found to improve soil microbial diversity and nutrient cycling, which are essential for long-term soil health and sustainable crop production [11].

This study aims to assess the impact of reducing chemical fertilizer usage in rice production by integrating organic fertilizers such as poultry manure and vermicompost. By comparing the effects of different treatment combinations on rice growth, yield, and soil properties, the research seeks to determine the optimal balance between organic and inorganic fertilizers for sustainable rice farming. It is anticipated that the findings will provide valuable insights into the potential for minimizing chemical fertilizer dependence while maintaining or enhancing rice yield, offering a pathway toward more sustainable agricultural practices.

Given the growing global demand for rice and the environmental challenges associated with conventional farming practices, this research is both timely and critical. The findings could provide an evidence-based approach to the adoption of organic fertilization strategies that not only reduce the environmental impact of rice farming but also contribute to long-term agricultural sustainability. As the world continues to grapple with climate change, soil degradation, and the depletion of natural resources, sustainable farming practices will play a crucial role in ensuring food security for future generations [12,13].

Minimizing chemical fertilizer usage in rice production through organic fertilization strategies represents an important step toward sustainable agriculture [14]. By investigating the effects of poultry manure, vermicompost, and their combinations with reduced chemical fertilizers, this study aims to contribute to the development of farming practices that balance productivity with environmental stewardship, ultimately leading to more resilient and sustainable food systems for the future.

Materials And Methods

Experimental soil and weather

The location experienced a subtropical climate with relatively high temperatures and significant rainfall during the kharif season (November to March). In contrast, the Rabi season (November to March) featured limited rainfall and cooler temperatures. The experimental site was level and equipped with an irrigation and drainage system. The land was situated above the flood level, and adequate sunlight was available throughout the experimental period. Soil samples were taken from the 0-15cm depth in the experimental field. The analyses were conducted by the Soil Resources and Development Institute (SRDI). The physicochemical characteristics of the initial soil are detailed in (Table 1).

Table 1: Initial physicochemical properties of soil.

Characteristics	Value
Textural class	Silty Clay Loam
Particle size analysis % Sand	29
%Silt	41
% Clay	32
pH	6.42
Organic carbon (%)	0.49
Organic matter (%)	0.84
Total N (%)	0.11
Available P (ppm)	18
Exchangeable K (me/100 g soil)	0.13

Collection of poultry manure and vermicompost

The poultry manure and vermicompost used in the study were sourced from a local village market. The NPK compositions are presented in (Table 2).

Variety and Experimental treatments

BRRI dhan28 was used in the experiment. BRRI dhan28 was collected from the Bangladesh Rice Research Institute (BRRI). The treatments are sole and combined application of the Recommended Dose of Fertilizer (RDF) which is recommended by BARI 2016, Poultry Manure (PM), and Vermicompost (VC), the treatments are T_1 = Control (No fertilizer), T_2 = 100% RDF, T_3 = 75% RDF, T_4 = 100% PM, T_5 = 100% VC, T_6 = 50% PM+50% VC, T_7 = 25% RDF+75% PM, T_8 = 25% RDF+75% VC, T_9 = 50% RDF+50% PM, T_{10} = 50% RDF+50% VC.

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Table 2: Nutrient content of PM and VC.

Source	Nitrogen (N) %	Phosphorus (P) %	Potassium (K) %
PM	2.14	1.73	1.61
VC	1.3	1.32	1.4

Cultivation techniques

Healthy seeds were soaked for 24 hours, allowed to sprout in darkness, and then sown in a prepared seedbed on 19 December 2023. The seedbed was regularly maintained through weeding, irrigation, and pest control measures. Before transplanting, the field was flooded to decompose weeds, then plowed and leveled. The final field preparation and layout for transplanting were completed on 1 February 2024. NPK fertilizers (urea, TSP, MoP) were applied according to BARI recommendations for RDF and PM and VC applied as per amount for specific treatments during the crop growth phase. Seedlings were uprooted and transplanted on 1 February 2024 using conventional methods. Intercultural practices included gap filling, manual weeding, herbicide use, flood irrigation, and pest management. Rice stem borer and green leaf hopper infestations were controlled with Furadan and Sumithion. Regular monitoring ensured healthy plant growth with vigorous tillering and no lodging. Data collection was done from five randomly selected hills per plot. The crop reached full maturity and was harvested on 20 May 2024. Post-harvest, the crop from each plot was bundled, labeled, and threshed separately. The grains and straw were sun-dried to a 14% moisture content, and yields were calculated in tons per hectare. The field maintained good health throughout the growing period, with no significant disease issues.

Collection of experimental data

The data recording procedure involved measuring plant height from five randomly selected plants in each plot at different maturity. At maturity, yield data were collected by uprooting five hills per plot, excluding border rows, and harvesting the crop from a $1m^2$ area. Yield parameters recorded included panicle length, filled and unfilled grains per panicle, 1000-grain weight, grain yield, straw yield, biological yield, and harvest index. Grain and straw yields were measured, dried, and converted to tons per hectare. Biological yield was calculated by summing grain and straw yields, and the harvest index was determined as the ratio of economic yield to biological yield.

Determination of post-harvest soil physicochemical properties

Soil samples were analyzed for physicochemical properties such as bulk density, particle density, porosity, pH, organic carbon, organic matter, nitrogen, available phosphorus, and exchangeable potassium. Bulk density was determined using the core sampler method, while particle density was measured with the pycnometer method. Porosity was calculated from the bulk and particle densities using a specific formula. Soil pH was assessed with a glass electrode pH meter, maintaining a 1:2.5 soil-to-water ratio. Organic carbon was determined by the wet oxidation method, where organic matter was oxidized with $K_2Cr_2O_7$, and the excess titrated with $FeSO_4$, with results calculated using a defined formula. Organic matter was calculated by multiplying the percentage of organic carbon by 1.72. Nitrogen was determined using the Kjeldahl method, where soil was digested with sulfuric acid and a catalyst, and then distillation and titration were performed. Phosphorus and potassium were measured after digesting the soil with a nitric-perchloric acid mixture. Phosphorus was quantified by developing a blue color and measuring absorbance, while potassium was analyzed using atomic absorption flame photometry. Nitrogen content was calculated based on titration results.

Statistical analysis

The collected data were analyzed statistically using the analysis of variance technique and a least significant difference (LSD; at 0.05 level of probability) test was applied to assess the differences between the means using IBM SPSS Statistics for Windows, Version 28. Correlation heatmap and principal component analysis are prepared using Origin Pro software.

Results

Plant height

The plant height results indicate significant variations among the treatments. Compared to the control (T_1), all treatments significantly improved plant height. T_2 showed the highest increase, with a 14.21% improvement over the control, highlighting the effectiveness of 100% RDF. T_9 and T_{10} also performed exceptionally well, with increases of 12.13% and 12.99%, respectively, demonstrating the benefits of combining 50% RDF with 50% organic fertilizers. Moderate improvements were observed with T_7 and T_8, which increased plant height by 8.28% and 9.08%, respectively. T_3, T_4, T_5, and T_6 exhibited lower but still notable increases, ranging from 3.84% to 6.61%, indicating that partial RDF or sole organic treatments positively influence growth but to a lesser extent than combinations or full RDF (Table 3).

Panicle length

The panicle length results indicate significant variations among the treatments. Compared to the control (T_1), which recorded the shortest panicle length at 17.61 cm, all treatments significantly increased panicle length. T_2, T_8, T_9, and T_{10}

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demonstrated the highest increases, with panicle lengths of 24.43 cm, 23.79 cm, 24.25 cm, and 24.07 cm, respectively, all grouped as the top-performing treatments. T_7 and T_6 followed closely with 23.39cm and 22.37cm, respectively, showing moderate improvements. T_3 and T_5, with similar panicle lengths of 21.32 cm and 21.19 cm, performed better than T_4 (20.04 cm) but were less effective than the top treatments. The percentage increase in panicle length compared to the control ranged from 13.79% (T_4) to 38.74% (T_2) (Table 3).

Table 3: Yield contributing characters of rice under different treatments.

Treatment	Plant height (cm)	Panicle length (cm)	Effective grain panicle^{-1}	Non-effective grain panicle^{-1}	1000-grain weight (g)
T_1	81.3±0.93d	17.61±0.11e	114.89±0.28f	10.11±0.19a	21.02±0.26c
T_2	92.85±0.89a	24.43±0.31a	121.73±0.58cd	5.27±0.22e	22.39±0.29a
T_3	85.75±0.87c	21.32±0.2c	119.59±0.57de	6.77±0.2cd	21.89±0.39abc
T_4	84.42±0.47c	20.04±0.32d	116.63±0.69f	8.23±0.2b	21.3±0.22bc
T_5	85.5±0.78c	21.19±0.35c	119.35±0.37e	7.95±0.08b	21.83±0.42abc
T_6	86.66±1.15bc	22.37±0.28b	120.24±0.4de	7.3±0.65bc	21.92±0.2abc
T_7	88.03±0.29b	23.39±0.24b	123.32±0.78bc	6.07±0.19de	21.98±0.33ab
T_8	88.69±0.19b	23.79±0.2a	124.17±0.32b	5.97±0.2de	22.03±0.27ab
T_9	91.16±0.2a	24.25±0.54a	132.17±1.4a	5.7±0.38e	22.1±0.12ab
T_{10}	91.85±0.54a	24.07±0.64a	134.08±0.83a	5.41±0.41e	22.34±0.17a
LS	0.05	0.05	0.05	0.05	0.05
CV (%)	1.4	2.75	0.99	7.9	2.24

In each column, lowercase lettering is used to show the significant differences between different types of treatment at P<0.05 level as per DMRT. Values show the mean of three replicates ± standard errors (SE), DAS=Days after sowing, LS=Level of Significance, NS=Non-significant, T_1 = Control (No fertilizer), T_2 = 100% RDF, T_3 = 75% RDF, T_4 = 100% PM, T_5 = 100% VC, T_6 = 50% PM+50% VC, T_7 = 25% RDF+75% PM, T_8 = 25% RDF+75% VC, T_9 = 50% RDF+50% PM, T_{10} = 50% RDF+50% VC.

Effective grain panicle^{-1}

The results for effective grain per panicle indicate significant variations among the treatments. Compared to the control (T_1), which had 114.89 effective grains per panicle, all treatments showed an increase. T_9 and T_{10} recorded the highest values, with 132.17 and 134.08 effective grains per panicle, respectively, both significantly outperforming the control and other treatments. T_8 and T_7 followed closely with 124.17 and 123.32 grains, respectively, also showing substantial improvements. T_2, T_3, T_6, and T_5 demonstrated moderate increases, ranging from 119.35 to 121.73 grains per panicle. T_4, with 116.63 grains, showed the least improvement but still performed better than the control. The percentage increase in effective grains per panicle compared to T_1 ranged from 1.48% (T_4) to 16.67% (T_{10}) (Table 3).

Non-effective grain panicle^{-1}

The results for non-effective grains per panicle show significant variations among the treatments. T_1, the control, had the highest number of non-effective grains at 10.11 per panicle, significantly more than all other treatments. The treatments that reduced non-effective grains the most were T_2, T_{10}, and T_9, with values of 5.27, 5.41, and 5.7 grains, respectively, indicating that these treatments were particularly effective in minimizing non-effective grains. T_8 (5.97 grains) and T_7 (6.07 grains) also showed significant reductions compared to T_1, while T_6 (7.3 grains), T_5 (7.95 grains), and T_4 (8.23 grains) demonstrated moderate reductions in non-effective grains. T_3, with 6.77 grains, showed a slight improvement over the control. The percentage decrease in non-effective grains compared to T_1 ranged from 13.6% (T_4) to 47.4% (T_2) (Table 3).

1000-grain weight

The results for 1000-grain weight show significant variations among the treatments. T_1, the control, had the lowest 1000-grain weight at 21.02 g. The treatments that significantly increased 1000-grain weight compared to the control were T_2 (22.39 g), T_{10} (22.34 g), and T_9 (22.1 g), all of which were in the top group and demonstrated substantial improvement. T_8 (22.03 g) and T_7 (21.98 g) also showed notable increases, while T_6 (21.92 g), T_5 (21.83 g), and T_4 (21.3 g) had moderate increases. T_3 (21.89 g) performed similarly to T_5 and T_6 but was not significantly different from T_4. The percentage increase in 1000-grain weight compared to the control ranged from 1.42% (T_4) to 6.5% (T_2) (Table 3).

Grain yield

The grain yield results reveal considerable differences across the treatments. Compared to the control (T_1), which had a grain yield of 4.04 t ha^{-1}, all other treatments demonstrated significant improvements. T_2, with a yield of 6.12 t ha^{-1}, achieved the highest increase, reflecting a 51.98% improvement over the control, and was significantly higher than all other treatments. T_9 (5.82 t ha^{-1})

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and T_{10} (5.96 t ha^{-1}) also showed notable increases of 44.19% and 47.53%, respectively, and were significantly different from the other treatments. T_8 (5.67 t ha^{-1}) and T_7 (5.51 t ha^{-1}) saw moderate increases of 40.10% and 36.27%, respectively, both of which were significantly higher than T_1, but not different from each other. T_3 (5.48 t ha^{-1}), T_4 (5.3 t ha^{-1}), and T_5 (5.42 t ha^{-1}) showed increases ranging from 31.86% to 35.80%, with no significant differences among them. T_6 (5.48 t ha^{-1}) performed similarly to T_3, with a 35.80% increase, and was not significantly different (Table 4).

Straw yield

The straw yield results show significant variations among the treatments. Compared to the control (T_1), which had a straw yield of 6.15 t ha^{-1}, all other treatments resulted in significantly higher straw yields. T_2, with a yield of 7.56 t ha^{-1}, had the highest increase, representing a 23% improvement over the control, and was significantly different from T_1. T_8 (7.74 t ha^{-1}) and T_{10} (7.53 t ha^{-1}) followed closely, with increases of 25.72% and 22.35%, respectively, both showing significantly higher yields than T_1. Other treatments, including T_7 (7.47 t ha^{-1}), T_6 (7.24 t ha^{-1}), T_5 (7.28 t ha^{-1}), T_4 (7.16 t ha^{-1}), and T_3 (7.21 t ha^{-1}), also demonstrated considerable increases ranging from 17.63% to 21.71%, but none of these were significantly different from each other (Table 4).

Biological yield

The biological yield results indicate significant differences among the treatments. The control (T_1) had the lowest biological yield of 10.19 t ha^{-1}, while all other treatments showed significantly higher yields. T_2 recorded the highest yield at 13.68 t ha^{-1}, reflecting a 34.26% increase over T_1, and was significantly different from the control. T_{10} (13.5 t ha^{-1}) and T_8 (13.41 t ha^{-1}) followed closely with increases of 32.46% and 31.59%, respectively. T_9 (13.26 t ha^{-1}) and T_7 (12.98 t ha^{-1}) also demonstrated substantial improvements of 30.1% and 27.33%, respectively. The other treatments, including T_6 (12.71 t ha^{-1}), T_5 (12.7 t ha^{-1}), T_4 (12.46 t ha^{-1}), and T_3 (12.69 t ha^{-1}), exhibited increases ranging from 22.27% to 24.48%, though these differences were not significant among themselves (Table 4).

Harvest index

The results for the harvest index (%) show some variations among the treatments, although the differences are not statistically significant, as indicated by the non-significant (NS) level of significance. The control (T_1) had the lowest harvest index at 39.41%. T_2 recorded the highest harvest index at 44.76%, representing a 13.59% improvement over the control. T_{10} (44.19%) and T_9 (43.96%) followed closely, with increases of 12.13% and 11.53%, respectively. Other treatments, including T_3 (43.17%), T_6 (43.07%), T_5 (42.68%), T_4 (42.48%), T_7 (42.47%), and T_8 (42.32%), showed modest improvements ranging from 7.39% to 9.54% over T_1. Despite these numerical differences, the lack of statistical significance indicates that variations in harvest index among treatments could be attributed to random variation rather than treatment effects (Table 4).

Table 4: Yield of rice under different treatments.

Treatment	Grain Yield (t ha^{-1})	Straw Yield (t ha^{-1})	Biological Yield (t ha^{-1})	Harvest Index (%)
T_1	4.04±0.52c	6.15±0.5b	10.19±1.02b	39.41±1.31
T_2	6.12±0.2a	7.56±0.21a	13.68±0.38a	44.76±0.62
T_3	5.48±0.21ab	7.21±0.24a	12.69±0.45a	43.17±0.15
T_4	5.3±0.21b	7.16±0.14a	12.46±0.35a	42.48±0.47
T_5	5.42±0.17ab	7.28±0.2a	12.7±0.37a	42.68±0.15
T_6	5.48±0.16ab	7.24±0.17a	12.71±0.32a	43.07±0.37
T_7	5.51±0.09ab	7.47±0.22a	12.98±0.3a	42.47±0.35
T_8	5.67±0.11ab	7.74±0.21a	13.41±0.31a	42.32±0.44
T_9	5.82±0.18ab	7.43±0.3a	13.26±0.23a	43.96±1.63
T_{10}	5.96±0.12ab	7.53±0.16a	13.5±0.25a	44.19±0.49
LS	0.05	0.05	0.05	NS
CV (%)	7.25	6.04	6.14	3.05

In each column, lowercase lettering is used to show the significant differences between different types of treatment at P<0.05 level as per DMRT. Values show the mean of three replicates ± standard errors (SE), DAS=Days after sowing, LS=Level of Significance, NS=Non-significant, T_1 = Control (No fertilizer), T_2 = 100% RDF, T_3 = 75% RDF, T_4 = 100% PM, T_5 = 100% VC, T_6 = 50% PM+50% VC, T_7 = 25% RDF+75% PM, T_8 = 25% RDF+75% VC, T_9 = 50% RDF+50% PM, T_{10} = 50% RDF+50% VC.

Bulk density

The post-harvest bulk density results reveal significant variations among the treatments. The control (T_1) had the highest bulk density at 1.27 g/cc, which was significantly higher than several treatments. T_2 (1.26 g/cc) and T_3 (1.25 g/cc) showed minimal reductions compared to T_1 and were not significantly

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different from it. T_4 (1.19 g/cc) and T_8 (1.21 g/cc) demonstrated moderate decreases in bulk density and were statistically similar to each other. T_5 (1.15 g/cc), T_6 (1.16 g/cc), and T_7 (1.14 g/cc) recorded further reductions and were significantly lower than T_1 but not different from one another. The lowest bulk densities were observed in T_9 (1.10 g/cc) and T_{10} (1.08 g/cc), which showed substantial decreases of 13.39% and 14.96%, respectively, compared to the control, and were significantly different from most other treatments (Table 5).

Particle density

The post-harvest particle density results indicate significant differences among the treatments. The control (T_1) had the highest particle density at 2.71 g/cc, which was significantly higher than all other treatments. T_2 (2.61 g/cc), T_3 (2.63 g/cc), T_4 (2.62 g/cc), and T_6 (2.60 g/cc) showed moderate reductions in particle density, ranging from 3.7% to 4.8%, and were not significantly different from one another. T_5 (2.55 g/cc) demonstrated a more substantial reduction of 5.9% compared to T_1 and was statistically different from T_1 and treatments with higher particle densities. The lowest particle densities were observed in T_7 (2.44 g/cc), T_8 (2.49 g/cc), T_9 (2.45 g/cc), and T_{10} (2.40 g/cc), with decreases ranging from 8.1% to 11.4% compared to T_1 (Table 5).

Porosity

The results for soil porosity across the treatments showed significant variation, with values ranging from 51.40% to 55.36%. The highest porosity was recorded in T_6 (55.36%), which significantly exceeded the values of other treatments, indicating a potential improvement in soil structure through organic amendments like poultry manure and vermicompost. Treatment T_5 (54.82%) and T_9 (54.94%) also exhibited relatively high porosity, comparable to T_6, suggesting that combining organic fertilizers can have a favorable effect on soil porosity. Conversely, treatments such as T_2 (51.84%) and T_8 (51.40%) displayed the lowest porosity values, which were significantly different from the other treatments, indicating that the control and some organic treatments might not enhance porosity as effectively (Table 5).

Organic carbon and organic matter

The post-harvest results for organic carbon (OC) and organic matter (OM) indicate significant variations among the treatments. The control (T_1) had the lowest OC (0.53%) and OM (0.91%) levels, significantly lower than many treatments. T_5 recorded the highest values for both OC (0.65%) and OM (1.12%), representing increases of 22.64% and 23.08%, respectively, over T_1, and was significantly different from the control. T_4 and T_6, with OC levels of 0.63% and OM levels of 1.08%, also showed substantial improvements of 18.87% and 18.68%, respectively, over T_1, and were not significantly different from T_5. T_8 (0.62% OC, 1.07% OM), T_7 (0.61% OC, 1.05% OM), and T_{10} (0.61% OC, 1.05% OM) demonstrated moderate increases of 15.09–17.56% in OC and 15.38–17.02% in OM over T_1, and were statistically similar to each other. T_9 (0.60% OC, 1.04% OM) showed a 13.21% improvement in OC and a 14.29% increase in OM compared to T_1, with no significant difference from the other improved treatments. T_2 and T_3 had identical OC (0.55%) and OM (0.95%) values, achieving smaller increases of 3.77% and 4.40% over T_1, and were not significantly different from it (Table 5).

Table 5: Effect of different treatments on the physicochemical properties of post-harvest soil.

Treatment	Bulk Density (g/cc)	Particle Density (g/cc)	Porosity (%)	Organic Carbon (%)	Organic Matter (%)
T_1	1.27±0.02a	2.71±0.02a	53.30±1.41ab	0.53±0.01c	0.91±0.01c
T_2	1.26±0.01a	2.61±0.02b	51.84±0.69b	0.55±0.02bc	0.95±0.04b
T_3	1.25±0.01a	2.63±0.04ab	52.39±0.62ab	0.55±0.02bc	0.95±0.04b
T_4	1.19±0.01ab	2.62±0.03b	54.38±0.25ab	0.63±0.02a	1.08±0.04a
T_5	1.15±0.01bc	2.55±0.02bc	54.82±0.57ab	0.65±0.02a	1.12±0.04a
T_6	1.16±0.01bc	2.6±0.04b	55.36±1.74a	0.63±0.02a	1.08±0.03a
T_7	1.14±0.01bc	2.44±0.04d	53.10±0.52ab	0.61±0.01ab	1.05±0.02ab
T_8	1.21±0.08ab	2.49±0.01cd	51.40±1.72b	0.62±0.03a	1.07±0.04a
T_9	1.1±0.01c	2.45±0.03d	54.94±0.25ab	0.6±0.02ab	1.04±0.03ab
T_{10}	1.08±0.02c	2.4±0.02d	54.90±0.61ab	0.61±0.03ab	1.05±0.05ab
LS	0.05	0.05	0.05	0.05	0.05
CV (%)	3.78	2.15	3.71	5.28	6.14

In each column, lowercase lettering is used to show the significant differences between different types of treatment at P<0.05 level as per DMRT. Values show the mean of three replicates ± standard errors (SE), DAS=Days after sowing, LS=Level of Significance, NS=Non-significant, T_1 = Control (No fertilizer), T_2 = 100% RDF, T_3 = 75% RDF, T_4 = 100% PM, T_5 = 100% VC, T_6 = 50% PM+50% VC, T_7 = 25% RDF+75% PM, T_8 = 25% RDF+75% VC, T_9 = 50% RDF+50% PM, T_{10} = 50% RDF+50% VC.

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Nitrogen

The nitrogen content results after harvest demonstrate substantial and significant differences among the treatments. The control (T_1) recorded the lowest nitrogen level at 0.45%, which was significantly lower than all other treatments. T_{10} and T_9 achieved the highest nitrogen levels at 1.61% and 1.57%, respectively, reflecting remarkable increases of 257.78% and 248.89% over T_1, and were significantly different from the other treatments. T_8 (1.23%) showed a substantial improvement of 173.33% compared to T_1, followed by T_6 (1.03%) and T_7 (0.99%), which exhibited respective increases of 128.89% and 120%. T_4 (0.91%) displayed a 102.22% increase, while T_5 (0.67%) showed a moderate improvement of 48.89%. T_2 (0.62%) and T_3 (0.58%) recorded smaller increases of 37.78% and 28.89%, respectively, but were still significantly higher than T_1 (Figure 1 A).

Available phosphorous

The available phosphorus levels after harvest exhibited significant differences among the treatments. The control (T_1) recorded the lowest phosphorus content at 19.87 ppm, significantly lower than all other treatments. T_9 had the highest phosphorus level at 24.76 ppm, representing an increase of 24.6% compared to T_1, and was significantly different from most treatments. T_8 (23.86 ppm) and T_{10} (23.96 ppm) also demonstrated notable improvements, with increases of 20.1% and 20.6%, respectively, and were statistically similar to T_9. T_7 (23.68 ppm) showed a comparable improvement of 19.2% over T_1, indicating a significant enhancement. T_2 (21.72 ppm), T_3 (21.46 ppm), T_4 (21.44 ppm), T_5 (21.52 ppm), and T_6 (21.51 ppm) exhibited moderate increases in phosphorus content, ranging from 7.9% to 9.3%, and were not significantly different from one another (Figure 1 B).

Exchangeable potassium

The results for exchangeable potassium content after harvest reveal significant differences among the treatments. The control (T_1) had the lowest potassium level at 0.44 meq/100g soil, which was significantly lower than all other treatments. T_{10} recorded the highest exchangeable potassium at 1.31 meq/100g soil, representing a 197.73% increase over T_1 and was significantly higher than the other treatments. T_9 (1.13 meq/100g soil) also showed a substantial increase of 156.82% compared to T_1, and was significantly different from the control. T_8 (0.87 meq/100g soil) and T_7 (0.84 meq/100g soil) demonstrated moderate increases of 97.73% and 90.91%, respectively, over T_1, with no significant differences between them. T_6 (0.68 meq/100g soil) and T_5 (0.79 meq/100g soil) showed increases of 54.55% and 79.55%, respectively, and were significantly higher than T_1, but not significantly different from each other. T_2 (0.59 meq/100g soil) and T_3 (0.56 meq/100g soil) exhibited the smallest improvements of 34.09% and 27.27%, respectively, compared to T_1, but were still significantly higher than the control (Figure 1 C).

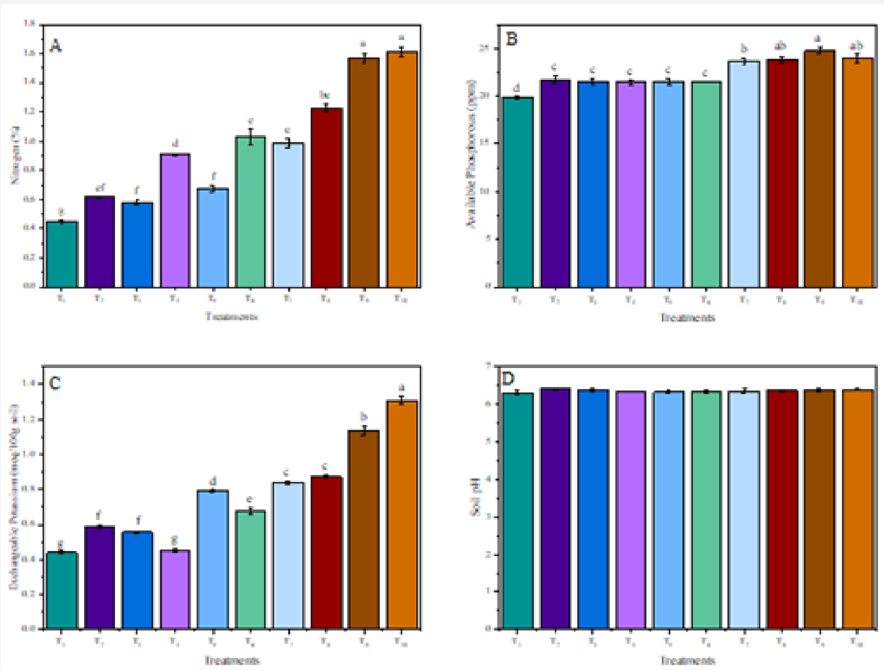

Figure 1: Nitrogen (A), Available phosphorous (B), Exchangeable potassium (C) and Soil pH (D) of post-harvest soil under various treatments. A small bar on the mean bar shows standard error and bar with a different letter (s) on the top differs significantly.

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Soil pH

The post-harvest soil pH results show minor variations among the treatments, but these differences are not statistically significant, as indicated by the non-significant (NS) level of significance. The control (T_1) recorded a pH of 6.32, the lowest among all treatments. T_2 had the highest soil pH at 6.41, representing a minimal increase of 1.42% over the control. T_{10} (6.4), T_3 (6.39), T_8 (6.38), and T_9 (6.38) also showed slight increases in soil pH, ranging from 0.95% to 1.26%. T_7 (6.36) and T_4 (6.34) exhibited modest improvements over T_1, while T_5 and T_6 had pH values equal to 6.33, showing almost no change. Although the numerical differences suggest that treatments involving RDF and organic amendments may slightly affect post-harvest soil pH, the lack of statistical significance indicates these changes are likely due to natural variability rather than treatment effects (Figure 1 D).

Principle component analysis

This PCA biplot includes 10 treatments (T_1 to T_{10}), with T_9 and T_{10} positioned in a favorable quadrant indicating strong positive associations with important agronomic and soil parameters. T_9 and T_{10} align closely with productivity-related vectors such as nitrogen, available phosphorus, effective grain, plant height, panicle length, biological yield, and overall grain yield, suggesting that these treatments significantly enhance crop growth and yield outcomes. Their placement reflects superior performance compared to other treatments, highlighting their effectiveness in promoting soil fertility and productivity (Figure 2).

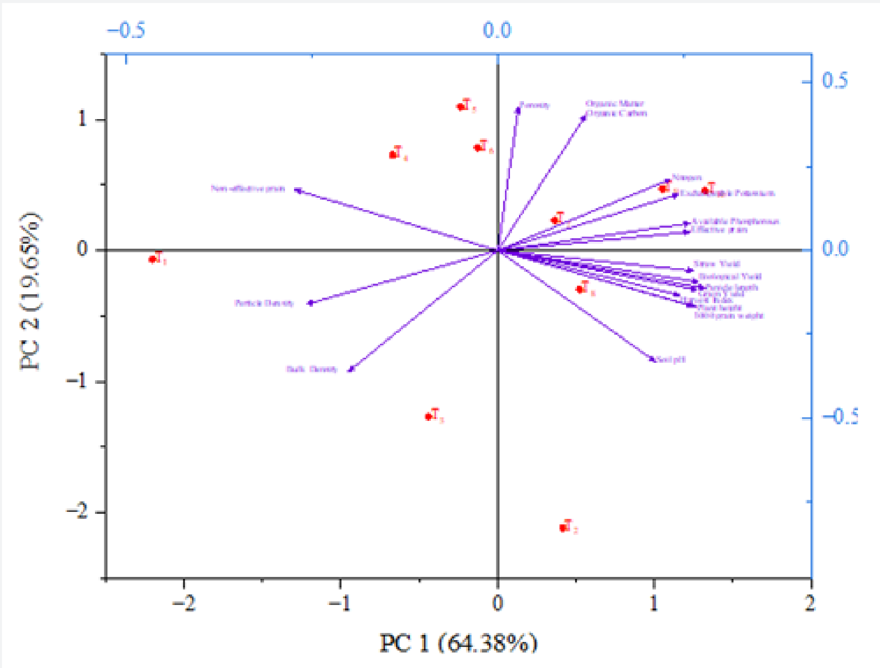

Figure 2: Biplot of Principle Component Analysis (PCA).

Pearson correlation

The Pearson correlation analysis of the data reveals the relationships between different important parameters of this study, indicating how changes in one variable might be associated with changes in another. A significant positive relationship was observed with the yield and soil parameters of rice under various sole and combined application of RDF, PM and VC (Figure 3).

Discussion

The results from this study on soil fertility and crop yield through different treatments demonstrate significant effects on various soil and plant parameters, providing valuable insights into how fertilizers and organic amendments can influence soil health and crop productivity. The study highlights the effects of sole and combined application of RDF, PM and VC on soil properties, including pH, bulk density, porosity, organic carbon, nitrogen, and potassium levels, as well as their impact on plant growth indicators such as grain yield, straw yield, and biological yield.

Impact of fertilizer and organic amendments on soil properties

Soil pH is a crucial factor that influences nutrient availability and microbial activity. The results from this study shows that there

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was no significant difference in soil pH among the treatments, with all treatments maintaining a pH level that is suitable for plant growth. Similar findings were reported by [15], who found that various organic amendments, such as compost and manure, do not drastically alter soil pH but help to maintain it within the optimal range for most crops. In contrast, inorganic fertilizers, especially those high in ammonium, can sometimes acidify the soil, but this effect was not observed in this study.

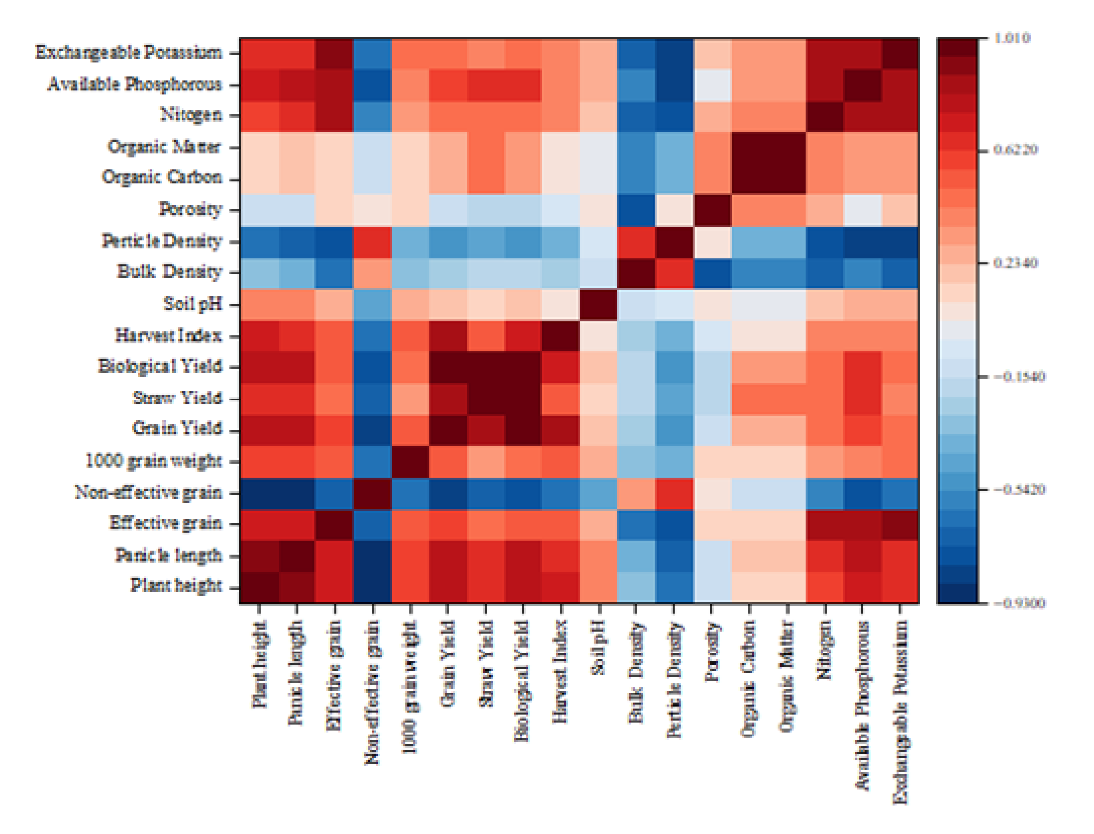

Figure 3: Pearson Correlation analysis.

Bulk density, which is a key indicator of soil compaction and porosity, was significantly lower in treatments T_9 and T_{10}, which involved organic amendments. A lower bulk density indicates better soil structure, allowing for improved root growth, water infiltration, and nutrient absorption. This trend was similarly observed by [16], who found that organic amendments significantly improved soil structure by reducing compaction and promoting soil aggregation. The reduction in bulk density in treatments like T_9 and T_{10} aligns with findings from recent studies that suggest organic materials such as poultry manure and compost can improve soil physical properties [17,18].

Organic carbon and organic matter, which are indicators of soil fertility, showed significant increases in treatments with higher organic amendment content, such as T_4, T_5, T_6, and T_{10}. Organic matter plays a crucial role in enhancing nutrient and water retention in soil and fostering beneficial microbial activity. Studies by [6,19] have shown that adding organic matter to the soil not only improves fertility but also promotes the formation of stable aggregates, which help prevent erosion and improve soil structure. These results highlight the potential of organic amendments to improve soil fertility and sustainability in agricultural systems.

Effects on nitrogen, phosphorus, and potassium

In terms of nitrogen content, treatments T_9 and T_{10} showed significantly higher nitrogen availability compared to the control. This is in line with findings from recent studies on the use of organic amendments to increase nitrogen levels in soil. Organic materials, particularly those rich in nitrogen like poultry manure, are known to release nitrogen slowly through microbial processes, making it more available to plants [20]. A similar trend was observed by [21], who reported that poultry manure and other

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organic fertilizers contributed to higher nitrogen availability in the soil, enhancing crop growth and yield.

Phosphorus availability, as indicated by the available phosphorus content in this study, showed significant increases in treatments such as T_9 and T_{10}, which combined different organic and inorganic fertilizers. Phosphorus is an essential nutrient for plant growth, and its availability can be affected by soil pH and organic matter content. These results are consistent with recent studies by [22], who found that organic amendments can increase phosphorus availability in soils, especially when combined with other fertilizers. The improvement in available phosphorus in treatments like T_9 suggests that organic amendments can help to mobilize phosphorus in the soil, making it more accessible to plants.

Exchangeable potassium, which is vital for plant growth and development, was also found to increase significantly in treatments T_9 and T_{10}. This result supports the findings of [23], who showed that organic fertilizers, particularly those containing high levels of potassium, can significantly improve soil potassium levels. Potassium is essential for various plant processes, including water regulation, enzyme activation, and photosynthesis. Organic amendments can improve potassium retention in the soil, preventing leaching and making it available to plants for longer periods [24].

Impact on plant growth and yield

The plant growth parameters, including plant height, panicle length, effective grain panicle^{-1}, and non-effective grain panicle^{-1}, showed significant improvements in treatments with higher levels of organic and inorganic fertilizers. Specifically, treatments T_9 and T_{10} exhibited the highest values for these parameters, demonstrating that both organic and inorganic fertilizers are essential for improving crop growth and yield. These findings are consistent with the results of recent studies by [25,26], who reported that organic amendments, particularly when combined with mineral fertilizers, result in enhanced plant growth, higher yields, and better overall plant health.

The grain yield, straw yield, and biological yield results further reinforce the positive impact of organic and inorganic fertilizer combinations on crop productivity. Treatments T_9 and T_{10}, which involved a combination of 50% RDF and 50% organic amendments (PM+VC), resulted in significantly higher grain and biological yields compared to the control. This outcome aligns with recent research by [27], which showed that combining organic amendments with conventional fertilizers leads to higher crop yields, as it provides a balanced supply of nutrients and improves soil health. Additionally, the findings from [28,29] support the idea that organic amendments enhance nutrient cycling and improve soil physical properties, which collectively contribute to higher yields.

The harvest index, which indicates the proportion of biomass allocated to grain production, did not show significant differences among the treatments in this study. This could be attributed to the fact that harvest index is influenced by multiple factors, including crop variety, weather conditions, and management practices. While organic amendments can improve yield components, the impact on harvest index may not always be as pronounced, especially in the short term. This finding is consistent with studies by [30], who noted that while organic amendments can improve overall yield, their effect on harvest index might vary depending on other factors such as plant density and nutrient management strategies.

Conclusion

The study demonstrates the positive impact of integrating organic and inorganic fertilizers on soil fertility and crop productivity. Treatments incorporating organic amendments, particularly poultry manure and vermicompost, significantly improved key soil properties such as nitrogen content, organic carbon, and potassium levels, which in turn enhanced plant growth and grain yield. The combination of organic and mineral fertilizers showed the most promising results, supporting sustainable agricultural practices that optimize soil health while increasing crop yields. This study aligns with recent findings on the importance of balanced nutrient management for improving soil structure and enhancing agricultural sustainability. Future research should focus on long-term studies to assess the cumulative effects of these treatments and their potential for sustainable agriculture. Moreover, studies investigating the interaction between different crop varieties and organic amendments will help to optimize the use of these fertilizers for various cropping systems.

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