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Increasing the Efficiency of the Rice–Wheat Cropping System through Integrated Nutrient Management

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Abstract: The advancement of effective nutrient management strategies has been instrumental in enhancing crop productivity and economic viability. Thus, we investigated the effect of green manure and organic amendments at varying nitrogen levels in rice and their residual effect on wheat crops. A two-year research study (2018–2019 and 2019–2020) was conducted at two distinct locations: Punjab Agricultural University in Ludhiana and a Research Station in Dyal Bharang, Amritsar. The experimental design employed was a split-plot design. The main plot treatments consisted of four treatments (green manuring, farmyard manure, poultry manure, and no organic amendment (control)) and four subplot treatments (No N control, 50 kg N ha^{-1}, 75 kg N ha^{-1}, and 100 kg N ha^{-1}), replicated four times in the rice crop, and its residual effect was studied in wheat. The study found that applying organic amendments at different nitrogen levels significantly increased rice–wheat productivity, growth, yield qualities, nutrient uptake, and efficiency ($p < 0.05$). Poultry manure increased rice grain yield more than other modifications. It significantly increased grain yield by 67.3% and 61.4% over the control in both years of the research. Poultry manure (41.9 kg, 60.0%) increased AE (kg grain kg^{-1} N uptake) and ANR (%) compared to control due to higher total N (177.4 kg ha^{-1}), P (31.6 kg ha^{-1}), and K (179.6 kg ha^{-1}). Grain production was positively correlated with total nitrogen (N), phosphorus (P), and potassium (K) intake (r = 0.992**, 0.931**, and 0.984**, respectively). Total N uptake was positively correlated with P and K uptake (r = 0.963** and 0.991**, respectively). Poultry manure improved soil health by increasing total microbial count and alkaline phosphatase activity. In the subsequent wheat crop, rice grown with poultry manure yielded 24.3 and 24.4 percent more than no organic amendment control in rabi 2018–2019 and 2019–2020. The findings suggest that poultry manure and 100 kg N ha^{-1} or 75 kg N ha^{-1} afforded equivalent yields. This shows that even less nitrogen may be enough to boost rice and wheat yields.

Keywords: APA; agronomic efficiency; grain yield; n-uptake; p-uptake; rice–wheat

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Citation: Kaur, P.; Saini, K.S.; Sharma, S.; Kaur, J.; Bhatt, R.; Alamri, S.; Alfagham, A.T.; Hussain, S. Increasing the Efficiency of the Rice–Wheat Cropping System through Integrated Nutrient Management. *Sustainability* **2023**, *15*, 12694. https://doi.org/10.3390/su151712694

Academic Editors: James W. Muthomi, Alex M. Fulano and Nancy Karimi Njeru

Received: 15 July 2023
Revised: 17 August 2023
Accepted: 19 August 2023
Published: 22 August 2023

1. Introduction

The rice–wheat cropping system (RWCS) plays a crucial role in providing sustenance for a significant number of food producers and consumers in the Indo-Gangetic Plain (IGP) of South Asia [1]. The rice–wheat cropping system (RWCS) plays a crucial role, accounting for around 32% and 42% of the total rice and wheat cultivation areas, respectively [2]. India depends heavily on rice and wheat as the foundation of its food security, with approximately 58% of the total agricultural land and 77% of the food grain production in the country being dedicated to these crops [3]. The continuous cultivation of the RWCS results in the excessive depletion of soil nutrients, leading to soil nutrient mining [4] and a decline in productivity over time. Therefore, it is imperative to prioritize the enhancement of RWCS productivity to effectively meet the escalating food demands of India's rapidly growing population, which is projected to reach 1.35 billion by 2025. Therefore, a lack of productivity in the RWCS can be attributed to the deterioration of soil and water resources, along with ineffective management of nutrients [5,6]. In numerous intensive modern agricultural systems, there is a tendency to prioritize immediate production gains without adequate attention given to soil maintenance or long-term soil improvement. This often results in significant reliance on excessive application of inorganic fertilizers to maximize productivity. As a consequence, these practices can harm soil organic carbon levels, fertility, and overall productivity, highlighting the need for mitigation and sustainable approaches [7,8].

Soils play a crucial role in preserving the productivity of agroecosystems, and comprehending the effects of various management practices thus, ensuring agricultural sustainability. Soil organic matter (SOM) is widely acknowledged as a vital soil property and a key indicator of soil quality. Its influence on numerous soil properties and processes, makes it a key factor, to consider and thus its adequate levels are essential for improving soil fertility [9]. Maintaining or increasing agricultural yields requires enough soil SOM [8–10]. To attain this goal, organic amendments must be used to add carbon to the soil. However, correct stoichiometry requires that these organic inputs be complemented by the right nutrients [11,12]. Green manure and organic additions improve soil structure, protect organic matter, and promote biological activity. Agricultural systems enhance organic matter, soil enzymes, microbial population, and nutrient cycling, crucial for organic matter breakdown [13–16].

The application of fertilizers in the RWCS shows significant variation across various agro-climatic regions in India [17]. Rice and wheat, being nutrient-intensive crops, often require more nutrients than what is supplied externally [4,18,19]. This results in nutrient depletion in the soil and reduced productivity. The reliance on soil for approximately 50.8% of nitrogen requirements leads to poor factor productivity in RWCS [20,21]. The problems arising from insufficient nutrient management in the extensively cultivated rice–wheat cropping system of India's Indo-Gangetic plain include stagnant crop yields, inefficient water and nutrient utilization, soil organic carbon depletion, degradation, multiple nutrient deficiencies, and reduced productivity in crop production factors [22–25]. The continuous cultivation of the RWCS, despite the divergent nutrient needs of rice and wheat, has led to declining soil fertility and the appearance of multiple nutrient deficiencies [26].

Due to farmer ignorance, deficiencies in a number of micronutrients have become a new threat to RWCS sustainability. Therefore, resource-poor farmers in many places unwittingly utilize excessive nitrogen fertilizer to maintain yield levels [27]. This situation reduces economic rewards and pollutes the environment. RWCS are noted for having better productivity than other cropping systems in India, yet multi-nutrient insufficiency is more common in high-yielding systems [28]. Many researchers have reported yield improvement in the RWCS through balanced fertilization [29]. Therefore, adopting balanced fertilization practices is a practical solution for sustaining RWCS by ensuring appropriate nutrient supply. Balanced nutrition enables plants to efficiently absorb essential nutrients, resulting in improved crop productivity and input utilization efficiency. Therefore, nitrogen has been recognized as the primary nutrient limiting crop yield in various agro-ecological regions [30,31]. Nitrogen fertilizer has a significant impact on the physiological aspects of plants, including respiration rate, water balance, signaling pathways, overall growth and development [32–34]. Recent research has shown that applying fertilizers containing phosphorus (P) and potassium (K) together can enhance the uptake of nitrogen (N) fertilizers and improve N efficiency [35]. This approach has the potential to narrow yield gaps caused by nutrient deficiencies and imbalances across regions, potentially resulting in yield increases of around 20–30% with the implementation of improved management practices [36]. Consequently, to achieve sustainable yield improvements, it is crucial to better understand the response of rice and wheat crops to fertilizer application and the interactions among different nutrients [16].

Plant growth depends on the presence and balance of key nutrients, especially nitrogen (N), phosphorus (P), and potassium (K). Rice and wheat yield and nutrient uptake are affected by changes in nutrient supply [37–39]. The impact of N, P, and K fertilizers on crop production and nutrient use efficiency must be understood, incorporating both economic and environmental aspects, for agronomic purposes. Thus, the combination of chemical fertilizers with organic manure is imperative for enhancing soil health and fertility.

Increasing soil organic matter (SOM), soil fertility, and agricultural sustainability and production with inorganic fertilizers and organic amendments is beneficial [40,41]. To obtain the best results, both components should be tweaked carefully. Organic amendments improve phosphorus (P) utilization efficiency over time, minimizing environmental P losses [42]. Organic amendment nutrients are usually inaccessible to plants and must be mineralized to be absorbed [43]. To limit nutrient losses and meet crop nutrient needs, organic additions must be carefully controlled due to their slow release of nutrients [44,45]. Crop yields often increase when organic amendments and inorganic fertilizers offer the most nutrients. Inorganic fertilizers can be supplemented with organic amendments [46,47]. Scientists disagree on whether organic amendments boost yields due to increased nutrients or other soil features. To alter soil health and crop yield under RWCS, we expected GM, organic amendments, and nitrogen levels to dynamically change soil equilibrium. In order to measure the effects of organic amendments and nitrogen levels on soil health, nutrient use efficiency, and crop productivity in loamy sand and clayey loam soil in the IGPs of northwest India, we conducted scientifically designed experiments with rice and wheat, representing two locations in Punjab.

2. Materials and Methods

2.1. Experimental Site and Characteristics

The current study was carried out at two locations in the Indo-Gangetic plains in India's northwest during the 2018–19 and 2019–20 growing seasons. The first location was the experimental farm of Punjab Agricultural University in Ludhiana, Punjab (30°54′ N 75°48′ E), characterized by sandy loam soil. The second location was the Research Station in Dyal Bharang, Amritsar (31°37′ N 74°51′ E), which featured a clayey loam soil. The experimental site is situated at a height of 247 m above mean sea level. It exhibits a relatively flat topography with uniform textural composition and medium land quality. During the rainy season, the site has occasional periods of submergence. This particular characteristic makes it well suited for rice cultivation during the rainy season, while other crops are grown during the winter and summer seasons.

2.2. Climate and Weather

The experimental site has a subtropical, semi-arid climate. The region experiences four distinct seasons consisting of an extremely hot and dry summer (April to June), followed by hot and humid weather (July to September), then a cold winter (November to January), followed by a mild climate (February, March, and October). In May and June during the summer, the highest air temperature regularly exceeds 39 °C. In contrast, the minimum air temperature can fall below 4 °C and can be accompanied by cold spells during the winter months of December and January. Over 75% of the region's annual precipitation, or about 760 mm, falls during the monsoon season, which runs from July through September.

2.3. Experimental Treatments and Design

The split-plot design of the experiment involved four main plot treatments for rice (green manuring (GM), farmyard manure (FYM), poultry manure (PM), and no organic amendment (NA)), as well as four subplot treatments for the rice crop (no N control, 50 kg N ha^{-1}, 75 kg N ha^{-1}, and 100 kg N ha^{-1}). The residual effects on the succeeding wheat crop of the organic amendments and nitrogen levels given to rice were assessed. The plot dimensions were 7 m × 3.30 m, or 23.1 m^2. Rice was treated with various nitrogen concentrations, including control, 50 kg N ha^{-1}, 75 kg N ha^{-1}, and 100 kg N ha^{-1}. The rice crop received the full dosage of P_2O_5 (30 kg per hectare) and K_2O (30 kg per hectare) prior to the last puddling of the soil. Nitrogen application was divided into three equal splits. One-third of the nitrogen was applied before the final puddling of the soil, while the remaining two-thirds was applied in two subsequent applications. The second application was carried out three weeks after transplanting the rice seedlings, and the final application was performed three weeks after the second application. The Agricultural Research Farm provided well-decomposed farmyard manure (FYM) with nutritional compositions of N = 0.75%, P = 0.30%, and K = 0.70% and poultry manure with nutrient compositions of N = 3.40%, P = 2.73%, and K = 1.92%. The recommended fertilizer application for wheat is 125 kg N and 62.5 kg P_2O_5 per hectare. The whole dose of P_2O_5 and half of the nitrogen dose were applied during sowing, and the other half of the nitrogen dose was applied during the first irrigation.

2.4. Green Manure and Rice Crop Establishment

Just after the harvest of the preceding wheat crop, pre-sowing irrigation was applied, and in the selected green manure treatment plots, a *C. juncea* green manure crop was seeded in the third week of April using a seed rate of 50 kg per hectare. The seeds were mixed into the soil using a disc harrow once in the seeding plots. When the green manure crop reached 6–7 weeks of age, it was incorporated into the soil one day prior to transplanting the paddy crop. To transplant one hectare, 20 kg of seeds of the PR 126 variety were sown. Application of farmyard manure @ 15 t ha^{-1} and poultry manure @ 6.25 t ha^{-1} was performed in plots as per the treatments before puddling. The plants were spaced 15 cm apart from one another, and rows were 20 cm apart, when transplanting the seedlings.

2.5. Tillage and Residual Effect of Amendments in Succeeding Wheat

The seed bed was prepared under proper moisture conditions. The field was ploughed twice, followed by planking. The layout remained the same as for the preceding rice crop. Seeds of the wheat variety PBW 725 were sown manually using the kera method behind a manually operated plough. The sowing was performed with a 20 cm row spacing, and the seed rate used was 100 kg per hectare. The seeds were sown at a depth of 5–6 cm. The residual impact of nitrogen levels and organic amendments applied to rice was assessed in the wheat crop.

2.6. Biometric Observations of Rice and Wheat

2.6.1. Growth Parameters

At different growth phases of the wheat and rice crops, plant height and the accumulation of dry matter were measured. Five plants were randomly chosen from each experimental unit and marked for measurements. The average height of the five plants was measured from the plant's base to the base of the last completely opened leaf, and it was recorded in centimeters (cm). In order to measure the accumulation of dry matter, representative samples of five plants per plot were taken, dried in the sun, and then dried in a 60 °C oven until a constant weight was achieved. Subsequently that, the amount of dry matter accumulated was measured, and the results are represented as quintals per hectare (q ha^{-1}).

2.6.2. Yield Attribute Characteristics

Effective tillers were assessed by counting the number of tillers within a one-square-meter area at four randomly selected spots for each treatment. Additionally, five representative plants were chosen from each experimental unit to measure the panicle length in centimeters and count the quantity of grains per panicle.

2.6.3. Dry Matter Accumulation

Five representative plants at 30, 60, 90 DAT and at harvest of rice and at reproductive and at harvest of wheat crop were taken from each plot and sun dried and then dried in the oven at 60 °C to a constant weight. Dry matter accumulation was expressed as q $ha^{-1.}$

2.7. Soil and Plant Analysis

Using a 5 cm diameter auger, soil samples were taken from depths of 0–15 and 15–30 cm to evaluate the health of the soil. The textures of the experimental soils of Ludhiana were loamy sand and the soils of Dyal Bharang were clayey loam, with low N, and medium available P and K. The soil samples for the analysis of enzymatic activity were taken at depths of 0–7.5 cm and 7.5 to 15 cm.

2.8. Nutrient Uptake by Grains (N, P and K)

To determine the N, P, and K uptake by the grains of both crops, the percentage content of N, P, and K was multiplied by the grain yield of the respective crops. The resulting values are expressed in kilograms per hectare (kg/ha).

2.9. Nutrient Use Efficiency

2.9.1. Apparent N Recovery

Nitrogen use efficiency can be expressed as % utilization of nitrogen.

$$\text{Apparent N recovery (ANR)} = \text{N uptake in fertilized plot (kg ha}^{-1}) - (\text{N uptake in control plot (kg ha}^{-1})$$

$$\text{Apparent N recovery (ANR)(\%)} = \frac{\left[\text{N uptake in fertilized plot } \left(\text{kg ha}^{-1}\right)\right] - \left[\text{N uptake in control plot } \left(\text{kg ha}^{-1}\right)\right]}{\text{Fertilizer nitrogen applied } \left(\text{kg ha}^{-1}\right)} \times 100$$

2.9.2. Agronomic Efficiency (AE) (kg Grain kg^{-1} N Applied)

Agronomic efficiency can be expressed as:

$$\text{Agronomic efficiency (AE)} = \frac{\left[\text{Grain yield in fertilized plot } \left(\text{kg ha}^{-1}\right)\right] - \left[\left(\text{Grain yield in control plot } \left(\text{kg ha}^{-1}\right)\right]\right.}{\text{Fertilizer nitrogen applied } \left(\text{kg ha}^{-1}\right)}$$

2.9.3. Production Efficiency (PE) (kg Grain kg^{-1} N Absorbed)

Production efficiency can be expressed as:

$$\text{Production efficiency (PE)} = \frac{\left[\text{Grain yield in fertilized plot } \left(\text{kg ha}^{-1}\right)\right] - \left[\left(\text{Grain yield in control plot } \left(\text{kg ha}^{-1}\right)\right]\right.}{\left[\text{N uptake in fertilized plot } \left(\text{kg ha}^{-1}\right)\right] - \left[\text{N uptake in control plot } \left(\text{kg ha}^{-1}\right)\right]}$$

2.10. Quantification of Soil Microbial Population and Measurement of Alkaline Phosphatase Activity in Soil

The enumeration of bacteria, fungi and actinomycetes was performed on Nutrient Agar medium, Glucose Yeast Extract medium and Kenknight's medium, respectively, using the serial dilution spread plate technique. The media were prepared and sterilized in an autoclave at a pressure of 15 psi and a temperature of 121 °C for 20 min.

Ten grams of the fresh soil from a soil depth of 0–7.5 cm was transferred to an Erlenmeyer flask (150 mL) containing 90 mL sterile distilled water, and was shaken at 120 rpm for 15 min to make a homogenous solution. Serial dilutions (upto 10^{-10}) were made by pipetting 1 mL of the soil suspension into 9 mL of sterile water blank. Finally, 0.1 mL aliquot of the diluted soil suspension was uniformly spread using a sterilized spreader onto solidified petriplates with the corresponding medium (Nutrient Agar for bacteria, Glucose Yeast Extract agar medium for fungi and Kenknight's medium for actinomycetes). Dilutions of 10^{-6} to 10^{-8} were selected for the enumeration of bacteria, 10^{-2} to 10^{-4} for fungi and

10^{-3} to 10^{-5} for actinomycetes, relative to their population in soil. The petriplates were incubated for 2 to 6 days at 28 ± 2 °C in an inverted position. After incubation, the numbers of colonies appearing on the dilution plates were counted, averaged and multiplied by the dilution factor to find the number of cells per gram of soil sample:

$$\text{Cfu g}^{-1}\text{ soil} = \text{Number (average of 3 replicates) of colonies} \times \text{Dilution factor}$$

where Dilution factor = Reciprocal of the dilution (e.g., 10^{-7} = 10^{-7})

Alkaline phosphatase activity in the soil samples was assessed with the method described by Tabatabai and Bremner [48]. This involved mixing 1 g of soil with toluene, MUB buffer at pH 11, and p-nitrophenyl phosphate solution. Following incubation, $CaCl_2$ and NaOH were added. The mixture was then filtered, and the intensity of the yellow color in the filtrate was assessed using a spectrophotometer at a wavelength of 420 nm.

2.11. Statistical Analysis

To compare treatment means, statistical analysis was carried out using SAS 9.4 software (SAS institute 2013, Cary, NC, USA) with Proc GLM. The LSD procedure was used, and Tukey's HSD was performed where ANOVA was significant. Statistical comparisons were conducted at a significance level of 5 percent.

3. Results

3.1. Growth Parameters

The application of organic amendments and nitrogen levels (Table 1) had a significant impact on the growth characteristics, viz., the DMA, number of tillers, and plant height of the rice crop (Figures 1 and 2, and table entitled "Influence of amendments and nitrogen levels on growth and yield attributes of rice under the rice–wheat cropping system (pooled data of two years"). Significantly higher growth attributes were recorded with PM followed by GM and FYM, with the latter two showing statistically similar response towards growth attributes at both study locations. Compared to with the application of amendments, no application of amendments recorded considerably lower results for biomass production, tillering capacity and plant height. Upon perusal of the data, it was observed that incorporating amendments had a significant positive impact on crop growth, which persisted until harvest, as is evident from the comparison of periodic data with the control (Figures 1 and 2). The application of nitrogen at different levels had a statistically significant impact on plant height, tillers m^{-2} and DMA, with the results of 100 kg N ha^{-1} and 75 kg N ha^{-1} being statistically on par results throughout at all growth stages, and significantly higher than the results for 50 kg N ha^{-1} and no N control at both locations.

Table 1. Description of treatments.

Abbreviation	Treatment Details	
	Rice (PR-126)	**Wheat (PBW-725)**
Main plot treatments		
GM	Green manure (Sunhemp—*Crotolaria juncea*)	Residual effect (GM)
PM	Poultry manure @ 6.25 t ha^{-1}	Residual effect (PM)
FYM	Farmyard manure @ 15 t ha^{-1}	Residual effect (FYM)
NA	No application of amendments	NA
Sub-plot treatments		
N_0	Control	N0
N_{50}	50 kg N ha^{-1}	Residual effect (N_{50})
N_{75}	75 kg N ha^{-1}	Residual effect (N_{75})
N_{100}	100 kg N ha^{-1}	Residual effect (N_{100})

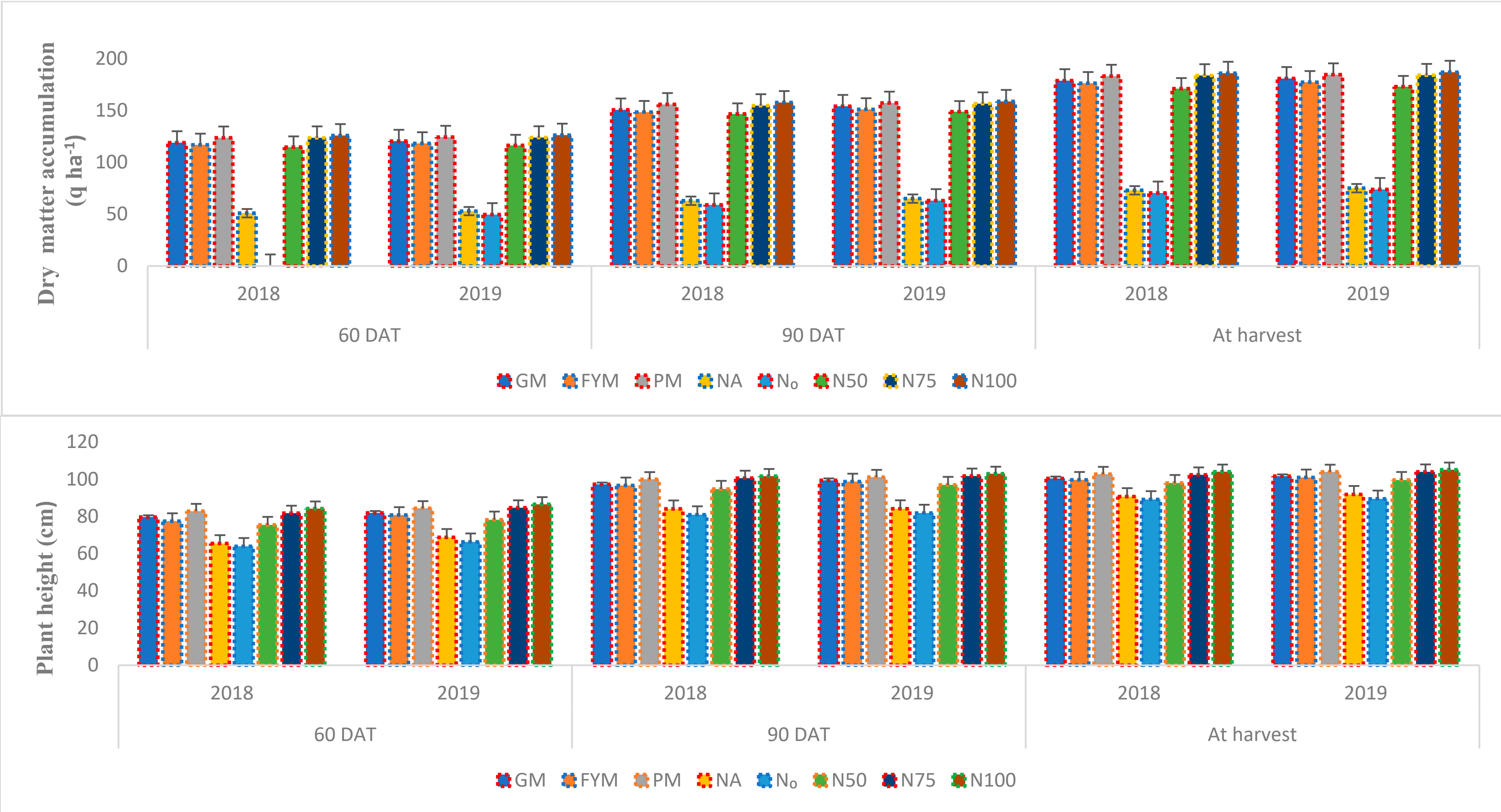

Figure 1. Influence on plant height and dry matter accumulation of the application to rice of different organic amendments and nitrogen levels in an R-W cropping system at PAU, Ludhiana. Note: GM = green manure; FYM= farmyard manure; PM = poultry manure; NA = no application of amendment; N_0 = control, N_{50} = 50 kg N ha^{-1}; N_{75} = 75 kg N ha^{-1}; N_{100} = 100 kg N ha^{-1} (bars represent error bars).

Figure 2. Influence on plant height and dry matter accumulation of the application to rice of different organic amendments and nitrogen levels in an R-W cropping system at Dyal Bharang, Amritsar. Note: GM = green manure; FYM= farmyard manure; PM = poultry manure; NA = no application of amendment; N_0 = control, N_{50} = 50 kg N ha^{-1}; N_{75} = 75 kg N ha^{-1}; N_{100} = 100 kg N ha^{-1} (bars represent error bars).

3.2. Yield Attributes

With the exception of 1000-grain weight, which was not statistically impacted by the application of amendments or nitrogen levels during the study period at either location, the application of organic amendments and treatment with various nitrogen levels statistically boosted the yield component of rice during the study period (Table 1). At PAU and Amritsar, the application of poultry manure increased the number of productive tillers by 1.68 and 1.71 times, respectively, in comparison to the control treatment (NA). Similarly, among the various nitrogen levels, the application of 100 kg N ha^{-1} considerably improved the number of effective tillers compared to the control (N0), with the results being comparable to those with the application of 75 kg N ha^{-1}. PM resulted in a higher number of grains per panicle and longer panicles in comparison to incorporation of green manure and farmyard manure, and all three were statistically superior to with no amendment, for which the lowest grains per panicle value was observed. Significant increases in grains per panicle of 42.9 and 43.7% compared to the control treatment were observed at Ludhiana and Amritsar, respectively, with the application of 100 kg N ha^{-1}, which was on par with the results with the application of 75 kg N ha^{-1}, while statistically higher results were observed with both treatments than with the application of 50 kg N ha^{-1} and the no-N control.

Influence of amendments and nitrogen levels on growth and yield attributes of rice under the rice–wheat cropping system (pooled data of two years) are showed in Table 2.

Table 2. Influence of amendments and nitrogen levels on growth and yield attributes of rice under the rice–wheat cropping system (pooled data of two years).

Treatments	Plant Height (cm)		Dry Matter Accumulation (q ha^{-1})		Grains per Panicle (no.)		Effective Tillers (m^{-2})		Panicle Length (cm)		Grain Yield (q ha^{-1}) Rice		Grain Yield (q ha^{-1}) Wheat	
	PAU	AMR	PAU	AMR	PAU	AMR	PAU	AMR	PAU	AMR	PAU	AMR	PAU	AMR
Amendments application														
GM	326.4b	96.6b	179.7b	175.9b	125.8b	124.3b	329.5b	321.8b	24.2ab	23.6b	80.1a	79.2a	57.0b	55.5b
FYM	344.5a	95.9b	176.6b	172.8b	124.2b	122.6b	326.4b	318.4b	23.4b	22.7b	78.9b	78a	58.7b	57.2b
PM	205.0c	98.9a	183.7a	179.8a	133a	131.5a	344.5a	337.3a	25.6ab	25.0a	82.5a	81.6a	61.2a	59.6a
NA	91.2c	86.8c	73.9c	70.1c	96.6c	95.1c	205.0c	196.2c	20.6c	20.0c	50.4c	49.5b	49.1c	48.1c
Nitrogen levels														
N_0	89.2c	84.9c	72.1c	68.15c	94.1c	92.5c	200.6cd	192.4c	19.5c	18.8c	49.9c	49.6c	47.4c	46.0c
N_{50}	98.7c	94.3b	171.9b	168.0b	117.5b	115.9b	309.7bc	302.2b	22.6b	21.9b	74.6b	73.9b	55.3b	53.9b
N_{75}	103.1a	98.9a	183.7a	179.9a	133.6a	132a	344.6ab	336.1a	25.8a	25.1a	82.9a	81.8a	61.3a	59.7a
N_{100}	104.5a	100.2a	186.3a	182.5a	134.5a	133a	350.5a	343.0a	26.0a	25.3a	84.5a	83.6a	62.0a	60.4a

Identical letters within a column indicate no significant differences at the $p < 0.05$ level, determined by Tukey's multiple comparison test. GM = green manure; FYM = farmyard manure; PM = poultry manure; NA = no application of amendment; N_0 = control; N_{50} = 50 kg N/ha; N_{75} = 75 kg N/ha; N_{100} = 100 kg N/ha; PAU—Punjab Agricultural University, Ludhiana; AMR—Dyal Bharang, Amritsar.

3.3. Grain Yield of Rice

The application of poultry manure in rice resulted in a significant increase in grain yield compared to the other amendments, with 63.6% and 64.9% higher grain yield than control being recorded at the two locations. At Amritsar, grain yield was statistically equivalent for all three organic amendments, but the poultry manure treatment resulted in a numerically higher grain output, followed by green manure and farmyard manure. However, all three amendments outyielded the crop to which no amendment was applied. At Ludhiana, with the application of PM and GM, a statistically similar grain yield was observed, which was significantly better than the yield obtained with the application of farmyard manure. The grain yields of all three were significantly higher than those of the control, which was the lowest.

Significant variations in the grain yield of rice were also observed in response to different nitrogen levels throughout the study period. The application of 100 kg N ha^{-1} resulted in significant improvements in grain yield of 1.93% and 2.20% with respect to the 75 kg N ha^{-1} treatment in Ludhiana and Amritsar, respectively. Additionally, it resulted in a grain production increasing by 13.4% and 13.1%, respectively, in comparison to the application of 50 kg N ha^{-1}. Additionally, the grain yield of rice in the absence of nitrogen application (N0) was considerably lower than in all other treatments.

3.4. Grain Yield of Wheat

Upon perusal of the data related to the residual impact of amendments applied to rice on the wheat grain yield, it was observed that the treatment involving the application of poultry manure significantly increased grain yield by 1.70% and 1.74% compared to with the addition of farmyard manure (FYM). Furthermore, it led to increases in grain yield of 1.75% and 1.80% compared to with the incorporation of green manure (GM) in Ludhiana and Amritsar, respectively. When compared to treatments in which amendments were applied, the absence of amendment application (NA) resulted in a noticeably lower wheat grain yield. The impact of nitrogen levels on wheat grain yield were recorded as significant in both years of the study, and at both locations. Higher grain yields of wheat (62.1 q ha^{-1} and 60.4 q ha^{-1}) were obtained with the application of 100 kg N ha^{-1} (N100), values which are comparable to those obtained with 75 kg N ha^{-1} (61.3 q ha^{-1} and 59.7 q ha^{-1}), with the results of both treatments being statistically superior to 50 kg N ha^{-1} (N_{50}), which achieved yields of 55.3 q ha^{-1} and 53.9 q ha^{-1} at the two locations.

3.5. Soil Biological Properties

3.5.1. Microbial Population

Organic amendments of N fertilizer improve the biological properties of soil by enhancing microbial populations (bacteria, fungi and actinomycetes) and enzymatic activities. The microbial population was enumerated after the completion of two cycles of the RWCS. Among the various amendments and nitrogen levels applied, the treatment with the application of PM exhibited the highest bacterial growth (39.4×10^6 cfu g^{-1} soil) after the completion of the RWCS at both Ludhiana and Amritsar. Conversely, the lowest bacterial growth was observed for the treatment without amendment. Meanwhile, with respect to nitrogen rates, the highest rates of bacterial growth at both Ludhiana (39.4×10^6 cfu g^{-1} soil) and at Amritsar (38.0×10^6 cfu g^{-1} soil) were obtained with the treatment where 100 kg N ha^{-1} was applied, whereas the control treatment was associated with the lowest bacterial growth.

The treatment involving the application of PM showed the highest fungal population at both Ludhiana (27.3×103 cfu g^{-1} soil) and Amritsar (26.0×103 cfu g^{-1} soil). Conversely, the lowest fungal population was observed for the treatment without amendment. Additionally, of the different nitrogen levels, the treatment with 100 kg N ha^{-1} resulted in the highest fungal population (27.8×10^3 cfu g^{-1} soil) during the same period. No significant differences in actinomycete count were observed among the various amendments and nitrogen levels. However, relatively higher viable actinomycete counts were observed at both Ludhiana (31.2×10^4 cfu g^{-1} soil) and Amritsar (29.8×10^4 cfu g^{-1} soil) for the treatment in which poultry manure (PM) was applied during the 2019–20 season. The lowest actinomycete count was found for the treatment without amendment. Regarding nitrogen rates, the treatment with 100 kg N ha^{-1} resulted in the highest actinomycete count at both Ludhiana (31.2×10^4 cfu g^{-1} soil) and at Amritsar (28.7×10^4 cfu g^{-1} soil). Conversely, the control treatment exhibited the lowest viable count of actinomycetes.

3.5.2. Alkaline Phosphatase Activity (APA)

The activities of alkaline phosphatase were significantly influenced by various amendments, as well as by nitrogen levels, at both the 0–7.5 cm and 7.5–15 cm depths (Table 3). In the study conducted at Ludhiana and Amritsar, it was observed that the application of PM significantly enhanced alkaline phosphatase activity (APA) at a depth of 0–7.5 cm (44.2 µg, 35.4 µg). These increases were notably higher than the effects recorded with green manure (GM) and farmyard manure (FYM). Of the different nitrogen levels, 100 kg N ha^{-1} resulted in the highest alkaline phosphatase activity (46.7 µg, 37.9 µg) at both Ludhiana and Amritsar, whereas for the treatments with N_{75}, N_{50}, and N_0, lower alkaline phosphatase activities were observed.

Table 3. Influence of amendments and nitrogen levels on alkaline phosphatase activity and microbial count after completion of the rice–wheat cropping system (data pooled for two years).

Treatments	Alkaline Phosphatase (µg PNP/g/hr)		Viable Count (cfu g^{-1})					
	PAU	AMR	Bacteria (×10^6)		Fungi (×10^3)		Actinomycetes (×10^4)	
			PAU	AMR	PAU	AMR	PAU	AMR
Amendments application								
GM	39.9ba	31.1ba	38.1ab	36.7b	26.1a	24.6b	30.2ab	27.2b
FYM	41.6ba	32.8ba	37.0b	35.6b	25.0a	23.5b	29.5b	26.5b
PM	44.2a	35.35a	39.4a	38.0a	27.3a	26.0a	31.2a	29.8a
NA	31.2ba	22.35ba	32.3c	31.2c	20.1b	19.2c	23.2c	22.3c
Nitrogen levels								
N_0	29.1ba	20.2cb	31.9c	30.9c	19.8c	18.8c	22.1c	21.4c
N_{50}	35.9ba	27.1ba	36.5b	35.1b	24.4b	23.0b	28.5b	25.8b
N_{75}	45.2a	36.35a	38.6a	37.1a	26.5a	25.6a	30.5a	27.3a
N_{100}	46.7a	37.9a	39.8a	38.4a	27.8a	26.4a	31.2a	28.7a

Identical letters within a column indicate no significant differences at the $p < 0.05$ level, determined by Tukey's multiple comparison test. GM = green manure; FYM = farmyard manure; PM = poultry manure; NA = no application of amendment; N_0 = control; N_{50} = 50 kg N/ha; N_{75} = 75 kg N/ha; N_{100} = 100 kg N/ha; PAU—Punjab Agricultural University, Ludhiana; AMR—Dyal Bharang, Amritsar.

3.6. Nutrient Uptake

During the study years, nitrogen fertilizer (N) application considerably boosted rice grain, straw, and total (grain + straw) nutrient uptake (Table 4). It was observed that the total nutrient uptake increased significantly with the application of 100 kg N ha^{-1} and 75 kg N ha^{-1} compared to with the application of 50 kg N ha^{-1} and the control treatment. Total N, P and K uptake respectively increased by 2.08 and 2.10 times, 2.92 and 3.31 times, and 2.02 and 2.00 times with 100 kg N ha^{-1} at Ludhiana and Amritsar, respectively, compared to the control, with no application. In terms of organic amendments, the total N, P and K uptake by rice varied between 91.7 and 173.2 kg ha^{-1}, 11.5 and 29.8 kg ha^{-1}, and 99.2 and 176.2 kg ha^{-1} at Ludhiana, and 87.3 and 165.5 kg ha^{-1}, 9.2 and 25.6 kg ha^{-1}, and 91.9 and 167.2 kg ha^{-1} at Amritsar, respectively.

Table 4. Influence of amendments and nitrogen levels on N, P, and K uptake and N-use efficiencies of rice (data pooled for two years).

Treatments	Total N Uptake (kg/ha)		Total P Uptake (kg/ha)		Total K Uptake (kg/ha)		Production Efficiency (kg Grain kg^{-1} N Uptake)		Agronomic Efficiency (kg Grain kg^{-1} N Applied)		Apparent N Recovery (%)	
	PAU	AMR	PAU	AMR	PAU	AMR	PAU	AMR	PAU	AMR	PAU	AMR
Amendments application												
GM	162.9b	156.3b	25.5b	21.8b	165.7b	157.0b	51.2	52.6	38.45	38.05	56	54.5
FYM	157.1b	151.2b	23.9b	20.8b	157.7c	148.8b	49.95	52.8	38.4	37.9	57.5	54
PM	173.2a	165.5a	29.8a	25.6a	176.2a	167.2a	51.15	52.2	41.8	41.8	61.5	60.5
NA	91.7c	87.3c	11.5c	9.2c	99.2d	91.9c	24.85	21.75	6.1	4.5	18	15.5

Table 4. *Cont.*

Treatments	Total N Uptake (kg/ha)		Total P Uptake (kg/ha)		Total K Uptake (kg/ha)		Production Efficiency (kg Grain kg^{-1} N Uptake)		Agronomic Efficiency (kg Grain kg^{-1} N Applied)		Apparent N Recovery (%)	
	PAU	AMR	PAU	AMR	PAU	AMR	PAU	AMR	PAU	AMR	PAU	AMR
Nitrogen levels												
N_0	86.5c	82.2c	10.7c	8.3c	89.9c	85.0c	-	-	-	-	-	-
N_{50}	146.2b	140.3b	21.4b	17.6b	151.8b	143.6b	60.1	60.75	47.7	46.85	71.5	67.5
N_{75}	172.2a	164.9a	26.9a	22.7a	176.7a	166.5a	59.15	60.05	43.05	42	67.5	63.5
N_{100}	180.0a	172.9a	31.3a	27.5a	182.4a	170.4a	57.9	58.65	33.95	33.45	55	52.2

Identical letters within a column indicate no significant differences at the $p < 0.05$ level, determined by Tukey's multiple comparison test. GM = green manure; FYM = farmyard manure; PM = poultry manure; NA = no application of amendment; N_0 = control; N_{50} = 50 kg N/ha; N_{75} = 75 kg N/ha; N_{100} = 100 kg N/ha; PAU—Punjab Agricultural University, Ludhiana; AMR—Dyal Bharang, Amritsar.

3.7. N-Use Efficiencies

The production efficiency (PE_N), measured as the grain yield in relation to nitrogen uptake, exhibited a significant decline with increasing N fertilizer application rate in rice. The PE_N for rice ranged from 57.9 to 60.1 kg ha^{-1}, with the highest PE_N being recorded in the treatment with 50 kg N ha^{-1}, while the lowest PE_N was recorded with 100 kg N ha^{-1}. At both locations, the PE_N increased most with the application of farmyard manure (FYM) and green manure (GM), followed by poultry manure (PM), while the lowest production efficiency was observed in the treatment without amendment (NA). Agronomic efficiency (AE_N), which depicts economic yield per unit of nitrogen applied, was statistically significantly higher with poultry manure—by 87.3%—compared to without amendment at both Ludhiana and Amritsar. The agronomic efficiency (AE_N) of nitrogen (N) ranged from 33.9 to 47.7 kg kg^{-1} at Ludhiana, and 33.4 to 46.8 kg kg^{-1} at Amritsar. With respect to nitrogen levels, the highest AE_N values of 47.7 kg kg^{-1} at Ludhiana and 46.8 kg kg^{-1} at Amritsar were observed with the N_{50} treatment. The apparent nitrogen recovery (ANR) ranged from 55 to 72% at Ludhiana and 53 to 68% at Amritsar. The treatment with 50 kg N ha^{-1} provided the maximum ANR, while the treatment with 100 kg N ha^{-1} resulted in the lowest nitrogen recovery. In terms of organic amendments, the application of poultry manure resulted in a (61.6 and 60.5%) increase in apparent nitrogen recovery compared to treatment without amendment.

3.8. Relationship between Crop Yields, Soil Enzymatic Activities, N-Use Efficiencies and Nutrient Uptake

The correlation analysis demonstrated strong positive associations between rice and wheat grain yield and various factors in Ludhiana and Amritsar. Notably, significant positive correlations were recorded between grain yield and total nitrogen (N) uptake (r = 0.79, 0.77 $p < 0.01$), total phosphorus (P) uptake (r = 0.91, 0.88 $p < 0.01$), and total potassium (K) uptake (r = 0.77, 0.77 $p < 0.01$) at both locations (Figures 3 and 4). Additionally, there were significant positive associations between grain yield and agronomic efficiency (r = 0.81, $p < 0.01$), apparent nitrogen recovery (r = 0.80, $p < 0.01$), production efficiency (r = 0.85, $p < 0.01$), effective tillers (r = 0.94, $p < 0.01$), and grains per panicle (r = 0.91, $p < 0.01$). Bacterial, fungal, and actinomycete populations also showed positive and statistically significant correlations with grain yield. However, there were only slight positive correlations between alkaline phosphatase activity and the grain yield of rice (r = 0.46, $p < 0.01$) and N-use efficiency at both Ludhiana and Amritsar.

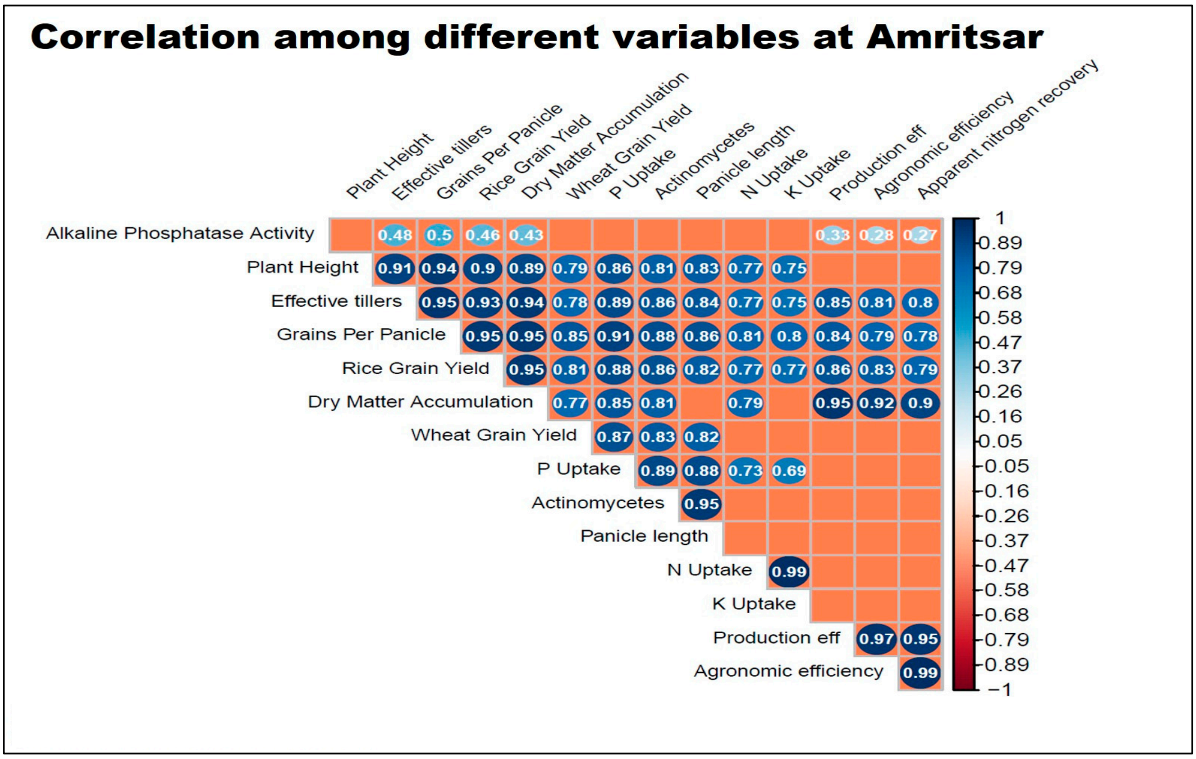

Figure 3. Correlation matrix depicting relationships between different variables and rice and wheat grain yield (the reported correlation coefficients are significant at $p < 0.05$; blanks indicate non-significant correlation).

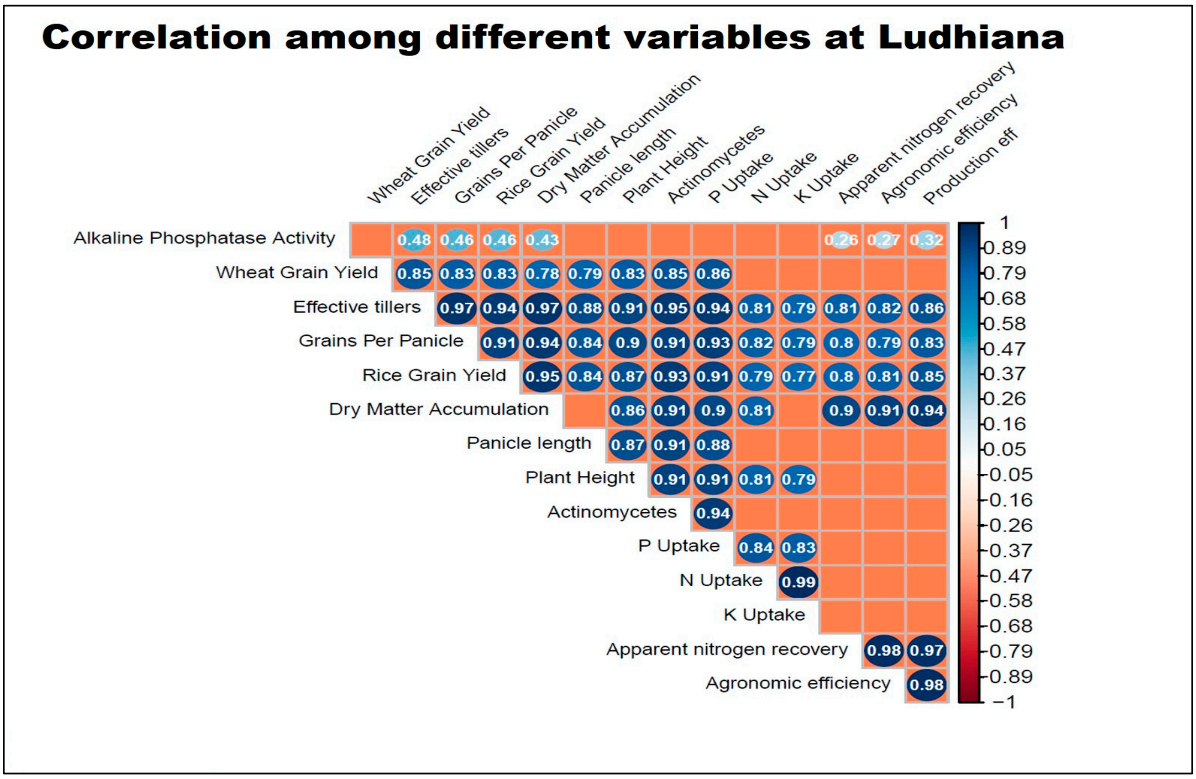

Figure 4. Correlation matrix depicting relationships between different variables and rice and wheat grain yield (the reported correlation coefficients are significant at $p < 0.05$; blanks indicate non-significant correlation).

4. Discussion

4.1. Impact of Organic Amendments and Nitrogen Levels on Crop Productivity

Integrated Nutrient Management (INM) can be used to effectively achieve balanced nutrition, especially in India's semiarid regions. By combining green manure, organic amendments, or other organic nutrient inputs with chemical fertilizers, it is possible to sustain crop yield levels without negatively affecting the status of organic carbon [49]. The present study demonstrates the beneficial effects of organic amendments and varied nitrogen levels on nutrient availability in rice cultivation and its consequential impact on subsequent wheat yield. In addition to creating the favorable conditions necessary for plant growth during the grain filling stage, the addition of PM, FYM, and GM supplies additional crucial nutritive substrates [50]. Similarly, a residual effect of PM was also evident in the subsequent wheat crop. According to earlier research, organic sources (PM, GM, and FYM) can provide balanced nutrition to plants, specifically by supplementing major nutrients with micronutrients, thus increasing grain production and yield. The research by Sharma et al. [51] corroborates these results.

Incorporating organic manures into the soil offers several benefits to crop plants, including increased availability of vital nutrients and the enhancement of critical soil characteristics like water retention and aeration. These improvements contribute to favorable conditions for seed germination and root development in crops [52]. According to Mehra and Singh [53], the highest grain and straw yield in wheat was achieved with the integration of PM, FYM, GM, and inorganic fertilizers. Additionally, the highest uptake of N, P, and K by the wheat plants was observed with this combination. In a study carried out by Irin et al. [54], it was found that the application of various amendments and higher nitrogen rates had a significant and positive impact on nitrogen contribution and its assimilation into the soil. Moreover, the study revealed that these practices also had a beneficial effect on the yield of succeeding crops.

4.2. Impact of Organic Amendments and Nitrogen Levels on Soil Microbiological Composition and Enzymatic Activity

The enzymatic activity and microbiological characteristics of soil are significantly impacted by the addition of organic amendments combined with chemical fertilizers. The presence of a diverse and active microbial community in the surface layer contributes to the decomposition of organic matter, nutrient cycling, and overall soil health. Research findings consistently demonstrate that incorporating poultry manure (PM), farmyard manure (FYM), and chemical fertilizers together leads to significant enhancements in soil biological properties. These improvements include increased microbial activity and improved soil health compared to the use of inorganic fertilizer alone [55]. Supplementing nutrients through the application of manure (PM, FYM, GM) and chemical fertilizers can lead to enhanced soil organic carbon (SOC) content, improved soil microbiological status, and better root development, which are increased further by the incorporation of plant residues [56].

Alkaline phosphatase is an agriculturally important enzyme, as it plays a vital role in the hydrolysis of organic P compounds, converting them into various forms of inorganic P that can be readily absorbed by plants [57]. Changes in the biological processes of soil can be effectively assessed by examining variations in enzyme activities [13], whereby treatment with poultry manure (PM) application exhibited the highest alkaline phosphatase activity (44.2 μg PNP g^{-1} of soil $hour^{-1}$), followed by farmyard manure (FYM) and green manure (GM), indicating variations in nutrient mobilization (Table 3). The findings from a previous study carried out by Mitran et al. [58] further support the notion that organic matter has a significant impact on soil enzyme activities. It was observed that treatments with higher bacterial populations exhibited higher alkaline phosphatase activity, indicating a relationship between microbial biomass and enzyme activity.

4.3. Impact of Organic Amendments and Nitrogen Levels on Nutrient Uptake and N-Use Efficiency

When the application rate of N fertilizer surpasses the crop's nitrogen demand, the utilization of the applied nitrogen by the crops decreases, increasing the amount of unused nitrogen in the soil or resulting in its loss. Conversely, the nitrogen content of the soil is depleted when the rate of N fertilizer is lower than the crop's need. According to Gill and Aulakh [59], the combined application of organic manures and nitrogen fertilizers, as well as different combinations of organic manures, results in increased nitrogen uptake in rice. This could be related to increased nitrogen availability in the soil and greater production. Additionally, combining organic manures with nitrogen fertilizers enhances phosphorus uptake through positive nitrogen–phosphorus synergy (Table 4). Similar findings have been observed by Rani and Sukumari [60] and Mohammed et al. [61]. The present study demonstrates that with each successive increase in nitrogen rate from 50 kg N ha^{-1} to 100 kg N ha^{-1}, along with the supplementation of amendments such as GM, FYM, and PM, there is an improvement in source-sink assimilation (Table 4). This improvement can be attributed to the increased binding of the nutrient supply to the crop plants for an extended period, coupled with consistent enhancement of physical, chemical, and biological properties in both consecutive years.

Nitrogen use efficiency encompasses various factors, such as production efficiency, apparent nitrogen recovery, and agronomic efficiency in crops. The availability of a nutrient to a plant affects its utilization efficiency. Niu et al. [62] observed that crops adapted to environments with low soil nitrogen availability tended to exhibit higher nutrient use efficiency. In the current study, the application of N fertilizer at a higher rate (N_{100}) led to a significant decrease in nitrogen use efficiency compared to N_{50}. These findings align with previous research, which also reported higher nitrogen use efficiency at lower application rates due to reduced losses. Rajneesh et al. [63] observed that the use of various manures in conjunction with chemical fertilizers under the RWCS increased the levels of N, P, and K. Several researchers have also suggested that a balanced approach to fertilization, combined with the incorporation of organic amendments, can enhance nutrient use efficiency while reducing environmental impacts. Considering the current scenario of increased fertilizer costs and grain prices, these findings hold significant relevance. Moreover, the incorporation of organic amendments offers potential benefits such as reducing the carbon footprint of arable farming and enhancing soil characteristics in order to support ecosystem services. This highlights the importance of exploring sustainable practices that not only optimize productivity but also promote environmental and economic sustainability.

5. Conclusions

Organic manures and chemical fertilizers boost microbial activity, soil health, and nutrient availability, increasing crop output in succeeding crops. Balanced amounts of minerals and organic amendments increased macronutrient (N, P, and K) accumulation and uptake. Poultry manure uptakes more total nitrogen (177.4 kg ha^{-1}), phosphorus (31.6 kg ha^{-1}), and potassium (179.6 kg ha^{-1}), making it more efficient and recovering more nitrogen than the control. Grain yield was positively correlated with total nitrogen, phosphorus, and potassium intake. Poultry dung increased microbial population and alkaline phosphatase activity, indicating soil health. The following wheat crop had a higher grain yield than the control due to chicken manure's residual effects. Poultry manure with 100 kg N ha^{-1} or 75 kg N ha^{-1} afforded equal yields, suggesting that even lower nitrogen doses could boost rice and wheat yields. In Punjab's loamy sand and clayey loam soils, effective management of organic amendments is crucial to sustaining agricultural productivity in the rice–wheat cropping system.

Author Contributions: Conceptualization, P.K. and K.S.S.; Methodology, P.K. and K.S.S.; Software, P.K. and J.K.; Validation, P.K., S.S. and R.B.; Formal Analysis, P.K. and J.K.; Investigation, P.K., K.S.S. and S.S.; Resources, S.S., K.S.S., S.A., A.T.A., S.H. and R.B.; Data Curation, P.K., J.K. and S.S.; Writing—Original Draft Preparation, P.K. and J.K.; Writing—Review and Editing, P.K., K.S.S., J.K. and R.B.; Visualization, P.K.; Supervision, K.S.S. and S.S. All authors have read and agreed to the published version of the manuscript.

Funding: Researchers Supporting Project number (RSP2023R194), King Saud University, Riyadh, Saudi Arabia.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to extend their sincere appreciation to the Researchers Supporting Project number (RSP2023R194), King Saud University, Riyadh, Saudi Arabia. The Agronomy and Soil Science department at PAU in Ludhiana and the Research Station Dyal Bharang in Amritsar generously supported the authors' field and lab studies, which the authors gratefully recognize. We also acknowledge the contributors of the field staff at the Student Research Farm, PAU and at Research Station Dyal Bharang, Amritsar.

Conflicts of Interest: The authors declare no conflict of interest.

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