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Exploring the potential of organic, mineral, organomineral, and biofertilizers on growth and yield attributes of *Triticum aestivum* L. and post-harvest soil

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ABSTRACT

Sustainable agriculture relies on fertilizers as they increase crop output; yet, their proper use is absolutely essential to reduce environmental pollution. From 2022 to 2024, a field experiment was conducted to evaluate the effect of different fertilizers on the growth and yield of Wheat (*Triticum aestivum L).* cultivated in a field in Kurukshetra, Haryana, India. The experiment was conducted in a randomized block design with 15 treatments and each with three replicates. The highest growth and yield parameters were recorded in plots treated with organomineral made by -50% recommended dose of fertilizers (RDF) + Composted Pond slurry (9 tons/ha) + *Azotobacter* (4 kg/ha), followed by treatments having Farmyard manure (8 tons/ha) + Poultry manure (8 tons/ha) + Composted Pond slurry (8 tons/ha) + *Azotobacter* (4 kg/ha) and recommended dose of mineral fertilizers. Organic and organomineral fertilizers positively influenced soil physical properties, resulting in higher nutrient release and improved biological properties. On the other hand, mineral fertilizer applications affect the physicochemical and biological properties of the soil. The study concluded that organomineral fertilizers strengthen the growth and yield attributes of the crops, with the organic fraction of mixed fertilizers being beneficial for soil health.

1. INTRODUCTION

Fertilizers boost crop production in various ways. They provide nutrients that maintain and improve soil fertility, resulting in increased crop output. In addition, fertilizers enable high-yielding cultivars to increase productivity significantly. High-yielding cultivars cannot produce higher yields without an adequate supply of essential nutrients from fertilizers [1]. Poor fertilization can result in nutrient deficiencies, which may negatively impact soil fertility and agricultural yield [2]. Soil deficient in nutrients such as nitrogen, phosphorus, potassium, magnesium, sulfur, and organic matter can result in reduced growth and yield and low soil fertility and microbial activity [3,4]. Fertilizers are often classified as organic and inorganic.

Organic fertilizers contain organic matter as well as macro and micronutrients. These nutrients are slowly released, resulting in a constant supply for long-term soil fertility [5,6]. Organic fertilizers improve soil structure, water-holding capacity (WHC), and microbial activity. However, their lower nutritional contents often require larger application rates. Inorganic fertilizers, on the other hand, are cheaper and release nutrients more quickly. However, their improper use may lead to soil acidification, decreased soil microbiota, and environmental challenges such as eutrophication [7-9]. Organomineral fertilizers, which blend organic and inorganic fertilizers, offer a balanced nutrient content that increases crop productivity and soil fertility [10]. Similarly, biofertilizers improve the availability of nutrients and promote agricultural sustainability [11,12]. Integrating mineral fertilizers with organic manures to create organomineral fertilizers is a better alternative for managing animal waste and restoring soil fertility [13]. Various researchers have stated that combining mineral fertilizers with organic sources significantly boosts the productivity of crops [12,14].

Rural areas produce significant amounts of organic waste, such as animal waste, poultry droppings, and pond slurry, that can be recycled as manure. In rural India, village ponds fulfill multiple purposes, frequently receiving wastewater from households and farm animals. After some time, suspended organic matter accumulates at the bottom, resulting in a nutrient-rich slurry. This nutrient-rich slurry possesses significant potential for use as manure.

Wheat (*Triticum aestivum L.*) serves as an essential food crop that meets substantial global demand and is grown across various regions around the world. It is India's second-largest food crop after rice, covers about 31 million hectares, and produces about 110 million tons [15]. Intensive agricultural practices and reliance on conventional mineral fertilizers have led to a decline in soil fertility and possess negative

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environmental impacts [7]. Hence, it is necessary to use sustainable production strategies to ensure long-term production and food security. Despite being suggested that organic and organomineral fertilizers could serve as alternatives to enhance crop productivity and support soil health, there is a limited comprehension of their comparative effects on wheat growth, yield, and soil characteristics. Developing effective fertilization strategies that balance productivity with long-term soil sustainability is significant. Thus, it is essential to evaluate the comparative potential of mineral, organic, and organomineral (pond slurry and poultry-based) fertilizers on the growth and yield attributes of wheat crops and various soil health parameters.

2. MATERIALS AND METHODS

2.1. Source of Materials

The seeds of wheat variety Super 252 were procured from a certified seed shop in Kurukshetra, Haryana. Poultry manure was bought from R.K Poultry Farm, located in Kurukshetra, Haryana. Moreover, pond slurry was collected from village ponds in Kurukshetra district. Vermicompost was prepared on-site using poly bags. In addition, *Azotobacter* biofertilizer was procured from Agro-Biotech Research Center Ltd. in Kerala, India. Organomineral fertilizers were developed by mixing and homogenizing the mineral, organic fertilizers, and binders like bentonite clay (2% w/w) in the ratio described in Table 1. Scientific literature generally categorizes organomineral fertilizers into two types. The first type consists of inorganic fertilizer mixed separately with organic fertilizers. In the second type, the inorganic and organic fractions are mixed in powdered form with a suitable binder and then granulated or pelletized [10]. Various nutrients, in different forms and quantities, can be incorporated into manure [16]. We used the first type of organomineral fertilizer in which mineral fertilizer (urea, single super phosphate, and muriate of potash) are mixed with organic fertilizers (poultry and pond slurry) in desired ratio. The chemical composition of organic manure utilized in preparation of organomineral fertilizer is given in subsection 3.1.

2.2. Analysis of Soil and Organic Manure

Soil samples from a depth of 0–15 cm were collected from the experimental site before sowing and after harvesting. These samples were dried in a hot air oven at 50°C. The physicochemical analysis of the soil was conducted using standard laboratory procedures. The pH and electrical conductivity (EC) were measured using a pH/EC/TDS/salinity meter (Systronics 372). Nitrogen content was analyzed by the micro Kjeldahl digestion distillation method (Pelican Kelplus-Supra LX VA) [17] while potassium content was determined by the Flame photometer method (Elico CL-378) [18]. Phosphorus content was determined by the ascorbic acid method [19], and calcium and magnesium content was determined by extracting in ammonium acetate solution and titrating against EDTA solution [20]. The acid digestion method was used to determine the organic carbon content [21] and the turbidity method [22] was used for sulfur estimation. In addition, WHC, porosity, bulk density (using a pycnometer), and activity of enzymes such as urease [23], alkaline phosphatase [24], and dehydrogenase [25] in post-harvest soil were analyzed.

Organic manure samples were analyzed for their N.P.K. content. Samples were digested using sulfuric acid for nitrogen analysis while nitric+perchloric acid for potassium and phosphorus analysis. The methods used for mineral analysis in manure were similar to those used for soil analysis.

Table 1: The experimental design of the fertilizer treatments.

S. No.	Treatments	Fertilizer combinations
1.	T1	100% recommended dose of mineral fertilizers – RDF at the rate 90:60:40 kg/ha N (Urea), P (Single super phosphate), K (Muriate of potash), and 60 kg urea at 45 days after sowing.
2.	T2	50% RDF
3.	T3	Poultry manure (12 tons/ha)+*Azotobacter* (7 kg/ha)
4.	T4	Composted Pond slurry (12 tons/ha)+Azotobacter (7 kg/ha)
5.	T5	Composted Pond slurry (18 tons/ha)+Azotobacter (10 kg/ha)
6.	T6	Composted Pond slurry (9 tons/ha)+poultry manure (9 tons/ha)+Azotobacter (4 kg/ha)
7.	T7	Composted Pond slurry (8 tons/ha)+Vermicompost (4 tons/ha)+Azotobacter (4 kg/ha)
8.	T8	Poultry manure (8 tons/ha)+Vermicompost (4 tons/ha)+Azotobacter (4 kg/ha)
9.	T9	Organomineral comprises 30% RDF+Poultry manure (9 tons/ha)
10.	T10	Organomineral comprises 50% RDF+Poultry manure (9 tons/ha)+Azotobacter (4 kg/ha)
11.	T11	Organomineral comprises 30% RDF+Composted pond slurry (9 tons/ha)
12.	T12	Organomineral comprises 50% RDF+Composted pond slurry (9 tons/ha)+Azotobacter (4 kg/ha)
13.	T13	Farmyard manure (8 tons/ha)+Poultry manure (8 tons/ha)+Composted pond slurry (8 tons/ha)+Azotobacter (4 kg/ha)
14.	T14	Poultry manure (3 tons/ha)+Composted pond slurry (3 tons/ha)+Vermicompost (6 tons/ha)
15.	T15	Farmyard manure (18 tons/ha)
16.	Control (C)	No fertilizer

2.3. Experimental Site and Design

A field experiment was conducted during the crop seasons 2022–2024 at a field in Marcheri, Kurukshetra, Haryana, India (N 30.044628, E 76.929583). The soil of the field site was brown in color, well-drained, and had a loamy texture. Before sowing, the land was irrigated and ploughed. We used a randomized block design to carry out the experiment. The net plot size was 2.3 × 2.7 m^2. Seeds were sown at a rate of 100 kg/ha in the month of December, and harvesting was done in the April. Dust mulching and hand weeding were done at regular intervals.

2.4.Climatic Conditions and Irrigation Pattern

The field study was conducted in Kurukshetra, Haryana, India, where the climate is subtropical. The average temperature in the region during the crop cycle is 6°C–30°C [Figure 1a]. The total rainfall in the area is about 400–500 mm. Around 80% of the total rainfall occurs in the monsoon season. In the winter season, rainfall is significantly less. It ranges from 0 mm to 15 mm during the crop cycle from November to April [Figure 1b] [26]. Crops depend on irrigation for the water needed. Based on water availability, 4–5 irrigations were scheduled in total. The first irrigation was planned at the crown root initiation stage

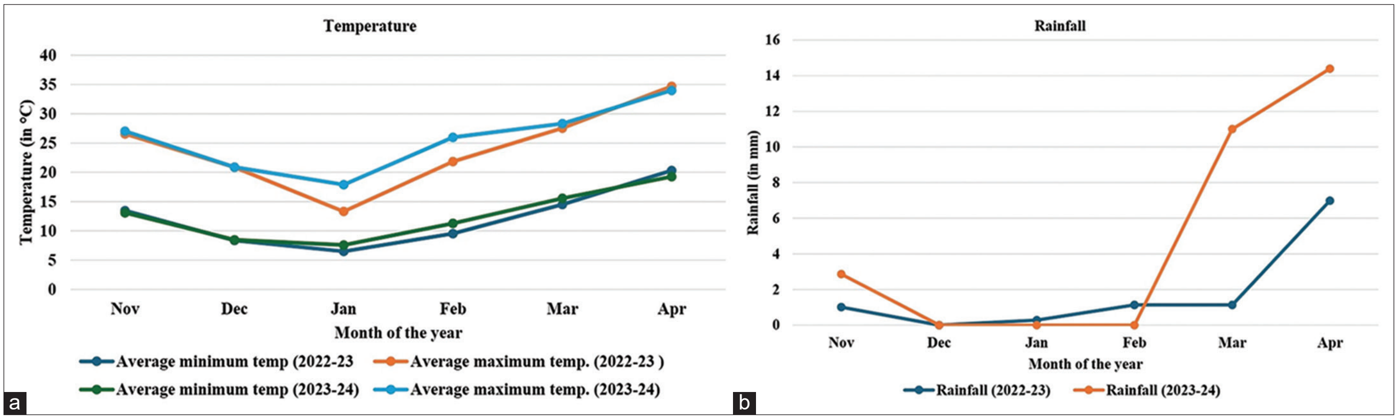

Figure 1: (a) Graph showing the average temperature changes in Kurukshetra during crop cycle. (b) Graph showing the total rainfall in different months in Kurukshetra during crop cycle.

(23 days after sowing [DAS]), the second at the first node stage, the third at jointing, and the fourth at the boot or milking stage.

2.5. Fertilizer Treatment and Application

The treatments included a control (no fertilizer) and 15 other combinations of manure, mineral fertilizer, and biofertilizers, with each treatment having three replicates. Table 1 provides the experimental design for each treatment. Numerous factors, such as nutritional requirements of crop, fertility status of soil, and prior research findings, are taken into consideration while determining fertilizer dosages in this study. In comparison to inorganic fertilizers, various researchers have evaluated the effects of varying dosages of farmyard manure and poultry (10–30 tons/ha) on wheat and found a significant rise in yield [27-29]. The recommended fertilizer doses were taken into consideration when formulating different fertilizer applications for wheat to ensure optimal growth and yield. Long-term agricultural sustainability depends on increasing agricultural productivity while preserving soil fertility [30]. Fertilizers play a vital role in agriculture, as their employment influences soil fertility and crop productivity, but their improper use can cause environmental problems [31]. Prolonged use of different fertilizers with improper management creates nutrient imbalances, soil salinity, acidification, loss of organic matter, and soil microbiota. Therefore, adopting sustainable nutrient management strategies including crop rotation, organic amendments, organomineral fertilizer, and precision fertilization is essential to preserve soil health while maximizing crop yields [32]. All treatment combinations were homogeneously spread in the field plots and lightly incorporated within the soil with the help of a rotavator.

2.6. Data Collection

Growth parameters such as plant height and leaf area index (LAI) [33] were recorded at 30, 60, and 90 DAS and at the harvesting stage. Additional parameters, including the number of tillers and dry matter content, were measured at the harvesting stage using standard procedures. Chlorophyll content was determined by the method given by Arnon [34]. For yield parameters such as spike length, seeds per spike, and test weight, ten plants were randomly chosen from the plots, and their average values were recorded. Harvesting and threshing were performed after 120 days, and other yield parameters such as grain, straw, and biological yield were documented and converted into kg/ha. The mean values of the two crop cycles are presented in the tables and graphs. Soil samples were collected post-harvest and analyzed for various parameters.

2.7. Statistical Analysis

The data were analyzed using analysis of variance (ANOVA) in R software [Version- R 4.2.1 (2023)]. The Fisher's least significant difference test at $P < 0.01$ was used for the *post hoc* comparisons to distinguish between the means of various treatments. ANOVA was also applied to soil data. A correlation matrix was generated to indicate the strength and direction of the relationship between soil parameters and yield, as shown in Figure 4.

3. RESULTS AND DISCUSSION

3.1. Soil, Manure, and Compost Analysis

The soil at the experimental field site had a pH of 7.9 and an EC of 258 µs/cm. The organic carbon content of the soil was 0.5%. Nutrient analysis revealed low levels of nitrogen (128.5 kg/ha), potassium (160 kg/ha), and phosphorus (12.39 kg/ha). However, the calcium (998 ppm) and magnesium (350 ppm) content were within optimal ranges. Poultry manure was characterized by N (2.15%), P (0.83%), and K (2.02%). Farmyard manure was found to have N (0.60%), P (0.28%), and K (0.48%). Vermicompost exhibited N (1.04%), P (1.15%), and K (0.10%). Composted Pond slurry had the highest nutrient content with N (2.76%), P (2.43%), and K (1.03%).

3.2. Growth Parameters

All vegetative growth parameters of *T. aestivum* (L.) were significantly influenced by different fertilizer combinations ($P < 0.01$). The highest plant height was observed in treatment T12, with values of 25.76 cm, 55.66 cm, 101 cm, and 103 cm at 30 DAS, 60 DAS, 90 DAS, and harvesting stages, respectively. This was followed by T13 (24.83 cm, 53.93 cm, 99.50 cm, 102.46 cm) and T10 (25.30 cm, 53.90 cm, 99.40 cm, 101.33 cm). The lowest plant height was recorded in the control treatment (no fertilizer), with values of 15.83 cm, 39.03 cm, 85.16 cm, and 89.03 cm, followed by T15 (17.20 cm, 45.33 cm, 92.20 cm, 95.90 cm) and T8 (21.06 cm, 46 cm, 92.40 cm, 95.70 cm). The LAI also showed significant variation, with the highest values observed in T12 (0.67, 2.71, 3.82 at 30 DAS, 60 DAS, and 90 DAS, respectively), followed by T1 (0.59, 2.55, 3.63) and T13 (0.60, 2.42, 3.52). The control treatment recorded the lowest LAI values (0.25, 0.97, 1.49), followed by T15 (0.31, 1.17, 1.86) and T2 (0.33, 1.15, 1.83) [Figure 2a and b]. Values recorded for other treatments were statistically at par. Chlorophyll content at 60 DAS was significantly higher in T12 (1.82 mg/g FW) and T1 (1.78 mg/g FW), followed by T13 (1.73 mg/g FW) and T5 (1.66 mg/g FW). The control treatment

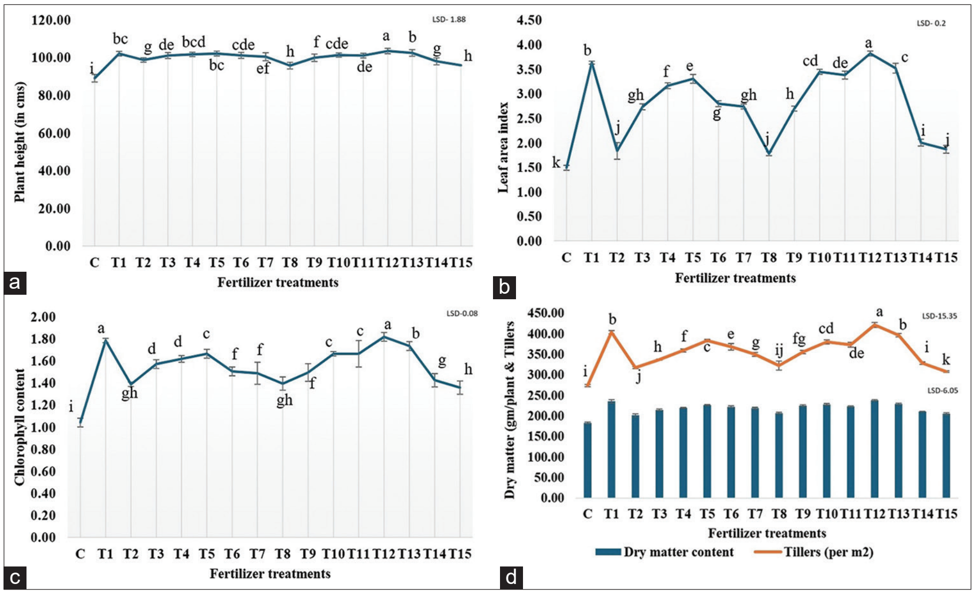

Figure 2: (a-d) Effect of different organic, mineral, organomineral, and biofertilizers on various growth parameters (a- Plant height [ω^2 = 0.98, 95% CI], b- Leaf area index [ω^2 = 0.97, 95% CI], c- Chlorophyll content [ω^2 = 0.97, 95% CI], d- Dry matter content and no of tillers [ω^2 = 0.98, 0.99, 95% CI]) of wheat. For treatment details, please refer to material and methods; values having similar superscripts are the same at $P < 0.01$.

had the lowest chlorophyll content (1.04 mg/g FW), followed by T15 (1.36 mg/g FW) and T14 (1.42 mg/g FW) [Figure 2c].

The highest values of tillers per square meter and dry matter content at the harvest stage were observed in T12 (421.66 and 238.5 g/plant), followed by T1 (404 and 236.66 g/plant) and T13 (396.66 and 229.66 g/plant). In contrast, the control treatment had the lowest values for tillers per square meter and dry matter content (274 and 182.89 g/plant), followed by T15 (308 and 201.66 g/plant) and T2 (317 and 205.18 g/plant) [Figure 2d].

Our results showed significant variations with different treatments in growth attributes such as height, LAI, dry matter content, number of tillers, and chlorophyll content. The organomineral fertilizers combined with biofertilizers (T12) showed the highest height, LAI, chlorophyll content, number of tillers, and dry matter content. This was followed by T1 (mineral fertilizers) and T13 (organic manures + biofertilizers). The lowest significant effects were observed in treatments with sole organic manure and lower doses of mineral fertilizers (T15, T14, and T2).

The use of no fertilizer treatment as a control in this study serves as a basis for analyzing the impact of the different fertilizer treatments on growth and production. This assessment enables us to evaluate the inherent soil fertility and the improvements made by applying various organic, inorganic, and organomineral fertilizers. Nutrient-deficient soil leads to reduced crop yields. This emphasizes the significance of fertilizers in preserving soil fertility and ensuring crop productivity [2]. Plants need a range of macro and micronutrients from the soil for their growth and development. Throughout their life cycle, they take up significant amounts of nutrients from the reserved pool of soil. We should replenish this pool after each harvest to ensure long-term agricultural sustainability [9]. Ye *et al*. [35] reported that plots treated with biochar-based fertilizer had a 25% higher yield in comparison to no fertilizer treatments.

The improvements in growth parameters resulting from the use of organomineral fertilizer may be attributed to the increased availability of essential nutrients for the growth and development of plants. These fertilizers enhance soil characteristics by increasing organic matter content, which benefits soil bacteria crucial for nutrient release and solubilization [36]. Organomineral fertilizers have an advantage over mineral fertilizers because they provide a variety of macro and micronutrients in addition to the organic fraction. This combination allows the fertilizers to function both as a gradual release (from the organic fraction) and a fast-release (from the mineral fraction) source of nutrients [37,38]. In contrast, the sole application of organic manure and the lowest dosages of mineral fertilizers can result in nutrient deficiencies in the soil, negatively affecting crop growth and yield.

3.3. Yield Parameters and Yield

Highly significant differences at $P < 0.01$ were present between the means of different fertilizer combinations, indicating that all fertilizer combinations significantly affected yield and yield parameters [Table 2]. The yield parameter spike length was significantly highest in T12 (13.33 cm), followed by T13 (12.94 cm) and T1 (12.90 cm). The lowest spike length was observed in control (No Fertilizer), followed by T2 (11.23 cm) and T8 (11.57 cm). The number of grains per spike was highest in T12 (54.80), followed by T1 (52.74) and T13 (52.53), while the lowest values were recorded in control (38.50), followed by T15 (41.88) and T8 (43.42).

For test weight (1000 grains), T12 recorded the highest value (45.39 g), followed by T1 (45.13 g) and T13 (44.52 g). The lowest test weight was recorded in C (40.32 g), followed by T2 (41.97 g) and T15 (41.57 g) [Table 2].

In terms of yield [Figure 3], the highest grain yield (61.84 q/ha) was recorded in the treatment T12, followed by T13 (59.40 q/ha) and T1 (58.44 q/ha). The control treatment had the lowest grain yield (35.97 q/ha), followed by T15 (46.46 q/ha) and T2 (46.94 q/ha). Similar trends were observed in straw and biological yield, with T12 showing the highest values (81.31 q/ha and 143.16 q/ha, respectively), followed by T1 (79.24 q/ha and 138.64 q/ha) and T13 (77.27 q/ha and 135.71 q/ha). However, the lowest straw and biological yield were also recorded in control (48.81 q/ha and 84.79 q/ha), followed by

Table 2: Effect of different organic, mineral, organomineral, and biofertilizers on yield attributes.

Treatment	Grains per spike	Test weight (1000 grains in grams)	Spike length (in cms)	Harvest index
C	38.50±0.36^{l}	40.32±0.12^{l}	9.17±0.06^{i}	42.43±0.24^{g}
T1	52.74±0.24^{b}	45.13±0.05^{b}	12.90±0.17^{b}	42.85±0.17^{f}
T2	43.75±0.45^{j}	41.97±0.07^{j}	11.23±0.25^{h}	43.27±0.14^{cde}
T3	46.11±0.18^{h}	42.65±0.11^{i}	11.80±0.10^{ef}	43.45±0.17^{bc}
T4	47.96±0.18^{g}	43.45±0.06^{e}	12.10±0.17^{d}	43.22±0.23^{cde}
T5	51.89±0.30^{cd}	43.92±0.04^{d}	12.74±0.07^{b}	43.43±0.29^{bcd}
T6	49.42±0.52^{f}	43.56±0.06^{e}	12.43±0.06^{c}	43.14±0.09^{cdef}
T7	47.65±0.33^{g}	43.04±0.06^{g}	12.03±0.12^{d}	43.77±0.35^{ab}
T8	43.42±0.72^{j}	42.55±0.10^{i}	11.57±0.06^{g}	42.95±0.15^{ef}
T9	48.45±1.27^{g}	42.84±0.07^{h}	11.97±0.21^{de}	43.23±0.08^{cde}
T10	51.05±0.09^{de}	43.99±0.11^{d}	12.73±0.12^{b}	43.12±0.16^{cdef}
T11	50.45±0.51^{e}	43.21±0.08^{f}	12.83±0.12^{b}	43.42±0.05^{bcd}
T12	54.80±0.44^{a}	45.39±0.16^{a}	13.33±0.15^{a}	43.20±0.09^{cde}
T13	52.53±0.13^{bc}	44.52±0.16^{c}	12.94±0.07^{b}	43.07±0.10^{def}
T14	45.14±0.24^{i}	42.09±0.06^{j}	11.70±0.00^{fg}	43.30±0.44^{cde}
T15	41.88±0.65^{k}	41.57±0.16^{k}	11.73±0.21^{fg}	44.02±0.32^{a}
Least significant difference	0.49	0.17	0.35	0.4
ω^2	0.98	0.97	0.97	0.98

For treatment details, please refer to material and methods; values having similar superscripts are the same at $P<0.01$. ω^2 (effect size) at 95% CI.

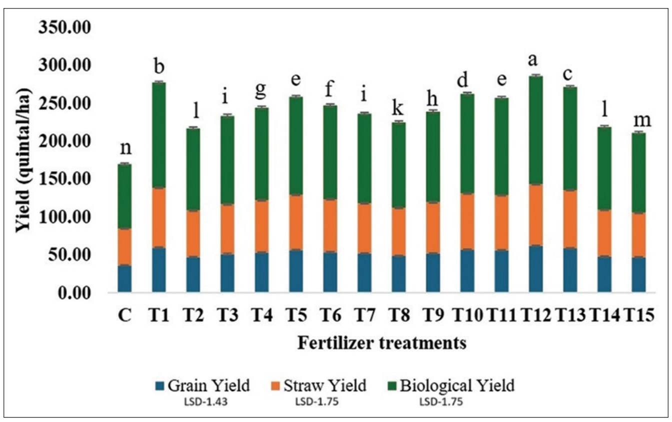

Figure 3: Effect of different fertilizer treatments on yield attributes of wheat (ω^2 = 0.98, 95% CI).

T15 (59.09 q/ha and 105.55 q/ha) and T2 (61.54 q/ha and 108.48 q/ha). The percent harvest index showed the highest values in T1 (44.02), followed by T7 (43.77) and T3 (43.46). The lowest values were observed in control (42.43), followed by T1 (42.84) and T8 (42.94).

Yield parameters, including spike length, seeds per spike, and test weight, were significantly higher in the *Azotobacter*-fortified organomineral fertilizer (T12), followed by T1 and T13. Similar findings were recorded for biological and grain yield as recorded with other yield parameters. However, slightly different trend was observed in harvest index, having maximum values in treatment T15, followed by T7 and T3. The harvest index is slightly higher in these treatments due to lower straw yield than grain yield. Chen *et al*. [39] also reported an increase in grain yield in wheat while using organic fertilizers. Yang *et al*. [13] studied the effects of different organic and organomineral fertilizer sources on wheat and maize fields and suggested that organomineral fertilizers change the soil structure that helps in better growth and yield of crops. Similarly, Egbuchua and Enujeke [40] observed an increase in the yield parameters and overall yield when using poultry-derived organomineral fertilizers in *Oryza sativa*.

An increase in the yield and yield attributes of wheat with the application of organomineral fertilizers was also reported by Azad *et al*. [41] and Makenova *et al*. [29]. Similarly, a study by Adeniyan and Ojeniyi [42] discovered that applying 3 tons/ha of poultry manure and 260 kg/ha of NPK fertilizer produced the highest grain yield, increased nutrient uptake, and higher dry matter content. Genrietta *et al*. [28] also found that combining 15 tons/ha of cow dung manure with NPK fertilizers increased yields by 70% compared to plots that did not receive fertilizer. In addition, Moe *et al*. [43] found that combining 50% of the recommended inorganic fertilizer dose with poultry manure significantly increased rice yield.

Optimal plant growth is crucial for achieving higher yields and enhancing crop quality. Organomineral fertilizers gradually release nutrients that give continual support during the growth and reproductive phases. This controlled release of nutrients improves nutrient uptake, increasing plant growth and yields [10]. The T12 treatment, an organomineral fertilizer fortified with biofertilizer, produced the highest yield, probably due to the combined action of organic, mineral, and biofertilizers. Mineral fertilizers are manufactured materials that provide essential nutrients directly to plants, enhancing growth and yield. At the same time, organic manures improve the biological activity of the soil, leading to better nutrient immobilization and availability of applied nutrients [5]. Other workers also reported that biochar and urea-based organomineral fertilizers increase yield compared to control [44]. Similarly, a 50% increase in yield and the number of pods were observed when assessing the effects of filter cake and mineral fertilizer-based organomineral fertilizer on beans [45].

Researchers reported that microbial communities in the rhizosphere region of the root synthesize plant growth-promoting substances, resulting in improved plant growth and yield. Furthermore, an increase in yield parameters and yield owing to the *Azotobacter* application may be credited to the alleviated fixation of nitrogen, growth hormone production, and enhancing soil microbial activity, collectively improving plant nutrient availability. Several other researchers have reported similar findings that *Azotobacter* when applied with organic fertilizers results in a considerable increase in the yield [11,46,47].

Azotobacter, a free-living nitrogen bacterium, improves the availability of nitrogen and serves as an alternative to mineral fertilizers [48]. In addition to nitrogen fixation, *Azotobacter* produces secondary metabolites, particularly phytohormones, and exopolysaccharides (EPS), which are absent in mineral fertilizers. The primary mechanisms by which *Azotobacter* acts as a biostimulant to promote the growth and development of plants include nitrogen fixation. This process involves the reduction of nitrogen gas to ammonia, catalyzed by nitrogenase [49]. Furthermore, these diazotrophs can solubilize insoluble phosphorus in the soil [50]. Various studies have reported that *Azotobacter* strains can solubilize approximately 43% of phosphate rock in Egypt [51]. Another study highlighted that *Azotobacter* secretes EPSs, which play a crucial role in phosphorus solubilization [52]. Numerous studies have identified and quantified organic acid compounds produced by *Azotobacter*, confirming their role in nutrient solubilization. The widely accepted mechanism behind phosphorus solubilization involves the action of low–molecular-weight organic acids [53,54].

Furthermore, many researchers noticed that the suspension culture of *Azotobacter* contained phytohormones such as auxin, cytokinins, and gibberellins [55]. *Azotobacter* produces these phytohormones, which improve root formation and encourage plant growth. Applying *Azotobacter* mixed with organic manures to wheat will improve phosphorus uptake, increase root biomass, and improve grain yield [56,57]. It has been shown to replace 47.6 kg of nitrogen per hectare while maximizing wheat yield [57]. In short, *Azotobacter* serves as a biofertilizer to compensate or possibly increase the benefits of mineral fertilizers by nutrient solubilization.

3.4. Physical Attributes of Post-harvest Soil

The data presented in Table 3 show how the physical characteristics of the soil changed after various fertilizer treatments were applied. The pH varied very little between treatments, from 7.99 in the control to 8.32 in T1. Nonetheless, EC showed a noticeable change in pre-harvest and post-harvest soil. T1 had the highest EC value (0.43 ds/cm) in comparison to the control, while T15 had the lowest (0.29 ds/cm). When compared to pre-harvest soil, other physical characteristics of the soil, such as porosity and WHC, were significantly increased ($P < 0.001$). The highest WHC and porosity were shown by T13 (51.12%, 45.09%), while the lowest values were observed in T2 (45.82%, 41.49%), respectively. Bulk density was highest in T1 (1.48 g/cm^3) and lowest in T13 (1.21 g/cm^3).

Applying different nutrient sources resulted in several physiochemical changes in the soil. The pH change after harvest was not larger than that in the control. Nonetheless, the EC of the post-harvest soil indicated a major change in inorganic fertilizers (T1, T2). Prolonged use of inorganic fertilizers has been shown to elevate EC levels and reduce soil pH [45]. This can negatively impact soil fertility, hinder plant growth, and increase the risk of soil acidification [58-60].

An increase in the bulk density was observed in the case of inorganic fertilizer treatments (T1 and T2) compared to the control. In contrast, a decrease in the bulk density was noted with organic and organomineral fertilizers.

Table 3: Effect of different organic, mineral, organomineral, and biofertilizers on physical properties of soil.

Treatment	pH	EC (ds/cm)	BD (g/cm3)	OC (%)	WHC (%)	Porosity (%)
T1	8.32±0.010^{a}	0.43±00.3^{a}	1.48±0.004^{a}	0.613±0.00^{a}	46.15±0.07^{h}	42.95±0.03^{fg}
T2	8.15±0.005^{f}	0.35±0.005^{de}	1.44±0.005^{b}	0.553±0.00^{i}	45.82±0.08^{h}	41.49±0.04^{i}
T3	8.06±0.005^{k}	0.32±0.004^{gh}	1.31±0.028^{g}	0.7±0.01^{j}	49.05±0.43^{de}	44.45±0.13^{b}
T4	8.09±0.000^{j}	0.31±0.005^{h}	1.33±0.057^{fg}	0.68±0.00^{cde}	48.83±0.11^{e}	43.9±0.06^{c}
T5	8.12±0.003^{h}	0.37±0.015^{c}	1.21±0.011^{j}	0.693±0.01^{bc}	50.25±0.06^{b}	44.31±0.12^{b}
T6	8.13±0.005^{g}	0.36±0.005^{cd}	1.23±0.010^{i}	0.683±0.01^{cd}	49.01±0.10^{de}	43.92±0.04^{c}
T7	8.05±0.005^{kl}	0.33±0.000^{fg}	1.26±0.005^{h}	0.633±0.00^{gh}	47.74±0.16^{f}	42.92±0.11^{fg}
T8	8.04±0.006^{l}	0.33±0.010^{fg}	1.28±0.000^{h}	0.623±0.01^{hi}	47.31±0.22^{g}	42.77±0.02^{g}
T9	8.1±0.004^{i}	0.34±0.010^{f}	1.4±0.011^{ef}	0.666±0.00^{ef}	47.67±0.12^{f}	42.53±0.02^{h}
T10	8.2±0.015^{d}	0.4±0.005^{b}	1.37±0.015^{cd}	0.683±0.01^{cd}	48.99±0.03^{de}	43.7±0.12^{d}
T11	8.21±0.010^{c}	0.35±0.005^{e}	1.37±0.011^{fg}	0.66±0.00^{f}	49.16±0.57^{cd}	43.1±0.02^{f}
T12	8.28±0.005^{b}	0.4±0.002^{b}	1.34±0.008^{de}	0.673±0.00^{def}	49.32±0.07^{de}	44.37±0.21^{b}
T13	8.16±0.005^{e}	0.35±0.001^{de}	1.21±0.009^{i}	0.753±0.00^{a}	51.12±0.18^{a}	45.09±0.10^{a}
T14	8.02±0.017^{m}	0.32±0.000^{gh}	1.28±0.013^{h}	0.64±0.01^{g}	49.61±0.09^{c}	43.34±0.31^{e}
T15	8.01±0.006^{m}	0.29±0.003^{i}	1.22±0.007^{i}	0.63±0.01^{gh}	49.13±0.04^{de}	43.11±0.02^{f}
C	7.99±0.005^{n}	0.26±0.004^{j}	1.41±0.006^{c}	0.51±0.01^{k}	45.16±0.05^{i}	39.99±0.03^{j}
Least significant difference	0.01	0.01	0.03	0.01	0.3	0.2
ω^2	0.99	0.95	0.92	0.96	0.97	0.98

For treatment details, please refer to material and methods; values having similar superscripts are the same at $P<0.01$. ω^2 (Effect size) at 95% CI, EC: Electrical conductivity, BD: Bulk density

OC: Organic carbon, WHC: Water-holding capacity.

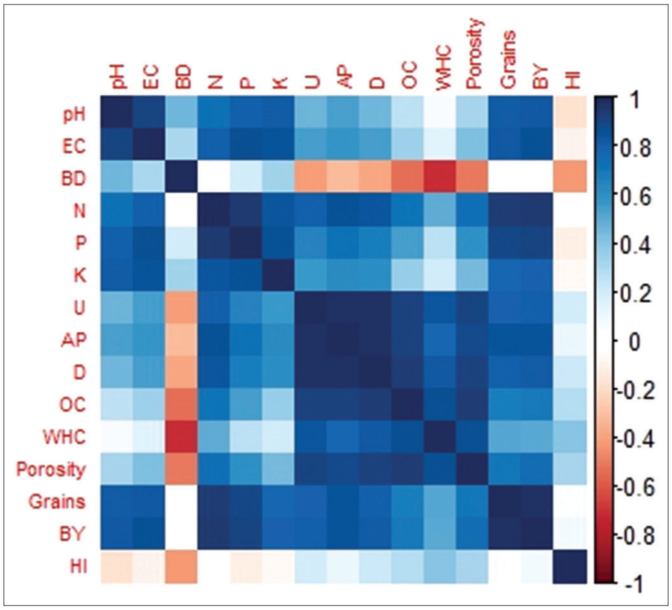

Figure 4: Heatmap showing the correlation among different soil and yield parameters. (Where, EC: Electrical conductivity, BD: Bulk density, N: Nitrogen, P: Phosphorus, K: Potassium, U: Urease, AP: Alkaline phosphatase, D: Dehydrogenase, OC: Organic carbon, WHC: Water-holding capacity, Grains: No. of grains, BY: Biological yield, HI: Harvest index).

Conversely, WHC and porosity increased with organic and organomineral fertilizers. The low organic carbon content of inorganic fertilizers resulted in soil compaction or high bulk density [61]. Higher bulk density reduces pore space and water drainage, which can hinder root development, ultimately suppressing plant growth and yield [62,63].

The heatmap analysis [Figure 4] indicates the distinct relationship between various soil and yield parameters. The varying degree of positive and negative correlation presents among the different parameters. The strong positive correlation between pH, EC, nutrient content, and biological yield highlighted the significance of these factors in maintaining crop growth and yield. Researcher reported that pH and EC are essential for preserving soil's osmotic balance. In the meantime, vital nutrients such as N.P.K. found in fertilizers are necessary for important plant functions such as metabolism, ATP synthesis, protein synthesis, and growth [9,46,59].

A strong positive correlation was also found between soil enzymatic activities, porosity, WHC, and organic carbon. This indicates the importance of organic carbon for improving soil structure and WHC [60]. Organic carbon present in the soil also influences better microbial activity. By immobilizing and recycling nutrients, soil microbiota help plants grow and produce more [10].

Bulk density also showed a strong negative correlation with soil enzymatic activities, organic carbon content, porosity, WHC, and yield attributes. Researchers suggested that long-term use of inorganic fertilizer causes a decrease in the organic fraction of soil, which causes soil compaction and negatively impacts growth and yield [58,61,62]. Furthermore, porosity and water retention capacity are negatively correlated with soil compaction, leading to poor water infiltration. Highly compacted soil results in reduced nutrient immobilization and stunted plant growth. Soil compaction caused by the long-term application of inorganic fertilizer creates a serious concern in farming [13,61,63]. Organic manures must be incorporated into the soil to improve soil fertility and long-term agricultural sustainability [5].

The physical characteristics of soil are important indicators of soil health because they directly impact vital processes such as drainage, temperature regulation, root development, nutrient uptake, and yield [64,65]. Compacted soil has a higher bulk density, which decreases porosity, preventing water infiltration. It raises aeration stress and affects nutrient recycling. It also inhibits root growth, reduces mycorrhizal fungal populations, and encourages denitrification [65,66]. Improved soil aggregation, on the other hand, facilitates carbon sequestration and increases microbial activity. The improved water and nutrient transport lowers soil erosion and promotes root growth and crop productivity [67].

Bulk density and agricultural yield are inversely correlated by many researchers [67,68]. Furthermore, soil pH and EC are important determinants of nutrient availability and are indicators of soil health. They directly affect crop productivity by limiting the absorption of vital nutrients such as calcium, phosphorus, potassium, and nitrogen by roots [69].

Further research should focus on nutrient management strategies that promote soil nutrient cycling and boost the effectiveness of nutrient utilization. Developing sustainable nutrient management strategies that limit the loss of nutrients due to leaching and volatilization while yet providing enough nutrient availability for crops would increase fertilizer use efficiency while contributing to soil health improvement [70]. Furthermore, such approaches will assist in reducing environmental degradation caused by runoff from fertilizers.

3.5. Nutrient Status and Biological Activity

Over the period, a significant increase was observed in the nutrient status and microbiota of the soil. Nitrogen (N), phosphorus (P), and potassium (K) content were all high ($P < 0.001$) but differed significantly among different treatments. The highest change in N.P.K. content between pre-harvest and post-harvest soil was observed in the organomineral treatment T12 with N (179.40 kg/ha), P (18.5 kg/ha), and K (185 kg/ha), while the lowest change was observed in T15 and T2 [Table 4] in comparison to control. Similar trends were observed in calcium content, while magnesium and sulfur content showed the lowest change in the treatment, with sole inorganic fertilizers T1 and T2. The maximum change was observed in the organomineral and high-dose organic fertilizers T12 and T13 [Table 4].

Organic carbon in the soil is responsible for the growth and development of microbiota. The organic carbon content was significantly lower in the pre-harvest soil, and considerable change was observed among treatments. The highest organic carbon content was recorded in T13 (.75 %) and the lowest in T2 and T1 (0.55% and 0.61%, respectively). The biological activity of the soil is measured in terms of enzymatic activity. Various enzyme assays such as urease, dehydrogenase, and alkaline phosphatase significantly increased ($P < 0.001$) in soil enzymatic activity among treatments. Compared to the control, the highest enzymatic activity was observed in organic fertilizer treatment T13, while the lowest was in inorganic fertilizer treatment T2 [Table 4].

Inorganic fertilizers offer immediate nitrogen availability, whereas organic and organomineral treatments facilitate a gradual release of nitrogen over time [71]. The consistent availability of other nutrients, such as phosphorus and potassium, is presumably due to the solubilization of nutrients by organic acids produced by the

Table 4: Effect of different organic, mineral, organomineral, and biofertilizers on nutrient content and enzymatic activity of soil.

Treatment	N (kg/ha)	P (kg/ha)	K (kg/ha)	Urease (µg of urea hydrolyzed g^{-1} soil h^{-1})	Alkaline phosphatase (µg of p-nitrophenol g^{-1} h^{-1})	Dehydrogenase (µg of p-Triphenyl Formazan g^{-1} h^{-1})
T1	159.43±2.13^{c}	18.23±0.15^{ab}	170.43±2.18^{b}	199.74±1.58^{fg}	105.2±0.60^{i}	34.12±0.24^{g}
T2	101.13±1.10^{l}	14.94±0.16^{g}	145.16±5.0^{gh}	184.04±3.49^{i}	92.6±0.361	27.31±0.07^{i}
T3	133.76±3.28^{ij}	15.96±0.25^{e}	149.50±0.43^{defg}	208.71±4.71^{d}	110.43±0.35^{f}	38.01±0.16^{e}
T4	143.6±1.44^{fg}	16.83±0.28^{d}	150±1.73^{ef}	204.54±4.12^{def}	109.23±0.30^{g}	37.51±0.48^{e}
T5	161.03±1.70^{c}	17.23±0.23^{c}	155.06±1.00^{c}	218.37±2.80^{bc}	115.13±0.30^{d}	40.9±0.13^{c}
T6	150.43±1.45^{e}	16.7±0.10^{d}	151.76±1.09^{cde}	215.69±4.97^{c}	112.26±0.40^{e}	39.92±0.14^{d}
T7	136.83±1.56^{hi}	15.83±0.15^{ef}	147.66±4.04^{efg}	195.25±4.71^{gh}	99.7±0.10^{jk}	32.42±0.29^{h}
T8	130.7±1.65^{j}	15.6±0.10^{f}	146.66±3.51^{fg}	193.83±3.15^{h}	99.1±0.70^{k}	32.16±0.08^{h}
T9	140.56±1.34^{gh}	15.9±0.11^{ef}	147.50±3.12^{efg}	218.74±1.26^{bc}	117.1±0.34^{c}	42.85±0.26^{b}
T10	174.4±0.52^{b}	18.06±0.20^{b}	182.4±2.13^{a}	206.01±1.18^{d}	110.1±0.78^{f}	37.74±0.55^{e}
T11	144.6±4.75^{f}	16.06±0.20^{e}	155.7±0.46^{c}	221.36±3.55^{b}	120.4±0.91^{b}	43.18±0.34^{b}
T12	179.4±0.90^{a}	18.5±0.45^{a}	185±4.35^{a}	204.98±3.77^{de}	107.9±0.52^{h}	37.98±0.13^{f}
T13	155.06±5^{d}	16.5±0.21^{d}	152.66±3.05^{cd}	233.08±3.07^{a}	127.53±0.75^{a}	45.5±0.55^{a}
T14	109.26±1.27^{k}	14.1±0.10^{h}	141.83±0.85^{h}	198.96±0.65^{gh}	99.56±0.20^{j}	34.47±0.55^{g}
T15	102.83±0.721	13.2±0.20^{i}	141.36±0.28^{h}	200.23±1.00^{efg}	100.53±0.58^{j}	34.59±0.53^{g}
C	79.6±0.60^{m}	13.16±0.37^{i}	135±4.35^{i}	170.18±0.99^{j}	85.03±0.76^{m}	22.03±0.20^{j}
Least significant difference	3.7	0.3	4.75	5.1	0.8	0.5
ω^2	0.99	0.97	0.93	0.93	0.99	0.99

For treatment details, please refer to material and methods; values having similar superscripts are the same at $P<0.01$. ω^2 (Effect size) at 95% CI.

microbiota [72]. Availability of nutrients during the growth season is the primary factor affecting growth and productivity [38,73].

Olaniyi and Ojetayo [74] reported that higher growth and yield in organomineral fertilizers are due to a consistent supply of nutrients provided during the crucial stages of the growing season by mineralizing organic nutrients and the quick solubilization of minerals. Several researchers have also noted that nutrient uptake increases with organomineral fertilizers due to the availability of nutrients in the soil, which results in better growth and yield [10].

Compared to organic and organomineral sources, inorganic nutrient sources have lower levels of Ca, Mg, and organic carbon. This affects soil fertility and substantially affects vegetative and reproductive growth, leading to reduced yield [75]. According to Kominko *et al*. [76], increasing the organic matter content in soil through the addition of organic amendments has several benefits, such as improved physicochemical properties and soil microbiota. Studies revealed that organic and organomineral fertilizers increase soil organic matter compared to mineral fertilizers alone [77]. In addition, Mandal *et al*. [78] found that applying organic and organomineral fertilizers increased the biological activity of microbes in the soil. This increased microbial activity improves soil health by nutrient recycling and solubilization.

The observed improvement in yield attributes may be due to improved nutrient content and organic matter of soil. The nutrients are essential for maintaining soil fertility, osmotic balance, metabolic processes, and soil composition. These factors contribute to making a favorable environment for the growth and development of plants [79,80]. According to Welbaum *et al*. [81] and Zhou *et al*. [82], combining organic fertilizers with mineral fertilizers improves photosynthetic efficiency and increased the grain filling time. It also delays the aging of crop roots and foliage. On the other hand, researchers have discovered that long-term use of chemical fertilizers can change microbial activity and reduce the amount of organic matter in the soil. These changes alter the nutrient recycling, solubilization, and soil fertility, which have a detrimental effect on crop yield [7,83].

Integrated use of organic and inorganic fertilizers increases fertilizer efficiency and provides easily accessible nutrients for crop growth. The organic and inorganic fraction of fertilizers ensures a steady supply of nutrients to plants, which increases crop productivity [10]. Long-term use of organic fertilizers promotes microbial growth and activity by providing an abundant source of carbon and energy from decomposed organic matter [70].

The intensive use of inorganic fertilizers contributes to greenhouse gas emissions and nutrient leaching in groundwater bodies [7]. It has been reported that combined application of organic and inorganic fertilizers improves agricultural productivity while minimizing nitrogen losses and reducing the adverse environmental impacts of mineral fertilizers [84]. To reduce greenhouse gas emissions, integrated nutrient management has proven to be more successful than other strategies. Studies by Nyamadzawo *et al*. [85] on wheat revealed that the use of integrated nutrient management strategies reduced greenhouse gas emissions by approximately 10% in comparison to conventional fertilizer strategies. Incorporating organic manure along with other techniques such as crop residue incorporation and conservation farming methods improves crop productivity and sustainability. Zero or reduced-tillage strategies can reduce greenhouse gas emissions and promote carbon sequestration [70,86]. By adopting precision nutrient management strategies and encouraging reuse and recycling, we can reduce the burden on our soil. In addition, we should use diversified cropping systems to reduce environmental pollution in agriculture.

4. CONCLUSION

The results of the present study suggest that applying organomineral fertilizers and biofertilizers together greatly increases soil biological activity and has a significant impact on crop growth and yield attributes. Applying organic and mineral fertilizers separately is less effective than applying them together. *Azotobacter*-inoculated organomineral fertilizers (T12) produced the maximum yield due to consistent nutrient availability during the crop cycle. However, detailed studies are required to understand the nutrient dynamics of organomineral fertilizers. Pond slurry, weeds, and other organic wastes underutilized by farmers can serve as sustainable alternatives to mineral fertilizers. This will reduce potential environmental hazards like eutrophication of mineral fertilizers and improve soil fertility. However, our findings are confined to particular geographical conditions and two growing seasons, necessitating additional study across various regions and longer-term trials to demonstrate broad application and economic feasibility.

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6. AUTHOR'S CONTRIBUTION

All authors made substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published; and agree to be accountable for all aspects of the work. All the authors are eligible to be an author as per the International Committee of Medical Journal Editors (ICMJE) requirements/guidelines.

7. CONFLICTS OF INTEREST

The authors report no financial or any other conflicts of interest in this work.

8. ETHICAL APPROVALS

This study does not involve experiments on animals and human subjects.

9. DATA AVAILABILITY

All the data is available with the authors and shall be provided upon request.

10. PUBLISHER'S NOTE

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11. USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declares that they have not used artificial intelligence (AI)-tools for writing and editing of the manuscript, and no images were manipulated using AI.

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