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ARTICLE

Integration of Organic Amendments with Chemical Fertilizers Boosts Crop Yields, Nutrient Uptake, and Soil Fertility in Farm and Char Lands

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ABSTRACT: Improving crop productivity and soil fertility through the balanced application of inorganic and organic nutrient sources is a sustainable approach in modern agriculture. Char land soils, widely distributed in riverine Bangladesh, are generally low in organic matter status and deficient in necessary nutrient elements for crop production. Addressing this challenge, the present study was conducted to investigate the effects of various organic nutrient sources with inorganic fertilizers on crop yields, nutrient uptake, and soil fertility in farm (L_1) and char land (L_2) of Brahmaputra River in Mymensingh, Bangladesh from 2022 (Y_1) to 2023 (Y_2). For each location, eight treatments *viz.* T_1 (Control), T_2 [100% recommended fertilizer dose (RFD)], T_3 (75% RFD), T_4 (75% N from RFD + 25% N from cow dung), T_5 (75% N from RFD + 25% N from poultry manure), T_6 (75% N from RFD + 25% N from vermicompost), T_7 (75% N from RFD + 25% N from household compost) and T_8 (75% N from RFD + 25% N from rice straw compost) were arranged in a randomized complete block design with three replications using Wheat–Mungbean–T. Aman rice cropping pattern where three way interaction was considered for results. Treatment T_5 performed the best in both years in both locations as it enhanced the yield components ($p < 0.05$) and caused yield increment over control. The yield improvement in Char land soils was higher than that in farm soils. For all three crops, treatment T_5 consistently augmented the uptake of nitrogen, phosphorus, potassium, and sulphur by different parts of the crops and improved soil fertility properties such as organic matter status, cation exchange capacity, total nitrogen, available phosphorus, and sulphur as well as exchangeable potassium in both locations in both years. Cost and return analysis of different treatments for the whole cropping system showed that the highest marginal benefit-cost ratio (16.35 and 15.07) and gross return (about Tk 768,595/ha and 728,341/ha) were obtained from the T_5 treatment in farm soils and Char land soils, respectively. Followed by poultry manure, vermicompost performed well in addition to mineral fertilizers for improving crop yield and soil fertility but its economic efficiency was less due to high input cost. These findings may be useful to the smallholder farmers in char areas, who could benefit from increased productivity, reduced reliance on chemical fertilizers, and improved soil health, contributing to the long-term sustainability of char land agriculture.

KEYWORDS: Organic nutrient sources; farm and char land soils; crop productivity; nutrient uptake; soil fertility

1 Introduction

To meet the growing global food demand, modern agricultural system focuses on maximizing crop production through strategies like using high-yielding varieties, chemical fertilizers and intensive cultivation practices. Increasing cropping intensity involving high-yielding crop varieties, improper fertilization and irrigation, and indiscriminate use of agrochemicals cause soil degradation and fertility depletion [1]. The continued rise in the use of chemical fertilizers is leading to higher production costs and greater environmental pollution. Besides, unbalanced use of these fertilizers with little or no addition of organic manures has affected soil health, causing a substantial decrease in soil organic matter (SOM), which is the single index of soil fertility [2]. Low organic matter content and poor nutrient status are considered one of the major reasons for the low productivity of many soils, including char land areas. Consequently, the maintenance of soil fertility is necessary for sustainable agriculture and future food security. Hence, the strategy of organic matter and balanced fertilizer management is essential to achieve improved and sustainable crop production.

The application of organic materials integrated with chemical fertilizers has been advocated as the best approach to provide greater stability in crop production [3,4] and improvement of soil fertility [5,6]. Combining organic manures like farmyard manure (FYM), green manure (GM), or wheat or rice straw (WS or RS) with chemical fertilizers effectively boosts crop yields, improves nutrient balance, and enhances soil fertility by increasing soil organic carbon (SOC) and macronutrients such as nitrogen (N), phosphorus (P), potassium (K) and sulphur (S) as well as micronutrients in long-term rice-based cropping systems [7–9]. Many researchers have highlighted the role of organic manures and composts as a source of nutrients and a means of soil rejuvenation [10–12]. Organic amendments restore SOM, improve nutrient availability, boost cation exchange capacity (CEC), buffer soil pH, and aid carbon sequestration. High-quality SOM enhances nutrient retention and cycling, water retention, disease suppression, crop productivity, and promotes long-term soil health and sustainability [13]. They are easily available, environment-friendly alternatives to mineral fertilizers.

Poultry manure (PM) is rich in nutrients, containing 3%–5% N, 1.5%–3.5% P, 1.5%–3% K, and significant micronutrients, with a pH of 6–7 [14]. When combined with urea, it improves cereal yield components more effectively than other organic manures [15]. Since poultry excreta is no longer used as fuel, it can serve as an excellent source of manure for field crops [16]. Vermicompost (VC) improves soil fertility by adding essential nutrients like NPK, enhances microbial activity, and boosts water retention, making the soil healthier and more productive naturally [17–19]. It contains 1.45% N, 0.46% P, 0.55% K, 0.39% S, and 1.32 ppm boron (B) [20], which helps uptake and store more nutrients. Cow dung (CD) is widely used organic manure, valued for its high nutrient and organic matter content. It improves soil fertility by increasing organic C and enhancing the activity of beneficial microorganisms, leading to better nutrient availability for plants [21]. Composting recycles agricultural wastes into organic matter that enhances soil quality and crop productivity and improves soil properties by forming humi c substances, making it more fertile and addressing issues like acidity and salinity [22]. To maintain optimal organic matter and nutrient levels, regular incorporation and recycling of organic wastes into the soil are essential [23]. The latest trends in nutrient recycling focus on enhancing the efficiency of organic amendments to improve soil health and nutrient availability [24]. Rice straw can enhance soil fertility, but its burning leads to nutrient loss and environmental pollution, with significant reductions in N (80%), P (25%), K (21%), silicon (Si) (4%–60%), and SOM [25]. In contrast, fields treated with rice straw compost (RSC) showed improvements in both plant health and soil quality, resulting in increases in nutrient l evels such as organic C (5.69%), N (16.67%), P (7.53%), and K (42.34%) [26]. Besides these, recent trends focus on biochar's role in carbon sequestration, precision application, optimized feedstock selection, and integration with organic amendments to enhance long-term soil health and crop productivity as it enhances soil fertility, improves water retention, reduces bulk density, and improves nutrient cycling, making it beneficial for sustainable agriculture [27].

Wheat, mungbean, and T. Aman rice are important crops for the agricultural landscape in Bangladesh, collectively addressing the country's food security. Wheat serves as a vital supplement to rice, offering higher protein content, vitamins, and minerals, thereby enhancing the nutritional quality of diets [21]. Mungbean, a short-duration leguminous crop, not only fits well into the cropping system between wheat and T. Aman rice but also enriches the soil with N, promoting better soil health [28]. On the other hand, rice is a staple food for over half of the world's population, providing more than 21% of human caloric intake globally [29]. Wheat–Mungbean–T. Aman rice cropping pattern requires a limited amount of irrigation water, maximizes land use efficiency, improves overall productivity, and helps meet the food demands of the growing population [28]. This cropping pattern with organic amendments is an eco-friendly and sustainable strategy that aligns with farmers' financial capacity, risk tolerance, and expected returns. This approach optimizes key investment factors, including capital allocation, input cost dynamics, and return on investment [30,31]. Organic amendments reduce dependency on synthetic fertilizers and improve nutrient-use efficiency, thereby lowering production costs. Additionally, t he diversified cropping system promotes efficient resource utilization, enhances soil health through biological nitrogen fixation and organic matter buildup, and stabilizes farm income by mitigating financial and yield risks. Using organic amendments showed significant positive effects on these crops and increased the yield of rice (33.4%–52.5%), wheat (20%–42.8%), and mungbean (up to 84%) over the control [32,33].

In Bangladesh, many charlands have formed along the banks of the Padma, Jamuna, and Meghna rivers, covering 5% of the country's total area (7200 sq. km) and are home to 6.5 million people [34]. These regions have poor soil fertility because of sandy texture, frequent flooding, and erosion. As a result, char soils are often deficient in essential nutrients like N, P, and K and have poor water retention, which makes crop production difficult [35]. Organic amendments such as compost, manure, and crop residues can improve these soils by increasing nutrient content, enhancing soil structure, and boosting microbial activity. This leads to better water retention, reduced soil erosion, increased crop productivity, and long-term fertility. However, very little research activities have been performed on using organic matter to improve char soils. The addition of C-enriched materials like CD, PM, FYM, VC, composts, and crop residues e.g., rice straw (RS), etc. can improve the health of char soils and help accumulate more C. Integrate organic amendments with chemical fertilizers is hypothesized to improve soil fertility and boost crop productivity in Wheat–Mungbean–T. Aman rice cropping systems, particularly in farm and char land soils. Intensive farming and unbalanced chemical fertilizer without using organic manure have degraded soils with low organic matter status and caused environmental hazards, particularly in resource-poor areas like char lands. To maintain sustainable agriculture in farm and char land soils, it is crucial to develop a strong workable, and compatible nutrient management package through organic and inorganic sources for various crops based on scientific facts, local conditions, and economic viability [36]. Therefore, the study was undertaken to determine the potentiality of various organic manures and composts integrated with chemical fertilizers on crop yield for Wheat–Mungbean–T. Aman rice cropping patterns and to evaluate the improvement of soil fertility on both farm and char land soils.

2 Materials and Methods

2.1 Experimental Site

The experiment was conducted at two locations *viz.* Soil Science Field Laboratory of Bangladesh Agricultural University (BAU) and a farmer's field in Brahmaputra Charland (Char Gobadia) in Mymensingh district during the 2022–23 growing seasons (Fig. 1). In both locations, the experiment was performed for two consecutive years (Y_1 = year 2022 and Y_2 = year 2023) to evaluate the impact of organic materials integrated with chemical fertilizers on crop productivity and soil fertility. Both the lands were located at an elevation of 18 m above sea level, at a latitude of 24°75′ N and a longitude of 90°50′ E for BAU farm whereas 24°43′ N and a longitude of 90°28′ E for char. The region experiences a subtropical climate with three seasons named Rabi, Kharif 1, and Kharif 2. Kharif 1 spanning from mid-March to mid-July, is characterized by high temperatures and low rainfall whereas Kharif 2 lasts from mid-July to mid-October by high humidity and significant rainfall. In contrast, the Rabi season, from October to February, has minimal rainfall and moderately low temperatures.

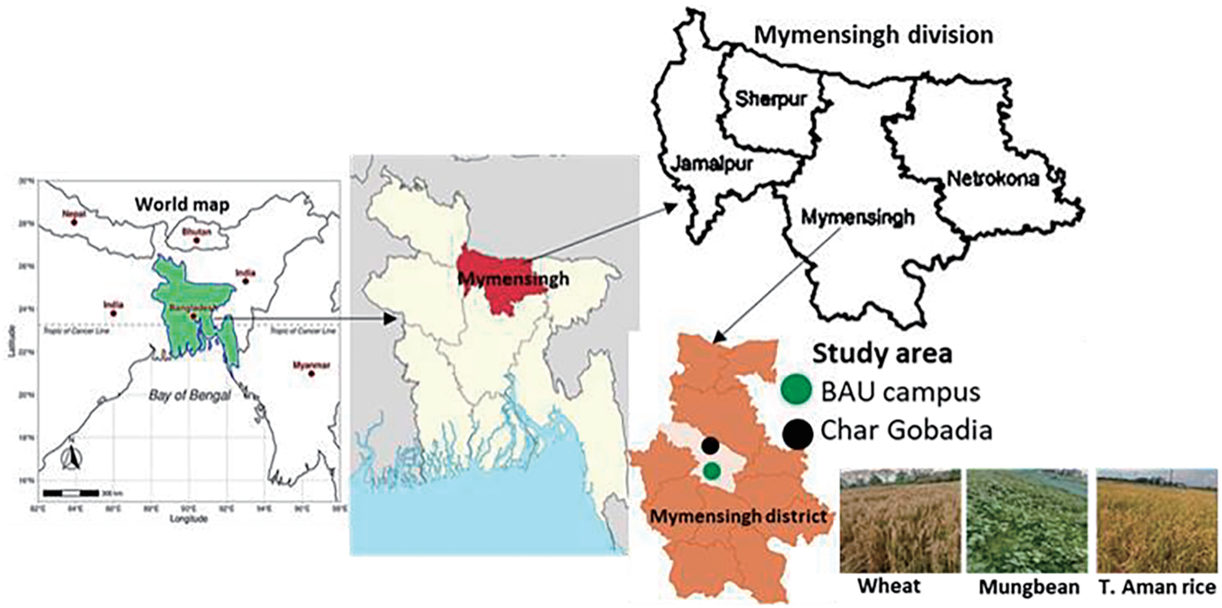

Figure 1: Study location of the field experiment

2.2 Soils

The soil at both locations was characterized as medium-high land, which is well-drained and generally suitable for various crops. The soil of the BAU farm was predominantly silt loam in texture with pH 6.55 and CEC of 7.5 milliequivalent/100 g soil (me%). This soil exhibited 1.81% soil organic matter (SOM), 0.17% total N, 7.43 ppm available P, 0.071 me% exchangeable K, and 9.98 ppm available S. The farmer's field had loam textured soil with pH 6.63 and CEC 6.49 me%. The SOM content of this soil was 1.32%, total N 0.12%, available P 5.12 ppm, exchangeable K 0.06 me%, and available S 8.12 ppm.

The mechanical analysis of soil was carried out using the hydrometer method [37], and the textural class was identified based on the USDA system by placing the percentages of sand, silt, and clay on Marshall's Triangular Coordinate. Soil pH was measured with a glass electrode pH meter, and SOC% was determined through the wet oxidation method proposed by Walkley et al. [38]. SOM% was calculated by multiplying SOC% with van Bemmelen factor (1.73). CEC was determined by the sodium saturation method [39], using 1 N NH_4OAc to replace Na^+ ions. The Na^+ concentration was then measured with a flame photometer (JENWAY PFP 7, Cambridgeshire, UK). Total N was measured using the semi-micro Kjeldahl method [40], and available P was assessed using the Olsen method [41] and determined using a spectrophotometer (JENWAY 6300, Cambridgeshire, UK). Exchangeable K was analyzed with a flame photometer using 1 N ammonium acetate (NH_4OAc) at pH 7, while available S was determined using a spectrophotometer with 0.15% calcium chloride ($CaCl_2$) solution as extractant.

2.3 Experimental Design

The field experiment was arranged in a Randomized Complete Block Design (RCBD) with three replications considering location, treatment and year as three factors. There were eight treatments which included T_1 (control), T_2[100% recommended dose of fertilizer (RFD)], T_3 (75% RFD), T_4 [75% N from RFD + 25% N from cow dung (CD)], T_5 [75% N from RFD + 25% N from poultry manure (PM)], T_6 [75% N from RFD + 25% N from vermicompost (VC)], T_7 [75% N from RFD + 25% N from household compost (HC)], and T_8 [75% N from RFD + 25% N from rice straw compost (RSC)]. The experiment consisted of 24 plots (8 treatments × 3 replications) in the BAU field (L_1) and 24 plots in the Farmer's field (L_2), each measuring 4 m × 2.5 m (10 m^2). Land preparation involved repeated plowing and cross-plowing using a power tiller, with each plowing followed by laddering to ensure fine tilth.

2.4 Crop Management

The cropping sequence was Wheat–Mungbean–T. Aman rice, whose varieties included BARI Gom 30, Binamoog-8, and BRRI dhan71, respectively. The seeds of these crops were collected from the divisional office of BADC (Bangladesh Agricultural Development Corporation) at Mymensingh in Bangladesh. Wheat was grown in November-March with a seed rate of 125 kg ha^{-1}, mungbean in March—June with a seed rate of 30 kg ha^{-1}, and T. Aman rice cultivated in July-October at a spacing of 20 cm × 20 cm with 3 seedlings $hill^{-1}$. All the crops were sown manually. The first crop in the sequence received organic amendments according to the Integrated Plant Nutrition System (IPNS), while the second and third crops were fertilized using chemical fertilizers only. CD and PM were sourced from the BAU farm, VC was obtained from the local market of Mymensingh Sadar, and HC and RSC were collected from farmers' homes and fields near BAU farm. Nutrient application, including N, P, K, S, Zn, and B was based on the Fertilizer Recommendation Guide [42], using urea for N, triple super phosphate (TSP) for P, muriate of potash (MoP) for K, gypsum for S, zinc oxide for Zn, and boric acid for B. These fertilizers were bought from the local market of Mymensingh Sadar. For wheat, the rates of N, P, K, S, Mg, Zn, and B were 120, 16, 60, 10, 4, 1.5, and 1 kg ha^{-1}, respectively. For Mungbean, the rates of N, P, K, S, and Zn were 18, 18, 16, 4, and 1 kg ha^{-1}, respectively. For T. Aman rice, the rates of N, P, K, and S were 90, 8, 50, and 4 kg ha^{-1}, respectively. These rates for each crop were used as 100% of RFD [42]. Intercultural operations such as irrigation, weeding, and pest control were performed as needed throughout the cropping season.

2.5 Data Record and Plant Sample Analysis

Yield and yield-contributing parameters for different crops were recorded, including plant height, the number of effective tillers $hill^{-1}$ for rice, total pod and seed number $plant^{-1}$ for mungbean, number of filled grains $spike^{-1}$ or $panicle^{-1}$, grain yield, and straw or stover yield. Data were recorded from five randomly selected plants per plot, excluding the outer two rows and row ends. Grain yield and straw or stover yields were measured at 14% moisture and converted to biological yield using the following equation and expressed in t ha^{-1}.

$$\text{Biological yield (t ha}^{-1}\text{)} = \text{Grain or Seed yield} + \text{Straw or Stover yield} \tag{1}$$

Representative samples of grain, straw, stover and organic amendments were oven-dried at 65°C for 72 h and then ground to a fine powder using a ball mill grinder. After passing through a 20-mesh sieve, the samples were stored in paper bags inside a desiccator until nutrient analysis Table 1. Total %N was determined using the Kjeldahl digestion method, following the protocol of Nelson and Sommers [43]. For total P, K, and S estimation, samples were digested with HNO_3-$HClO_4$ (3:1) di-acid mixture [44]. P and S were measured using colorimetric and turbidimetric methods with a spectrophotometer (JENWAY 6300, Cambridgeshire, UK) while K was analyzed using a flame photometer (JENWAY PFP 7, Cambridgeshire, UK) based on the Knudsen et al.'s [45] protocol. For each nutrient uptake in different plant parts, the total content of that nutrient and the yield of the plant parts were used. Nutrient uptake by plant parts was calculated using the following equation.

$$\text{Nutrient uptake (kg ha}^{-1}) = \{\text{Yield (t ha}^{-1}) \times \text{Nutrient content}(\%) \times 1000\}/100 \quad (2)$$

Table 1: Nutrient composition of organic amendments

Organic amendments	C (%)	N (%)	P (%)	K (%)	S (%)
CD	23.45	1.02	0.5	0.76	0.24
PM	10.98	1.43	1.13	1.18	0.46
VC	28.65	1.40	1.11	1.24	0.33
HC	10.5	0.49	0.1	0.62	0.09
RSC	35.5	0.52	0.11	1.52	0.11

2.6 Economic Analysis

The cost of production under different treatments was calculated based on total production volume and total production cost. Gross return was defined by the sum of the local market price of products and by-products of the cultivated crops per hectare area in the year [46]. The marginal benefit-cost ratio (MBCR) was used as a tool for the analysis of system profitability. It is the ratio of marginal or added benefits and costs. Yield and added benefits of crops due to different treatments were calculated. The analysis was computed for the system productivity of Wheat–Mungbean–T. Aman rice cropping pattern for 2 years. Only variable costs, i.e., manure or compost and chemical fertilizer were considered for each crop. The added cost and added benefit were computed. To compare the different treatments with the control treatment the following equation was used.

$$\begin{aligned}\text{MBCR (over control)} &= \text{Gross return (Ti)-Gross return (T1)/Variable cost (Ti)-Variable cost (T1)} \\ &= \text{Added benefit (over control)/Added cost (over control)} \quad (3)\end{aligned}$$

where, $T_i = T_2, T_3, \ldots, T_8$ treatments

T_1 = control treatment

Variable cost = Manure or compost and chemical fertilizers

Gross return = Yield × price

2.7 Statistical Analysis

The data on different parameters were statistically analyzed using three-way ANOVA to obtain significant differences among location, treatments and year with the help of software package R (version 4.3.1). Where the LSD test was significant, treatment means were separated by Duncan's Multiple Range Test (DMRT) using the statistical package R at a 5% level of significance ($p < 0.05$). To separate differences among treatment combinations means, Post-hoc tests were performed using the Least Significant Difference (LSD) test [47].

3 Results

3.1 Effect of Treatments on the Yield Parameters of Crops

The experiment demonstrated that different treatments significantly impacted the yield parameters of BARI Gom 30, Binamoog-8, and BRRI dhan71, both at the BAU farm and char land during the 2022–23 growing seasons (Table 2). For all three crops, treatment T_5 (75% N from RFD + 25% N from PM) consistently produced superior yield-related parameters, while the control (T_1) exhibited the lowest performance.

Table 2: Effect of treatment combinations on the yield parameters of wheat, mungbean, and T. Aman rice in 2022–23 at BAU and farmer's fields

Treatment combination	Wheat			Mungbean			T. Aman Rice		
	Plant height (cm)	Number of Spikelets/ Spike	Number of Filled Grains/ Spike	Plant Height (cm)	Number of Pods Plant-1	Number of Seeds Plant-1	Plant Height (cm)	Number of Effective Tillers Hill-1	Number of Filled Grains Panicle-1
Location (L) × Treatment (T)									
$L_1 \times T_1$	66.18 c	16.49 d	29.27 c	43.67 i	16.657 l	115.67 l	80.40 l	9.62 o	51.33 m
$L_1 \times T_2$	81.41 ab	19.09 a	46.51 ab	53.24 bcd	38.057 d	163.58 h	102.44 d	17.31 e	100.50 e
$L_1 \times T_3$	76.50 b	17.78 bc	44.61 b	47.15 h	30.343 j	147.38 k	97.00 j	12.91 m	85.47 k
$L_1 \times T_4$	81.43 ab	19.19 a	46.43 ab	52.26 bcde	36.098 ef	160.72 hi	100.70 f	16.43 g	99.33 f
$L_1 \times T_5$	82.25 a	19.53 a	47.75 a	56.74 a	42.593 a	176.48 f	105.82 a	20.97 a	106.40 a
$L_1 \times T_6$	81.46 ab	19.30 a	46.52 ab	54.12 abc	40.713 b	170.50 g	103.57 c	18.91 c	103.50 c
$L_1 \times T_7$	79.82 ab	18.80 abc	46.14 ab	49.65 efgh	32.503 i	152.89 jk	98.45 i	14.38 k	91.10 i
$L_1 \times T_8$	80.30 ab	18.89 ab	46.42 ab	51.09 cdefg	34.307 gh	157.23 ij	100.08 g	15.34 i	97.40 g
$L_2 \times T_1$	61.68 c	15.66 d	27.75 c	40.04 j	26.333 k	201.87 e	71.77 m	7.55 p	43.31 n
$L_2 \times T_2$	81.63 a	19.26 a	45.97 ab	51.97 bcdef	37.165 de	315.78 b	101.58 e	16.83 f	100.25 e
$L_2 \times T_3$	79.87 ab	17.73 c	44.12 b	48.61 gh	31.852 i	289.68 d	95.58 k	12.00 n	80.48 l
$L_2 \times T_4$	81.69 a	19.34 a	46.01 ab	50.74 defg	36.283 ef	313.41 b	100.40 fg	15.80 h	98.10 g
$L_2 \times T_5$	81.95 a	19.53 a	46.96 ab	54.42 ab	39.502 c	321.89 a	104.45 b	19.54 b	104.48 b
$L_2 \times T_6$	81.77 a	19.41 a	46.49 ab	52.97 bcd	38.060 d	317.02 ab	103.27 c	17.82 d	101.79 d
$L_2 \times T_7$	80.28 ab	18.64 abc	45.44 ab	49.16 fgh	34.155 h	297.77 c	98.05 i	13.70 l	88.01 j
$L_2 \times T_8$	81.13 ab	18.79 abc	45.85 ab	49.72 efgh	35.392 fg	303.19 c	99.39 h	14.87 j	95.85 h
Location (L) × Year (Y)									
$L_1 \times Y_1$	77.79	18.46 ab	44.14	51.02 ± a	32.110 ± c	12.96 ± c	98.04 b	15.39 b	91.27 b
$L_1 \times Y_2$	79.55	18.81 a	44.27	50.96 ± a	35.708 ± a	298.15 ± a	99.07 a	16.08 a	92.49 a
$L_2 \times Y_1$	78.18	18.17 b	43.25	47.86 ± b	34.865 ± b	291.39 ± b	96.20 d	14.54 d	88.34 d
$L_2 \times Y_2$	79.33	18.92 a	43.9	51.54 ± a	34.820 ± b	298.77 ± a	97.42 c	14.99 c	89.73 c
Treatment (T) × Year (Y)									
$T_1 \times Y_1$	64.10 c	15.97 f	28.02 c	38.70 j	20.853 l	102.67 m	73.20 k	7.95 o	45.49 l
$T_1 \times Y_2$	63.76 c	16.18 ef	29.00 c	45.00 i	22.137 k	214.87 g	78.96 j	9.22 n	49.16 k
$T_2 \times Y_1$	80.97 ab	19.03 abc	46.30 ab	51.88 bcdef	36.592 de	163.84 hi	101.81 d	16.95 f	100.31 d
$T_2 \times Y_2$	82.07 ab	19.31 abc	46.18 ab	53.33 bc	38.630 c	315.52 c	102.21 d	17.19 e	100.44 d
$T_3 \times Y_1$	77.37 b	17.25 de	44.23 b	48.21 gh	30.658 j	147.33 l	95.73 i	12.13 m	81.84 j
$T_3 \times Y_2$	79.00 ab	18.26 cd	44.49 ab	47.55 hi	31.537 ij	289.73 f	96.85 h	12.78 l	84.11 i
$T_4 \times Y_1$	80.87 ab	19.05 abc	45.95 ab	50.80 cdefg	34.990 fg	161.41 ij	100.46 e	16.00 h	98.37 e
$T_4 \times Y_2$	82.26 ab	19.48 ab	46.50 ab	52.20 bcde	37.392 d	312.72 c	100.64 e	16.23 g	99.06 e
$T_5 \times Y_1$	81.20 ab	19.28 abc	47.17 ab	54.03 ab	40.383 b	168.64 h	104.73 b	19.76 b	105.00 b
$T_5 \times Y_2$	83.00 a	19.78 a	47.54 a	57.13 a	41.712 a	329.74 a	105.55 a	20.75 a	105.88 a
$T_6 \times Y_1$	80.83 ab	19.13 abc	46.13 ab	52.89 bcd	38.778 c	165.92 hi	103.35 c	18.06 d	102.36 c
$T_6 \times Y_2$	82.40 ab	19.58 a	46.88 ab	54.20 ab	39.995 b	321.60 b	103.49 c	18.68 c	102.93 c
$T_7 \times Y_1$	78.80 ab	18.37 bcd	45.67 ab	49.08 fgh	32.073 i	151.96 kl	98.10 g	13.88 k	88.65 h
$T_7 \times Y_2$	81.30 ab	19.08 abc	45.91 ab	49.73 efgh	34.585 gh	298.71 e	98.41 g	14.21 j	90.46 g
$T_8 \times Y_1$	79.73 ab	18.43 bc	46.10 ab	49.94 defgh	33.573 h	155.64 jk	99.60 f	15.02 i	96.40 f
$T_8 \times Y_2$	81.70 ab	19.24 abc	46.17 ab	50.87 cdefg	36.125 ef	304.78 d	99.88 f	15.19 i	96.84 f

(Continued)

Table 2 (continued)

Treatment combination	Wheat			Mungbean			T. Aman Rice		
	Plant height (cm)	Number of Spikelets/ Spike	Number of Filled Grains/ Spike	Plant Height (cm)	Number of Pods Plant-1	Number of Seeds Plant-1	Plant Height (cm)	Number of Effective Tillers Hill-1	Number of Filled Grains Panicle-1
Location (L) × Treatment (T) × Year (Y)									
$L_1 \times T_1 \times Y_1$	66.67 c	16.40 fg	29.20 b	43.33 j	15.707 s	7.97 o	77.99 t	8.70 x	49.98 u
$L_1 \times T_1 \times Y_2$	65.70 c	16.57 efg	29.33 b	44.00 ij	17.607 r	223.37 k	82.80 s	10.55 w	52.69 t
$L_1 \times T_2 \times Y_1$	80.67 ab	19.00 abc	46.67 a	52.98 bcde	36.260 ghij	15.02 no	102.21 gh	17.22 hi	100.42 fg
$L_1 \times T_2 \times Y_2$	82.15 ab	19.18 abc	46.35 a	53.50 bcde	39.853 cd	312.14 cde	102.67 fg	17.40 gh	100.57 fg
$L_1 \times T_3 \times Y_1$	75.67 b	17.33 def	44.40 a	48.56 fgh	28.487 p	9.15 o	96.56 q	12.61 u	84.79 q
$L_1 \times T_3 \times Y_2$	77.33 ab	18.22 bcd	44.81 a	45.75 hij	32.200 lmn	285.61 j	97.45 p	13.21 t	86.15 p
$L_1 \times T_4 \times Y_1$	80.53 ab	19.10 abc	46.20 a	52.35 bcdef	33.727 kl	13.13 no	100.55 kl	16.37 k	98.96 hi
$L_1 \times T_4 \times Y_2$	82.33 ab	19.28 abc	46.67 a	52.17 bcdefg	38.470 cdef	308.30 ef	100.84 jk	16.48 jk	99.70 gh
$L_1 \times T_5 \times Y_1$	81.07 ab	19.40 abc	47.67 a	55.53 abc	41.860 a	18.33 n	105.30 b	20.10 b	105.73 b
$L_1 \times T_5 \times Y_2$	83.43 a	19.66 abc	47.83 a	57.95 a	43.327 a	334.63 a	106.33 a	21.84 a	107.07 a
$L_1 \times T_6 \times Y_1$	80.53 ab	19.20 abc	46.27 a	53.97 abcd	39.753 cd	17.86 n	103.44 e	18.60 e	103.28 d
$L_1 \times T_6 \times Y_2$	82.39 ab	19.41 abc	46.77 a	54.27 abcd	41.673 ab	323.13 b	103.69 de	19.22 d	103.72 cd
$L_1 \times T_7 \times Y_1$	78.33 ab	18.60 abcd	46.20 a	49.91 defgh	29.533 op	10.14 no	98.35 no	14.25 q	89.64 n
$L_1 \times T_7 \times Y_2$	81.31 ab	19.01 abc	46.08 a	49.39 efgh	35.473 hij	295.64 hi	98.56 n	14.52 p	92.55 m
$L_1 \times T_8 \times Y_1$	78.87 ab	18.63 abcd	46.53 a	51.57 cdefg	31.553 mn	12.09 no	99.92 lm	15.29 n	97.32 jk
$L_1 \times T_8 \times Y_2$	81.73 ab	19.14 abc	46.30 a	50.61 defg	37.060 fgh	302.38 fgh	100.25 kl	15.39 mn	97.47 j
$L_2 \times T_1 \times Y_1$	61.53 c	15.53 g	26.83 b	34.07 k	26.000 q	197.37 m	68.41 v	7.21 z	40.99 w
$L_2 \times T_1 \times Y_2$	61.82 c	15.78 fg	28.67 b	46.00 hij	26.667 q	206.37 l	75.13 u	7.90 y	45.63 v
$L_2 \times T_2 \times Y_1$	81.27 ab	19.07 abc	45.93 a	50.77 defg	36.923 fgh	312.66 cde	101.41 ij	16.68 j	100.19 g
$L_2 \times T_2 \times Y_2$	82.00 ab	19.44 abc	46.00 a	53.16 bcde	37.407 efg	318.90 bc	101.75 hi	16.98 i	100.31 g
$L_2 \times T_3 \times Y_1$	79.07 ab	17.17 def	44.07 a	47.87 ghi	32.830 lm	285.52 j	94.90 r	11.64 v	78.89 s
$L_2 \times T_3 \times Y_2$	80.67 ab	18.30 abcd	44.17 a	49.35 efgh	30.873 no	293.85 ij	96.25 q	12.35 u	82.07 r
$L_2 \times T_4 \times Y_1$	81.20 ab	19.00 abc	45.70 a	49.26 efgh	36.253 ghij	309.68 def	100.36 kl	15.63 m	97.78 j
$L_2 \times T_4 \times Y_2$	82.19 ab	19.69 abc	46.32 a	52.23 bcdefg	36.313 ghi	317.13 bcd	100.44 kl	15.97 l	98.41 ij
$L_2 \times T_5 \times Y_1$	81.33 ab	19.17 abc	46.67 a	52.54 bcdef	38.907 cde	318.94 bc	104.15 cd	19.41 cd	104.27 cd
$L_2 \times T_5 \times Y_2$	82.57 ab	19.89 a	47.25 a	56.30 ab	40.097 bc	324.84 b	104.76 bc	19.66 c	104.69 bc
$L_2 \times T_6 \times Y_1$	81.13 ab	19.07 abc	46.00 a	51.81 cdefg	37.803 efg	313.97 cde	103.25 ef	17.51 g	101.44 ef
$L_2 \times T_6 \times Y_2$	82.41 ab	19.76 ab	46.98 a	54.12 abcd	38.317 def	320.07 bc	103.29 ef	18.13 f	102.14 e
$L_2 \times T_7 \times Y_1$	79.27 ab	18.13 cde	45.13 a	48.24 fghi	34.613 jk	293.77 ij	97.84 op	13.50 s	87.66 o
$L_2 \times T_7 \times Y_2$	81.29 ab	19.15 abc	45.74 a	50.07 defgh	33.697 kl	301.77 fghi	98.25 no	13.90 r	88.37 o
$L_2 \times T_8 \times Y_1$	80.60 ab	18.23 bcd	45.67 a	48.31 fghi	35.593 hij	299.19 ghi	99.27 m	14.75 op	95.48 l
$L_2 \times T_8 \times Y_2$	81.67 ab	19.35 abc	46.04 a	51.12 defg	35.190 ijk	307.19 efg	99.52 m	14.99 o	96.22 kl
L × T	*	*	*	*	***	***	***	***	***
L × Y	ns	*	ns	**	***	***	*	***	*
T × Y	*	*	*	*	*	***	***	***	***
L × T × Y	*	*	*	*	***	***	*	***	**

Note: In a column, the same letter(s) indicate statistically similar, and different letter(s) indicate significant differences at the 5% level of probability ($p < 0.05$). *** = $p < 0.001$, ** = $p < 0.01$, * = $p < 0.05$, ns = Non-significant; L_1 = BAU field; L_2 = Farmer's field; T_1 = Control; T_2 = 100% RFD; T_3 = 75% RFD, T_4 = 75% N from RFD + 25% N from cow dung (CD); T_5 = 75% N from RFD + 25% N from poultry manure (PM); T_6 = 75% N from RFD + 25% N from vermicompost (VC); T_7 = 75% N from RFD + 25% N from household compost (HC); T_8 = 75% N from RFD + 25% N from rice straw compost (RSC); Y_1 = Year 2022; Y_2 = Year 2023.

3.1.1 Wheat (BARI Gom30)

Significant differences in wheat plant height, number of spikelets/spike, and number of filled grains/spike were observed across treatments, locations, and years. The three-way combination $L_1 \times T_5 \times Y_2$ (75% RFD + 25% PM at BAU farm in 2023) produced the tallest plants (83.43 cm), most spikelets (19.66/spike), and highest number of grains (47.83 grains/spike), representing 25.2%, 19.9%, and 67.7%

increases respectively over $L_1 \times T_1 \times Y_1$. In contrast, the poorest performance occurred in $L_2 \times T_1 \times Y_1$ (control treatment at farmer's field in 2022) with 61.53 cm height, 15.53 spikelets/spike, and 26.83 grains/spike. Two-way analysis revealed T_5 consistently outperformed across locations (82.25 cm in L_1 *vs*. 81.95 cm in L_2) and years (83.00 cm in Y_2 *vs*. 81.20 cm in Y_1), while L_1 generally performed better than L_2 (Table 2).

3.1.2 Mungbean (Binamoog-8)

For mungbean, significant differences in plant height, number of pods/plant, and number of seeds/plant were observed across treatments, locations, and years. The three-way interaction (Location × Treatment × Year) significantly affected mungbean yield parameters ($p < 0.001$). The combination $L_2 \times T_5 \times Y_2$ (75% RFD + 25% PM at farmer's field in 2023) produced the tallest plants (56.30 cm), highest pod count (40.10/plant), and maximum number of seeds (324.84 seeds/plant), representing increases of 34.6%, 88.5%, and 4075% respectively over the control ($L_1 \times T_1 \times Y_1$). In contrast, the poorest performance occurred in $L_1 \times T_1 \times Y_1$ (control treatment at BAU farm in 2022) with 43.33 cm height, 15.71 pods, and only 7.97 seeds. Two-way analysis revealed T_5 consistently outperformed across locations (55.58 cm plant height overall) and years (329.74 seeds in Y_2 *vs*. 168.64 in Y_1), while L_2 generally performed better than L_1 (Table 2).

3.1.3 T. Aman Rice (BRRI Dhan71)

Significant differences in T. Aman rice plant height, number of effective tillers/hill, and number of filled grains/panicle were observed across treatments, locations, and years. The three-way interaction (Location × Treatment × Year) significantly influenced rice growth parameters ($p < 0.01$). The combination $L_1 \times T_5 \times Y_2$ (75% RFD + 25% PM at BAU farm in 2023) produced the tallest plants (106.33 cm), most number of tillers (21.84/hill), and highest number of grains (107.07 grains/panicle), representing increases of 55.4%, 202.9%, and 161.2% respectively over the control ($L_2 \times T_1 \times Y_1$). In contrast, the poorest performance occurred in $L_2 \times T_1 \times Y_1$ (control treatment at farmer's field in 2022) with 68.41 cm height, 7.21 tillers, and 40.99 grains. Two-way analysis revealed T_5 consistently outperformed across locations (105.14 cm plant height overall) and years (105.88 grains in Y_2 *vs*. 105.00 in Y_1), while L_1 generally yielded better than L_2 (Table 2).

3.2 Crop Yield

Across both locations, treatments and years, $L_1 \times T_5 \times Y_2$ and $L_2 \times T_5 \times Y_2$ (75% N from RFD + 25% N from PM in 2023 at BAU field and Char land soils, respectively) consistently achieved the highest grain/seed yield for wheat, mungbean, and T. Aman rice (Table S1). For all crop yields, the treatments can be arranged as $T_5 > T_6 > T_2 > T_4 > T_8 > T_7 > T_3 > T_1$.

The biological yield for the Wheat–Mungbean–T. Aman rice pattern was significantly influenced by the treatments at two locations in both years (Fig. 2). The main effects and two-way interaction effects of the factors were mostly significant for the three crops (Table S2). Treatment T_5 (75% N from RFD + 25% N from PM) continuously yielded higher than other treatments for all the crops in both years at both locations.

The three-way interaction effects of location, treatment, and year on wheat biological yield revealed significant variations. At the BAU field (L_1), the combination $L_1 \times T_5 \times Y_2$ (10.83 t ha^{-1}) produced the highest biological yield, followed by $L_1 \times T_5 \times Y_1$ (10.50 t ha^{-1}), $L_1 \times T_6 \times Y_2$ (10.43 t ha^{-1}), and $L_1 \times T_6 \times Y_1$ (10.20 t ha^{-1}), all of which were statistically similar. These results indicate that T_5 consistently enhanced wheat productivity, particularly in the second year (Y_2). In contrast, the lowest yields were recorded in $L_1 \times T_1 \times Y_1$ (2.60 t ha^{-1}) and $L_1 \times T_1 \times Y_2$ (3.43 t ha^{-1}), where T_1 (control) was applied, highlighting the inefficiency of no fertilization. Similarly, at the farmer's field (L_2), $L_2 \times T_5 \times Y_2$ (10.77 t ha^{-1}) and $L_2 \times T_5 \times Y_1$ (10.43 t ha^{-1}) were the top-performing combinations, while $L_2 \times T_1 \times Y_1$ (2.53 t ha^{-1}) and $L_2 \times T_1 \times Y_2$ (3.03 t ha^{-1}) were the least productive.

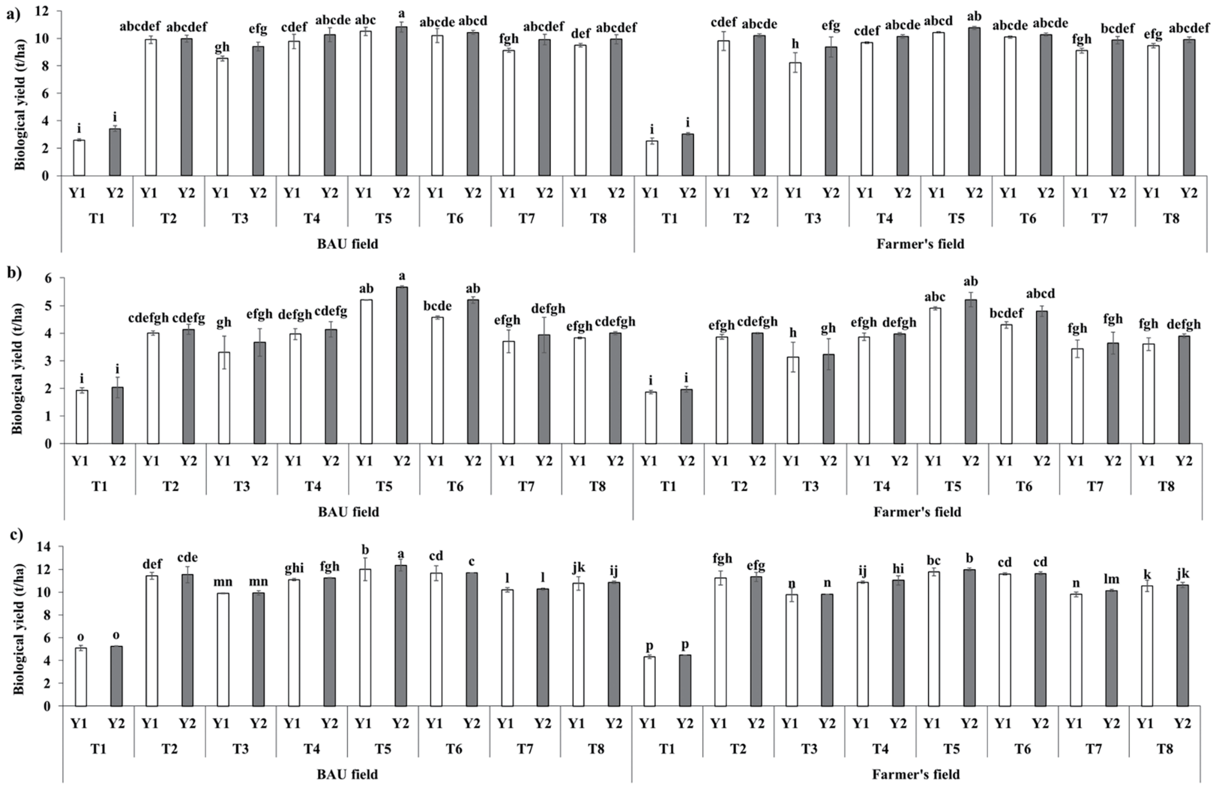

Figure 2: Effect of interaction among location, treatment and year on the biological yield of wheat (a), mungbean (b), and rice (c) at both BAU field and farmer's field. Different lowercase letter(s) on top of each bar represent significant differences among treatments at 5% level of probability ($p < 0.05$) according to DMRT. Error bars represent standard error means. L_1 = BAU field; L_2 = Farmer's field; T_1 = Control; T_2 = 100% RFD; T_3 = 75% RFD, T_4 = 75% N from RFD + 25% N from cow dung (CD); T_5 = 75% N from RFD + 25% N from poultry manure (PM); T_6 = 75% N from RFD + 25% N from vermicompost (VC); T_7 = 75% N from RFD + 25% N from household compost (HC); T_8 = 75% N from RFD + 25% N from rice straw compost (RSC); Y_1 = Year 2022; Y_2 = Year 2023

For mungbean, the interaction effects of location, treatment, and year on biological yield were also significant. At the BAU field (L_1), the combination $L_1 \times T_5 \times Y_2$ (5.67 t ha^{-1}) achieved the highest biological yield, followed by $L_1 \times T_5 \times Y_1$ (5.20 t ha^{-1}), $L_1 \times T_6 \times Y_2$ (5.20 t ha^{-1}), and $L_1 \times T_6 \times Y_1$ (4.57 t ha^{-1}). These results indicate that T_5 and T_6 performed well for enhancing mungbean productivity, particularly in the second year (Y_2). Conversely, the lowest yields were observed in $L_1 \times T_1 \times Y_1$ (1.93 t ha^{-1}) and $L_1 \times T_1 \times Y_2$ (2.03 t ha^{-1}), where no fertilization (T_1) was applied. At the farmer's field (L_2), $L_2 \times T_5 \times Y_2$ (5.20 t ha^{-1}) and $L_2 \times T_5 \times Y_1$ (4.90 t ha^{-1}) were the best-performing combinations, while $L_2 \times T_1 \times Y_1$ (1.87 t ha^{-1}) and $L_2 \times T_1 \times Y_2$ (1.97 t ha^{-1}) were the least productive.

The interaction effects of location, treatment, and year on biological yield of T. Aman rice were highly significant. At the BAU field (L_1), the combination $L_1 \times T_5 \times Y_2$ (12.37 t ha^{-1}) produced the highest biological yield, followed by $L_1 \times T_5 \times Y_1$ (12.00 t ha^{-1}), $L_1 \times T_6 \times Y_2$ (11.70 t ha^{-1}), and $L_1 \times T_6 \times Y_1$ (11.67 t ha^{-1}). In contrast, the lowest yields were recorded in $L_1 \times T_1 \times Y_1$ (5.10 t ha^{-1}) and $L_1 \times T_1 \times Y_2$ (5.27 t ha^{-1}), where no fertilization (T_1) was applied. Similarly, at the farmer's field (L_2), $L_2 \times T_5 \times Y_2$ (11.97 t ha^{-1}) and $L_2 \times T_5 \times Y_1$ (11.77 t ha^{-1}) were the top-performing combinations, while $L_2 \times T_1 \times Y_1$ (4.33 t ha^{-1}) and $L_2 \times T_1 \times Y_2$ (4.47 t ha^{-1}) were the least productive. These findings highlight the consistent superiority of T_5 across both locations and years, underscoring its potential to significantly improve T. Aman rice biological yield.

For all crops, if only treatments were considered, they can be arranged as $T_5 > T_6 > T_2 > T_4 > T_8 > T_7 > T_3 > T_1$ in case of biological yield.

3.3 Nutrient Uptake by the Crops

Nutrient concentrations in different parts of the plant samples were mostly significant across different locations, treatments and years combinations. The concentration of different nutrients (N, P, K and S) in grain and straw parts are given in Table S3–S5.

A significant interaction effect of different factors (locations, treatments and years) was found on the uptake of nutrients for all the crops (Figs. 3–5; Table S6). The nutrient uptake by BARI Gom30 varied significantly across different treatment combinations (Fig. 3). For N uptake, the values ranged from 21.73 kg ha^{-1} in the $L_2 \times T_1 \times Y_1$ treatment combination to 115.5 kg ha^{-1} in the $L_1 \times T_5 \times Y_2$ combination. P uptake showed a range from 3.156 kg ha^{-1} in the $L_2 \times T_1 \times Y_1$ treatment to 29.215 kg ha^{-1} in the $L_1 \times T_5 \times Y_2$ treatment combination. K uptake varied between 21.79 kg ha^{-1} in the $L_2 \times T_1 \times Y_1$ treatment combination and 106.23 kg ha^{-1} in the $L_1 \times T_5 \times Y_2$ treatment combination. S uptake ranged from 4.002 kg ha^{-1} in the $L_2 \times T_1 \times Y_1$ treatment to 20.69 kg ha^{-1} in the $L_1 \times T_5 \times Y_2$ treatment combination.

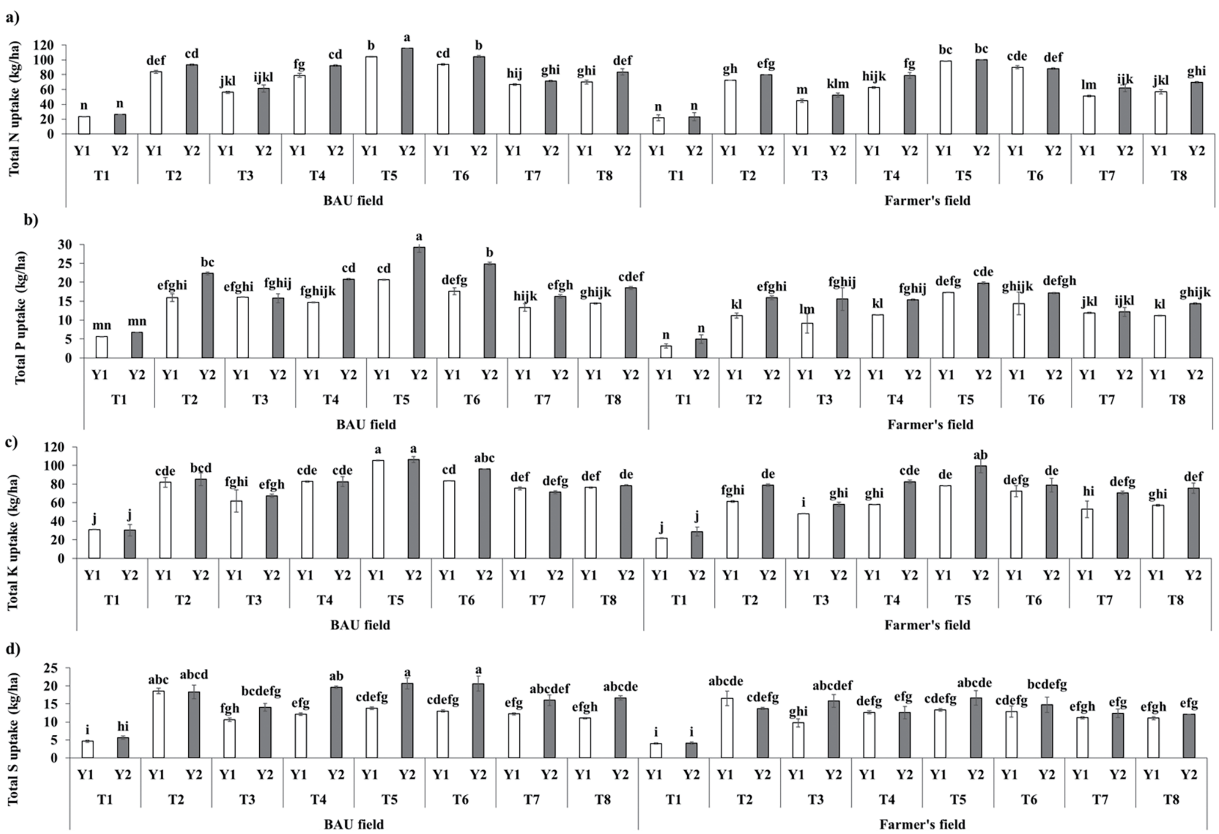

Figure 3: Effect of interaction among location, treatment and year on total uptakes of nitrogen (a), phosphorus (b), potassium (c), and sulphur (d) by wheat in BAU field and farmer's field. Different lowercase letter(s) on top of each bar represent significant differences among treatments at the 5% level of probability ($p < 0.05$) according to DMRT. Error bars represent standard error means. L_1 = BAU field; L_2 = Farmer's field; T_1 = Control; T_2 = 100% RFD; T_3 = 75% RFD, T_4 = 75% N from RFD + 25% N from cow dung (CD); T_5 = 75% N from RFD + 25% N from poultry manure (PM); T_6 = 75% N from RFD + 25% N from vermicompost (VC); T_7 = 75% N from RFD + 25% N from household compost (HC); T_8 = 75% N from RFD + 25% N from rice straw compost (RSC); Y_1 = Year 2022; Y_2 = Year 2023

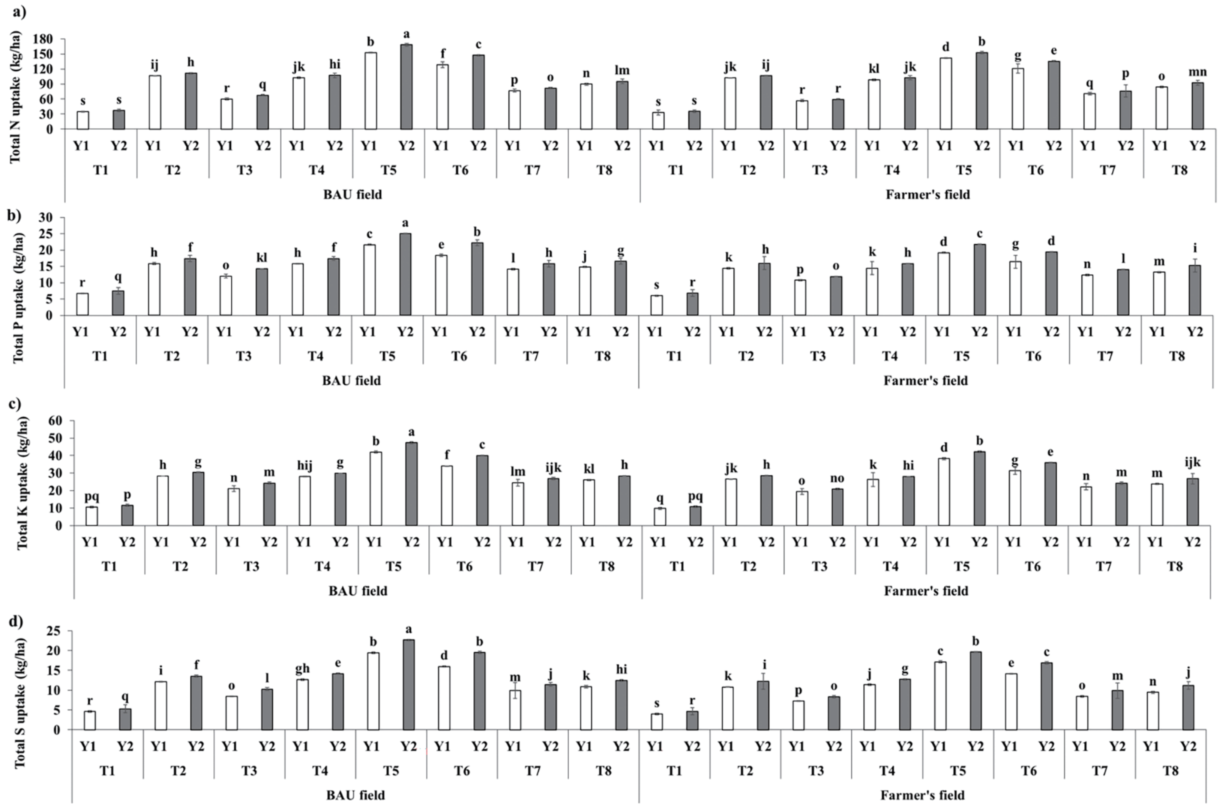

Figure 4: Effect of interaction among location, treatment and year on total uptakes of nitrogen (a), phosphorus (b), potassium (c), and sulphur (d) by mungbean in BAU field and farmer's field. Different lowercase letter(s) on top of each bar represent significant differences among treatments at the 5% level of probability ($p < 0.05$) according to DMRT. Error bars represent standard error means. L_1 = BAU field; L_2 = Farmer's field; T_1 = Control; T_2 = 100% RFD; T_3 = 75% RFD, T_4 = 75% N from RFD + 25% N from cow dung (CD); T_5 = 75% N from RFD + 25% N from poultry manure (PM); T_6 = 75% N from RFD + 25% N from vermicompost (VC); T_7 = 75% N from RFD + 25% N from household compost (HC); T_8 = 75% N from RFD + 25% N from rice straw compost (RSC); Y_1 = Year 2022; Y_2 = Year 2023

The nutrient uptake by Binamoog-8 showed a wide range across different locations, treatment and year combinations (Fig. 4). N uptake ranged from 33.19 kg ha^{-1} in the $L_2 \times T_1 \times Y_1$ treatment at the farmer's field to 168.17 kg ha^{-1} in the $L_1 \times T_5 \times Y_2$ treatment at the BAU field. P uptake varied between 5.983 kg ha^{-1} in the $L_2 \times T_1 \times Y_1$ treatment at the farmer's field and 25.005 kg ha^{-1} in the $L_1 \times T_5 \times Y_2$ treatment at the BAU field. K uptake ranged from 9.74 kg ha^{-1} in the $L_2 \times T1 \times Y_1$ treatment at the farmer's field to 47.28 kg ha^{-1} in the $L_1 \times T_5 \times Y_2$ treatment at the BAU field. S uptake varied between 3.994 kg ha^{-1} in the $L_2 \times T_1 \times Y_1$ treatment at the farmer's field and 22.666 kg ha^{-1} in the $L_1 \times T_5 \times Y_2$ treatment at the BAU field.

The nutrient uptake by BRRI dhan71 exhibited a wide range across different locations, treatments, and years (Fig. 5). N uptake ranged from 20.96 kg ha^{-1} in the $L_2 \times T_1 \times Y_1$ treatment at the farmer's field to 132.13 kg ha^{-1} in the $L_1 \times T_5 \times Y_2$ treatment at the BAU field. P uptake varied between 3.538 kg ha^{-1} in the $L_2 \times T_1 \times Y_1$ treatment at the farmer's field and 21.493 kg ha^{-1} in the $L_1 \times T_5 \times Y_2$ treatment at the BAU field. K uptake ranged from 31.33 kg ha^{-1} in the $L_2 \times T_1 \times Y_1$ treatment at the farmer's field to 143.14 kg ha^{-1} in the $L_1 \times T_5 \times Y_2$ treatment at the BAU field. S uptake varied between 3.974 kg ha^{-1} in the $L_2 \times T_1 \times Y_1$ treatment at the farmer's field and 27.267 kg ha^{-1} in the $L_1 \times T_5 \times Y_2$ treatment at the BAU field.

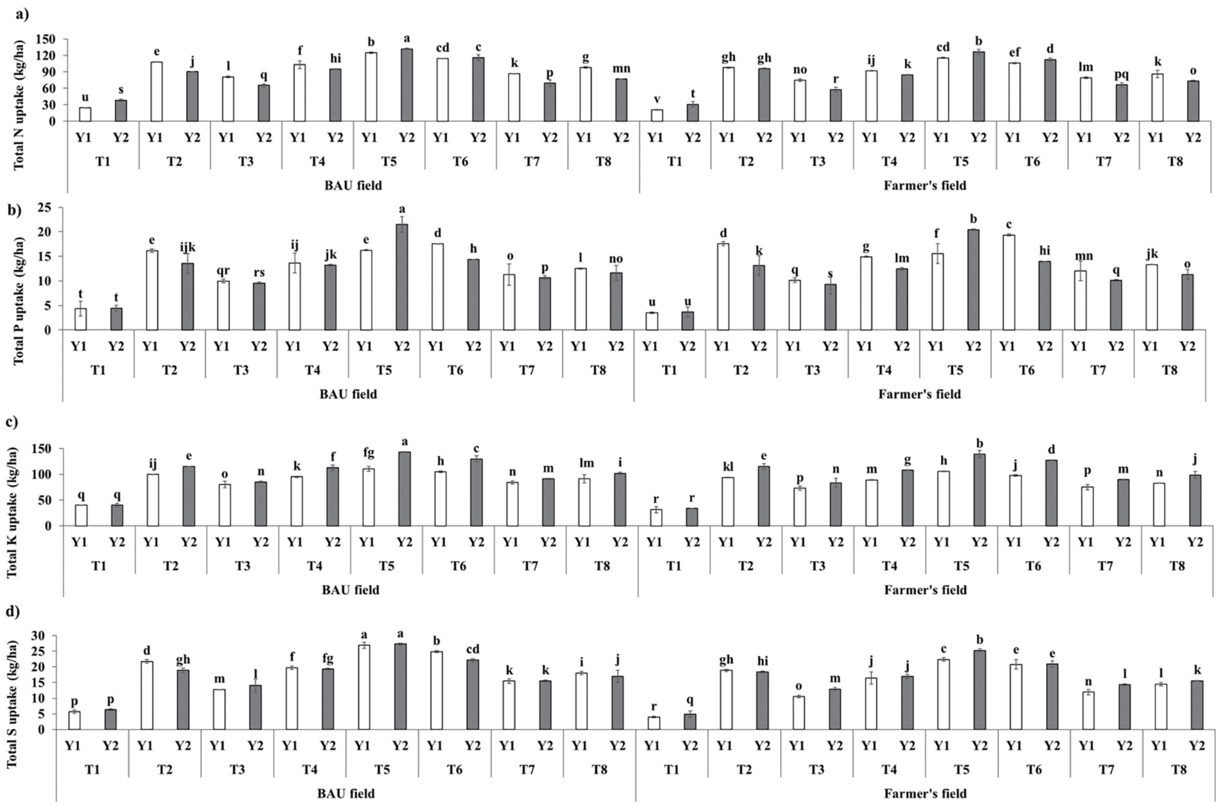

Figure 5: Effect of interaction among location, treatment and year on total uptakes of nitrogen (a), phosphorus (b), potassium (c), and sulphur (d) by T. Aman rice in BAU field and farmer's field. Different lowercase letter(s) on top of each bar represent significant differences among treatments at the 5% level of probability ($p < 0.05$) according to DMRT. Error bars represent standard error means. L_1 = BAU field; L_2 = Farmer's field; T_1 = Control; T_2 = 100% RFD; T_3 = 75% RFD, T_4 = 75% N from RFD + 25% N from cow dung (CD); T_5 = 75% N from RFD + 25% N from poultry manure (PM); T_6 = 75% N from RFD + 25% N from vermicompost (VC); T_7 = 75% N from RFD + 25% N from household compost (HC); T_8 = 75% N from RFD + 25% N from rice straw compost (RSC); Y_1 = Year 2022; Y_2 = Year 2023

For all three crops cultivated, the increase in uptake of N, P, K, and S was more pronounced in the second year compared to the first year.

3.4 Marginal Benefit-Cost Ratio (MBCR)

The system gross returns and marginal benefit-cost ratio (MBCR) of the Wheat–Mungbean–T. Aman rice cropping pattern was significantly influenced by the integrated application of manures and composts with chemical fertilizers at both locations in both years (Table 3, Table S7). The most profitable combination was the $L_1 \times T_5 \times Y_2$ treatment (BAU field, 75% N RFD + 25% N from PM in second year), which achieved the highest system gross return of Tk 768,595/ha and the highest MBCR of 16.35. This combination outperformed all others; in contrast, the least profitable combination was the $L_2 \times T_1 \times Y_1$ treatment (Farmer's field, control treatment in Year 2022), which recorded the lowest system gross return of Tk 235,133/ha and was economically inefficient. The BAU field (L_1) consistently showed higher returns and MBCR values compared to the Farmer's field (L_2). Among treatments, T_5 consistently delivered superior results across both locations and years, while the control treatment (T_1) performed poorly. Year 2023 (Y_2) generally showed higher gross returns than Year 2022 (Y_1), though with slight variations in MBCR.

Table 3: The marginal benefit-cost ratio of the Wheat–Mungbean–T. Aman rice cropping pattern as influenced by the integrated application of manures and composts with chemical fertilizers

Treatment combination	System gross return (Tk/ha)	System MBCR
Location (L) × Treatment (T)		
$L_1 \times T_1$	267,233 h	
$L_1 \times T_2$	625,131 cd	12.720 b
$L_1 \times T_3$	544,883 fg	13.313 b
$L_1 \times T_4$	623,102 cd	10.915 c
$L_1 \times T_5$	745,014 a	15.601 a
$L_1 \times T_6$	694,452 b	2.685 e
$L_1 \times T_7$	585,833 def	9.771 cd
$L_1 \times T_8$	600,135 de	12.971 b
$L_2 \times T_1$	243,562 h	
$L_2 \times T_2$	616,031 d	12.410 b
$L_2 \times T_3$	521,167 g	12.235 b
$L_2 \times T_4$	608,316 de	10.480 c
$L_2 \times T_5$	712,171 ab	14.562 a
$L_2 \times T_6$	667,874 bc	2.524 e
$L_2 \times T_7$	563,617 efg	9.121 d
$L_2 \times T_8$	585,951 def	12.442 b
Location (L) × Year (Y)		
$L_1 \times Y_1$	570,362 bc	10.708 bc
$L_1 \times Y_2$	601,084 a	11.571 a
$L_2 \times Y_1$	551,779 c	10.139 c
$L_2 \times Y_2$	577,893 ab	10.939 b
Treatment (T) × Year (Y)		
$T_1 \times Y_1$	243,550 h	
$T_1 \times Y_2$	267,245 h	
$T_2 \times Y_1$	614,567 cd	12.360 de
$T_2 \times Y_2$	626,596 cd	12.770 cde
$T_3 \times Y_1$	516,633 g	12.029 ef
$T_3 \times Y_2$	549,417 fg	13.519 bc
$T_4 \times Y_1$	605,167 de	10.387 gh
$T_4 \times Y_2$	626,251 cd	11.007 fg
$T_5 \times Y_1$	708,717 a	14.453 b
$T_5 \times Y_2$	748,468 a	15.711 a
$T_6 \times Y_1$	658,933 bc	2.469 j
$T_6 \times Y_2$	703,393 ab	2.739 j
$T_7 \times Y_1$	560,833 efg	9.040 i
$T_7 \times Y_2$	588,617 def	9.853 hi
$T_8 \times Y_1$	580,167 def	12.227 de
$T_8 \times Y_2$	605,919 de	13.186 cd

(Continued)

Table 3 (continued)

Treatment combination	System gross return (Tk/ha)	System MBCR
Location (L) × Treatment (T) × Year (Y)		
$L_1 \times T_1 \times Y_1$	251,967 m	
$L_1 \times T_1 \times Y_2$	282,500 m	
$L_1 \times T_2 \times Y_1$	621,267 defgh	12.588 defgh
$L_1 \times T_2 \times Y_2$	628,996 defgh	12.852 defgh
$L_1 \times T_3 \times Y_1$	525,533 kl	12.433 efgh
$L_1 \times T_3 \times Y_2$	564,233 hijkl	14.192 bcd
$L_1 \times T_4 \times Y_1$	611,767 efghi	10.581 ijk
$L_1 \times T_4 \times Y_2$	634,437 cdefg	11.248 hij
$L_1 \times T_5 \times Y_1$	721,433 ab	14.855 abc
$L_1 \times T_5 \times Y_2$	768,595 a	16.348 a
$L_1 \times T_6 \times Y_1$	668,500 bcde	2.527 m
$L_1 \times T_6 \times Y_2$	720,404 ab	2.842 m
$L_1 \times T_7 \times Y_1$	573,033 ghijkl	9.397 kl
$L_1 \times T_7 \times Y_2$	598,633 fghij	10.146 jkl
$L_1 \times T_8 \times Y_1$	589,400 fghijk	12.571 defgh
$L_1 \times T_8 \times Y_2$	610,869 efghi	13.371 cdef
$L_2 \times T_1 \times Y_1$	235,133 m	
$L_2 \times T_1 \times Y_2$	251,991 m	
$L_2 \times T_2 \times Y_1$	607,867 efghi	12.131 fghi
$L_2 \times T_2 \times Y_2$	624,196 defgh	12.688 defgh
$L_2 \times T_3 \times Y_1$	507,733 l	11.624 ghij
$L_2 \times T_3 \times Y_2$	534,600 jkl	12.845 defgh
$L_2 \times T_4 \times Y_1$	598,567 fghij	10.193 jkl
$L_2 \times T_4 \times Y_2$	618,065 efgh	10.767 ijk
$L_2 \times T_5 \times Y_1$	696,000 bc	14.050 bcde
$L_2 \times T_5 \times Y_2$	728,341 ab	15.074 ab
$L_2 \times T_6 \times Y_1$	649,367 cdef	2.411 m
$L_2 \times T_6 \times Y_2$	686,381 bcd	2.636 m
$L_2 \times T_7 \times Y_1$	548,633 ijkl	8.683 l
$L_2 \times T_7 \times Y_2$	578,600 ghijk	9.560 kl
$L_2 \times T_8 \times Y_1$	570,933 ghijkl	11.883 fghi
$L_2 \times T_8 \times Y_2$	600,968 fghij	13.002 defg
L × T	*	*
L × Y	*	*
T × Y	*	*
L × T×Y	*	*

Note: In a column, the same letter(s) indicate statistically similar, and different letter(s) indicate significant differences at the 5% level of probability ($p < 0.05$). * = $p < 0.05$, ns = Non-significant; L_1 = BAU field; L_2 = Farmer's field; T_1 = Control; T_2 = 100% RFD; T_3 = 75% RFD, T_4 = 75% N from RFD + 25% N from cow dung (CD); T_5 = 75% N from RFD + 25% N from poultry manure (PM); T_6 = 75% N from RFD + 25% N from vermicompost (VC); T_7 = 75% N from RFD + 25% N from household compost (HC); T_8 = 75% N from RFD + 25% N from rice straw compost (RSC); Y_1 = Year 2022; Y_2 = Year 2023.

3.5 Properties of POST-Harvest Soils

Analysis of post-harvest soils revealed significant variations in chemical and fertility properties among different factors in both the BAU farm and Farmers field in both years (Table 4). BAU field showed better chemical and fertility properties than the farmer's field. The pH of the soil in both locations was slightly affected by the treatments. The two-way interaction of location and treatment for the Wheat–Mungbean–T. Aman cropping pattern was significant for all the properties of post-harvest soil (Table 4). CEC was significantly increased from low to medium levels through the combination $L_1 \times T_5$ (8.73 meq/100 g soil), followed by $L_1 \times T_6$ (8.72 meq/100 g soil), which were statistically similar. In the Farmer's field, $L_2 \times T_5$ and $L_2 \times T_6$ recorded CEC values of 7.70 and 7.57 meq/100 g soil, respectively, indicating consistent improvement across locations. SOM also increased significantly, with $L_1 \times T_5$ achieving the highest SOM content of 2.41%, up from an initial 1.81%, and $L_1 \times T_6$ reaching 2.39%. In the Farmer's field, $L_2 \times T_5$ and $L_2 \times T_6$ recorded SOM values of 2.01% and 1.94%, respectively, up from an initial 1.32%. The increase in SOM directly influenced the total N content, which rose significantly across treatments. $L_1 \times T_5$ recorded the highest N content at 0.23%, followed by $L_1 \times T_6$ at 0.22%, while $L_2 \times T_5$ and $L_2 \times T_6$ recorded 0.19% and 0.18%, respectively. Available P and S levels were also significantly enhanced, particularly in $L_1 \times T_5$, which recorded 10.10 ppm for P and 15.10 ppm for S, and in $L_2 \times T_5$, which recorded 8.21 ppm for P and 12.89 ppm for S. Exchangeable K was significantly higher in $L_1 \times T_8$ (75% N from RFD + 25% N from rice straw compost) at 0.11 meq/100 g soil, followed by $L_2 \times T_8$ at 0.09 meq/100 g soil. In contrast, the control treatment in both locations ($L_1 \times T_1$ and $L_2 \times T_1$) showed the lowest levels of all the nutrients.

Table 4: Properties of the post-harvest soils of BAU and Farmer's fields for Wheat–Mungbean–T. Aman cropping pattern

Treatment combination	pH	CEC (meq/100 g soil)	SOM (%)	Total N (%)	Available P (ppm)	Exchangeable K (meq/100 g soil)	Available S (ppm)
Initial							
L_1 Initial	6.55	7.6	1.81	0.17	7.43	0.071	9.98
L_2 Initial	6.63	6.49	1.32	0.1	5.12	0.06	8.12
Location (L) × Treatment (T)							
$L_1 \times T_1$	6.55 i	7.60 f	1.78 hi	0.15 ef	7.40 h	0.06 de	9.55 k
$L_1 \times T_2$	6.56 i	8.17 d	2.04 cd	0.19 d	8.12 f	0.07 cd	10.78 i
$L_1 \times T_3$	6.55 i	8.13 d	1.82 gh	0.18 d	7.44 gh	0.06 de	9.98 j
$L_1 \times T_4$	6.59 gh	8.52 b	1.84 gh	0.21 bc	8.96 c	0.08 bc	13.99 c
$L_1 \times T_5$	6.60 fg	8.73 a	2.41 a	0.23 a	10.10 a	0.09 b	15.10 a
$L_1 \times T_6$	6.60 fg	8.72 a	2.39 a	0.22 ab	9.49 b	0.09 b	14.73 b
$L_1 \times T_7$	6.58 h	8.32 c	2.12 bc	0.20 cd	8.22 e	0.08 bc	13.34 e
$L_1 \times T_8$	6.59 gh	8.36 c	2.19 b	0.21 bc	8.34 d	0.11 a	13.86 d
$L_2 \times T_1$	6.61 ef	6.51 l	1.30 l	0.11 h	5.40 m	0.05 e	8.04 n
$L_2 \times T_2$	6.66 c	6.82 j	1.50 k	0.14 fg	6.62 j	0.07 cd	9.14 l
$L_2 \times T_3$	6.62 e	6.60 k	1.37 l	0.13 g	5.44 m	0.06 de	8.99 m
$L_2 \times T_4$	6.70 b	7.39 g	1.89 fg	0.18 d	7.21 i	0.07 cd	11.12 h
$L_2 \times T_5$	6.72 a	7.70 e	2.01 de	0.19 d	8.21 e	0.08 bc	12.89 f

(Continued)

Table 4 (continued)

Treatment combination	pH	CEC (meq/100 g soil)	SOM (%)	Total N (%)	Available P (ppm)	Exchangeable K (meq/100 g soil)	Available S (ppm)
$L_2 \times T_6$	6.71 ab	7.57 f	1.94 ef	0.18 d	7.49 g	0.08 bc	11.78 g
$L_2 \times T_7$	6.67 c	7.12 i	1.61 j	0.15 ef	6.48 k	0.07 cd	10.85 i
$L_2 \times T_8$	6.64 d	7.19 h	1.70 ij	0.16 e	6.34 l	0.09 b	10.89 i
L × T	***	***	***	*	***	*	***

Note: In a column, the same letter(s) indicate statistically similar, and different letter(s) indicate significant differences at the 5% level of probability ($p < 0.05$). *** = $p < 0.001$, * = $p < 0.05$, ns = Non-significant; L_1 = BAU field; L_2 = Farmer's field; T_1 = Control; T_2 = 100% RFD; T_3 = 75% RFD, T_4 = 75% N from RFD + 25% N from cow dung (CD); T_5 = 75% N from RFD + 25% N from poultry manure (PM); T_6 = 75% N from RFD + 25% N from vermicompost (VC); T_7 = 75% N from RFD + 25% N from household compost (HC); T_8 = 75% N from RFD + 25% N from rice straw compost (RSC); Y_1 = Year 2022; Y_2 = Year 2023.

4 Discussion

The gradual decline of soil fertility is leading to a concerning issue in crop yields that is alarming for scientists, policymakers, and farmers. Applying organic manures combined with inorganic fertilizers has improved crop yield and yield-related traits. This includes increases in plant height, the number of productive tillers hill^{-1}, the number of grains panicle^{-1}/spike^{-1}, as well as grain and straw yield noted by various researchers when they combine organic manures with inorganic fertilizers [21,48–50]. In this study, the growth and yield parameters of wheat, mungbean, and T. Aman rice were significantly improved by the integrated applications of organic and inorganic fertilizers. The highest biological yield for wheat, mungbean and T. Aman rice was observed in $L_1 \times T_5 \times Y_2$ combinations (25% N from PM with 75% N fertilizer at BAU field in 2023) with 10.83, 5.67 and 12.37 t ha^{-1}. PM with chemical fertilizers also performed well in the farmer's field in the second year ($L_2 \times T_5 \times Y_2$:25% N from PM with 75% N fertilizer at the farmer's field in 2023). This indicates that PM with chemical fertilizers is the most productive treatment across both locations and crops. The treatment combination $L_1 \times T_5 \times Y_2$ caused the maximum biological yield increase with an average of 328.06%, 203.57% and 185.41%, respectively, over $L_2 \times T_1 \times Y_1$ combination (No fertilization at farmer's field in 2022) that recorded the lowest biological yield among all combinations. After PM, 25% N from VC with 75% RFD (T_6) showed better performance, followed by 25% N from CD with 75% RFD (T_4) and 100% RFD (T_2) at both locations in both years. Yield parameters and yield for all three crops were better at location L_1 (BAU field) and in the second year (Y_2) which might be due to better fertility status and management practices throughout the cropping seasons. However, the yield improvement in Char land soil was higher than in farm soil which might be due to the difference in their baseline fertility and physico-chemical properties. Char soils are typically nutrient-poor and lack organic matter, making them highly responsive to organic amendments [35]. PM is considered one of the best types of animal manure for providing high N and balanced nutrients [18]. According to Ojo et al. [51], poultry manure effluent contains more organic carbon (OC), N, P, K, iron (Fe), and zinc (Zn) than rice bran and cow dung effluent. On the other hand, VC is particularly effective in increasing vegetative growth, root development, and yield components, as seen in studies where the application of VC resulted in the best outcomes [52,53].

In this study, the highest total uptake of macronutrients by the crops, including N, P, K, and S was recorded in treatment combination $L_1 \times T_5 \times Y_2$ (75% N from RFD + 25% N from PM in BAU field in 2023). After $L_1 \times T_5 \times Y_2$, treatment combination $L_2 \times T_5 \times Y_2$ (75% N from RFD + 25% N from PM in Char land soils in 2023) performed well for nutrient uptake. Followed by T_5, treatment T_6 (75% N from RFD + 25% N from VC) also showed better performance for nutrient uptake in combination with locations and years for the three crops under study. Organic materials improve nutrient availability by microbial activity, which boosts nutrient cycling. PM improves nutrient uptake by crops more effectively than NPK fertilizer alone due to its adequate supply of macro and micronutrients, including calcium (Ca) and magnesium (Mg), which are often lacking in NPK fertilizers [54]. Combining PM with NPK fertilizer enhances the residual effect of nutrients in the soil. Like PM, plants also absorbed nutrients more effectively when VC was applied with chemical fertilizers compared to chemical fertilizers alone. This result aligns with Ravimycin [55] and Moeinnamini et al. [56], who reported that nutrient uptake by crops was significantly increased than control by applying VC.

Economic analysis was done to find out the economically better treatment (s). The cost and return analysis showed that T_5 treatment (75% N from RFD + 25% N from PM) at BAU field (L_1) in second year (Y_2) had the highest gross return (about Tk 768,595/ha) and MBCR (16.35) followed by same treatment (T_5) at Char land soils (L_2) in second year (Y_2) (Gross return Tk 728,341/ha and MBCR 15.07), making it the most profitable treatment. The higher MBCR for T_5 treatment is due to its ability to boost grain yields across all crops in the system while keeping input costs relatively moderate compared to other integrated treatments. Treatment T_6 (75% N from RFD + 25% N from VC) in both locations in both years also had higher gross return but due to the high price of vermicompost, its economic efficiency was low. Singh et al. [57] reported that combining organic manures with chemical fertilizers in IPNS improves gross return, added benefit, and MBCR. Sarker et al. [58] reported that higher gross return and MBCR were observed in Wheat–Mungbean–T. Aman rice cropping pattern, due to favorable input-output balance.

Soil treated with organic amendments exhibited notable increases in soil chemical properties like CEC, organic matter, and availability of key macro elements such as N, P, K, S, Ca, and Mg compared to untreated soil [59]. Adding organic materials like animal manure and CD improves microbial activity and helps reduce metal toxicity [21]. In this experiment, BAU field showed T_5 (75% N from RFD + 25% N from PM) consistently caused the highest improvements in CEC, SOM, total N, exchangeable K, and available P and S in the soils of both fields after harvest, making it the most effective treatment for enhancing soil fertility. Again, treatment T_6 (75% N from RFD + 25% N from VC), being mostly statistically at par with treatment $T_{5,}$ showed substantial improvements in most of the parameters such as SOM, total N, and exchangeable K. However, K content in both soils was highest in treatment T_8 (75% N from RFD + 25% N from RSC), as RSC contains more K than other organic manures or composts. Chemical and fertility properties of soil were better in BAU field because farm soils are actively cultivated and managed with fertilization, crop rotation, and organic matter incorporation, while char land soils, often formed by river deposits, may lack these nutrients and adequate management practices [35]. Organic amendments in Char lands enhance soil structure, water retention, and nutrient availability, leading to more improvements in soil fertility from low to medium [42] compared to farmlands, which already have better soil fertility. PM and VC applications increase soil pH, enhance SOC, and improve soil health [59,60]. According to Li et al. [61], organic amendments with low C/N ratios can enhance the deposition of crop root exudates into stable organic C in soil and promote crop growth. Crop root exudates play a crucial role in forming stable SOC by directly associating with soil minerals [62]. In contrast, organic amendments must first degrade into small molecules before stabilizing SOC [63]. PM helps soil water retention and microbial activity, and promotes soil fertility, whereas VC aids in the slow release of P through microbial activity [64] and boosts soil P mineralization rates [65,66]. Besides these organic amendments increase nutrient availability, reduce K fixation, and raise CEC of soil [67–69]. However, the nutrient contents of organic amendments are highly variable. Users must understand and manage manure and compost variability to optimize their agronomic and environmental benefits. Manure requires careful management to avoid over- or under-application and to address the long-term environmental impacts of both application and storage [70]. To sustain crop productivity, farmers should use balanced inorganic fertilizers and integrate organic manures to improve soil health [35]. Applying organic manure at least once a year along with chemical fertilizers can help maintain soil fertility and ensure long-term sustainable yields [71]. In the char lands of Bangladesh, where soil fertility is poor, using organic materials along with chemical fertilizers is therefore, essential for enhancing physicochemical properties of soil and sustaining agricultural productivity [72].

The reduction in chemical fertilizers can mitigate potential risks to human health associated with the excessive use of chemical fertilizers. Furthermore, crops produced from integrated organic and inorganic farming systems offer superior food value. The economic implementation of this sustainable farming system highlights its potential to enhance the economic viability of small-scale farmers [73]. The findings of the present study could help the government and other organizations to take proper steps to improve the livelihood of char people [35] by increasing crop production and better soil management practices. However, long-term field trials in other char areas using different cropping patterns are needed to better understand nutrient balance, fertility restoration, and changes in physicochemical properties of soils, as multi-year trials in multi-locations can make findings more applicable. To provide deeper insights into farmers' benefits, using appropriate technology and cost-efficient organic amendments is crucial to predict improvement in crop yield and soil fertility.

5 Conclusions

From the present study, it was found that organic manures or composts could compensate for up to 25% of the recommended doses of inorganic fertilizers, and by combining both organic and inorganic sources of nutrients, a substantial increase in the yield parameters, yields and nutrient uptake of wheat, mungbean and T. Aman rice can be achieved. The integrated plant nutrition system can improve soil health by boosting soil fertility parameters in both farm and char lands. Particularly in char soils with poor fertility and low organic matter status, the integrated approach should be practiced for the betterment of the livelihood of char farmers. Although PM and VC performed well, the economic efficiency of the latter was low. Therefore, based on cost-effectiveness and superior performance, the use of poultry manure might be an industrially promising and economically sustainable approach for small-scale farmers in Wheat–Mungbean–T. Aman rice cropping pattern in char land areas.

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