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Lime and Manure Amendment Improve Soil Fertility, Productivity and Nutrient Uptake of Rice-Mustard-Rice Cropping Pattern in an Acidic Terrace Soil

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Abstract: Acid soil is an obstacle to agricultural development and a concern regarding food and environmental security. Therefore, a study was carried out for two consecutive years to see how lime and organic manure (OM) amendments affect yield and nutrient absorption in the Transplanted (T.) Aman–Mustard–Boro cropping pattern in an acidic terrace soil. With nine treatments and three replications, the experiment was set in a randomized complete block design. The treatments were applied to the first crop, T. Aman, with different dosages of lime (dololime at the rate of 1 and 2 t ha^{-1}), OM (cow dung at 5 t ha^{-1}, poultry manure at 3 t ha^{-1}) and lime–OM combination, and their residual effects were studied in the following mustard and boro rice crops. Results demonstrate that the effect of lime and manure was more pronounced in the case of the second and third crops in the first year and of all crops in the pattern in the second year. In the first year, grain and straw yield of T. Aman as well as the overall system productivity were not influenced significantly by the application of lime and manure, but significant increases were obtained in the second year. As an average of both years, the highest grain yield of 5.2 t ha^{-1} (12% over control) was recorded for T. Aman, 1.7 t ha^{-1} (41% over control) for mustard and 5.9 t ha^{-1} (47% over control, 3.9 t ha^{-1}) for boro rice when dololime was applied in combination with poultry manure. In both years, N, P, K and S uptake were significantly increased compared to the control in all the crops due to the combined application of lime and cow dung or poultry manure. Combined application of lime and manure amendment significantly improved nutrient availability and soil quality. Therefore, applying lime in combination with manure can be practiced to uplift crop productivity in acidic terrace soils.

Keywords: dololime; poultry manure; cow dung; soil acidity; rice; grain yield; soil pH; soil physico-chemical properties

1. Introduction

Rice is the second most widely cultivated staple food nourishing about 164 million people of Bangladesh and more than 60% of the world population [1–3]. In terms of area and output, mustard ranks first among the oilseed crops produced in Bangladesh. Bangladesh is anticipated to have a population of over 186 million by 2030, according to the UN World Population Prospects (2019 Revision). Rice is cultivated on around 11.6 million hectares of land in Bangladesh, with a yield of over 36.2 million metric tons [4]. Rice planted area will decline to 10.8 million hectares in the next decade, and output would need to be raised several times its current level to feed this growing population.

Acid soils are a major issue in Bangladesh, with the area of very highly acid and very acid soils increasing by 13% between 1988 and 2010 [5]. Soils in 5.06 Mha of Bangladesh's lands contain varying degrees of acidity (4.5–6.5), which may limit crop productivity in 30% of the country's land [6]. Geomorphologically, acid basin clays and terrace soils are moderately acidic. Soil acidification occurs due to acidic parent materials during soil formation, and basic cation leaching (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) with urea fertilizer application continuously. Urea acidifies the soil through nitrification ($NH_4^+ + 2O_2 = NO_3^- + 2H^+ + H_2O$). Inputs of S as elemental S or SO_2 from the atmosphere can also produce soil acidity when they are oxidized: (i) $2S + 3O_2 + 2H_2O = 2H_2SO_4$; (ii) $2SO_2 + O_2 + 2H_2O = 2H_2SO_4$. CO_2 is produced by microbial breakdown of manure or soil organic matter, which dissolves in water to generate H_2CO_3 in the same manner as rain. The humid tropical climate of Bangladesh encourages base leaching and the consequent accumulation of Fe^{2+}, Al^{3+}, and Mn^{2+} in acidic soils, resulting in micronutrient poisoning [7,8]. Lack of basic cations, excessive saturation of soil CEC with H^+ and Al^{3+} ions, and unavailability of macronutrients (notably P) are the factors that limit agricultural output [9,10]. Acidic soils (pH < 5.5) have a direct or indirect influence on plant growth, because it reduces microbial activity, causes Fe and Mn toxicity under reducing soil conditions, and changes the availability of plant nutrients such as P, secondary nutrients (Ca, Mg), and micronutrients (Mo, B, and Zn) (Al in some cases) [11]. If appropriate management techniques for amelioration are not adopted, soil acidity may worsen and impact crop output [12]. Liming is the most economical method of alleviating soil acidity. The release of P anions from Al- and Fe-(hydro) oxide surfaces was promoted by appropriate liming, resulting in increases in soil pH [13]. Liming accelerates the breakdown of agricultural wastes and soil manure by increasing microbial activity [14], this, in turn, can improve the availability of plant nutrients in the soil, particularly P [15]. On the other hand, P availability is limited by increasing P precipitation as Ca-phosphate at higher pH levels [16]. Liming can also help with nutritional deficits other than P (e.g., N) [17,18]. Rahman et al. [19] conducted field trials using a wheat–rice cropping pattern and found that applying lime at 2.4 t ha^{-1} enhanced crop yields adequately.

Liming is one of the most fundamental and successful management techniques for decreasing soil acidity [20]. Lime enhances soil quality by reducing exchangeable Al concentrations and increasing P availability, cation exchange capacity (CEC), and base saturation [21]. In addition, lime can increase the availability of Ca and Mg in soils [22]. As SOM regulates biological processes involved in nutrient availability, it is a leading indicator of long-term soil fertility. Top soil fertility and organic matter (OM) content have declined over time under high (above normal flood level) and moderately high land (flooded up to about 90 cm during the flooding season) conditions [23]. Organic amendments such as cow dung (CD) and poultry manure (PM) are used to maintain soil fertility as an alternative to chemical fertilizers as a source of plant nutrients, especially in rice production [24,25]. CD and PM improve the physicochemical and biological characteristics of the soil, increasing nutrient availability [26–28].

In Bangladesh's acidic soil regions, a combination of lime and organic amendments may be a more efficient method to improve soil fertility. In the Old Himalayan Piedmont Plain (AEZ-1) and Northern and Eastern Piedmont Plains (AEZ-22), Sultana et al. [29] reported that soil amendment with dololime at 1 t ha^{-1} combined with poultry manure at 3 t ha^{-1} or farmyard manure (FYM) at 5 t ha^{-1} could be an efficient practice for achieving higher crop yield due to optimization of soil acidity and nutrient uptake by plants. In another experiment, Venkatesh et al. [30] discovered that using FYM and lime together increased yield and P usage efficiency by 7–16 and 30%, respectively, with an average 124 kg ha^{-1} P absorption in maize. Cropping patterns in Bangladesh are mostly rice-based. In Bangladesh, the T. Aman–Mustard–Boro rice planting design is the most often used.

However, there are insufficient data on the management of acid soils in Bangladesh's Madhupur Tract. As a result, the aims of the study were to (i) evaluate the impacts of lime and manure amendment on yield of T. Aman–Mustard–Boro cropping pattern; (ii) investigate the influence of lime and manure amendment on nutrient uptake by crops; and (iii) observe the changes in soil characteristics as a result of the addition of lime and manure. An effective management approach for profitable crop production on acidic terrace soil of Madhupur Tract using the Aman–Mustard–Boro rice planting pattern was investigated. This research will assist farmers in increasing crop yields in acidic environments.

2. Materials and Methods

2.1. Experimental Site and Soil Properties

This field experiment was carried out at a farmer's field of Bakta Union, Fulbaria Upazila, Mymensingh (24°38′ N, 90°16′ E) during the period of July 2017 to May 2019. The experimental site belongs to the Agro-ecological Zone Madhupur Tract (AEZ-28). According to the General Soil Type classification, the site falls under mixed deep and shallow red-brown terrace soils [31]. Topographically the experimental site was medium high to high. Twenty initial composite soil samples (0–15 cm depth) were taken from the experimental plots and evaluated using standard procedures before the experiment began. Soil characteristics such as soil organic matter (SOM), soil total nitrogen (STN), accessible P, exchangeable Ca and Mg, pH, electrical conductivity (EC), and cation exchange capacity (CEC) were determined using initial and post-harvest soil samples. As recommended by Ghosh et al. [32], SOM content was estimated by multiplying organic carbon (OC) by 1.73, and OC was measured titrimetrically using the Walkley and Black technique [33]. STN was measured using the semi-micro Kjeldahl technique [34], and available P was recovered from the soil using the Bray and Kurtz method [35], which involved shaking with a 0.03 M NH_4F–0.025 M HCl solution. The ammonium acetate extraction technique was used to extract the exchangeable Ca and Mg levels, which were then measured using the EDTA titration [36]. A glass electrode pH meter was used to measure the pH of the samples in a 1:2.5 soil:water ratio [36]. Following the technique outlined by Ghosh et al. [32], the EC of collected soil samples was measured electrometrically (1:5; soil:water ratio) using a conductivity meter using 0.01 M KCl solution to calibrate the meter. Chapman [37] recommended using the NH_4OAC extraction technique to measure CEC. The soil was silt loam in texture and strongly acidic having pH 4.62, Organic C 0.85%, total N 0.078%, available P 7.8 ppm, exchangeable K 16 ppm and available S 4 ppm. The fertility indices are low according to the local interpretation.

2.2. Plant Materials and Treatments

In the field experiment, three crops were grown: mustard (*Brassica rapa*), T. Aman (*Oryza sativa*), and boro rice (*Oryza sativa*) in a T. Aman–Mustard–Boro rice cropping pattern. T. Aman rice was grown with BRRI dhan71, mustard with BARI Sorisha14, and boro rice with BRRI dhan28. T. Aman rice was cultivated from July to October (mid to late monsoon), then mustard from November to January (winter), and finally boro rice from February to May (late-winter to pre-monsoon season). T. Aman rice was grown under hot, humid and rainfed conditions whereas boro rice was grown at relatively low temperature in winter and irrigated conditions. Two to three irrigations were needed for T. Aman rice when there was scarcity of rain. On the other hand, 8–10 irrigations were applied in the case of boro rice. The management of T. Aman and boro rice are similar except irrigation water supply. There were nine treatments comprising two levels of lime (dololime at the rate of 1 and 2 t ha^{-1}) and two kinds of partially decomposed air-dried organic amendment (cow dung and poultry manure). The experiment was carried out with the treatments listed in Table 1.

Table 1. List of the treatments used in the study with description.

Treatment	Description
T_1	Control (no lime and organic amendment)
T_2	Lime-1 (Dololime 1 t ha^{-1})
T_3	Lime-2 (Dololime 2 t ha^{-1})
T_4	OM-1 (Cow dung 5 t ha^{-1})
T_5	OM-2 (Poultry manure 3 t ha^{-1})
T_6	Lime-1 OM-1 (Dololime 1 t ha^{-1}, Cow dung 5 t ha^{-1})
T_7	Lime-1 OM-2 (Dololime 1 t ha^{-1}, Poultry manure 3 t ha^{-1})
T_8	Lime-2 OM-1 (Dololime 2 t ha^{-1}, Cow dung 5 t ha^{-1})
T_9	Lime-2 OM-2 (Dololime 2 t ha^{-1}, Poultry manure 3 t ha^{-1})

The chemical compositions of the manures used in this study are presented in Table 2.

Table 2. Nutrient composition and source of manures and dololime used in the study (dry matter basis).

Manure	Dry Matter Content (%)	C (g kg^{-1})	N (g kg^{-1})	P (g kg^{-1})	S (g kg^{-1})	Ca (g kg^{-1})	Mg (g kg^{-1})	pH (Water)	Source
Cow dung	65.3	330	12.3	4.8	2.2	4.1	16.6	7.5	Local household
Poultry manure	76.8	339	30.9	23.6	5.3	6	18.9	8	Local poultry farm
Dololime	-	-	-	-	-	206	109	8.2	Local market

2.3. Preparation of Experimental Plots and Growing Crops

Ploughing and cross ploughing were done with a motorized tiller on the field. Using traditional methods, the land was then laddered. Before final land preparation and laying out, all types of weeds and stubbles were removed from the field. The experiment was set up in an RCBD, with the experimental area separated into three blocks reflecting the replications to reduce the heterogenic effects of soil. There were nine different treatments to choose from. After each block was divided into 9 plots, the treatments were assigned at random to the unit plots in each block. As a result, there were a total of 27-unit plots. Each plot measured 4 m $\times$ 2.5 m and was separated from the others by ails (30 cm). The blocks were separated by a 1 m drain that ran between them. The fertilizers were applied according to the recommendations in the Bangladesh Agricultural Research Council's Fertilizer Recommendation Guide (2012): Urea 140 kg N ha^{-1}, TSP (Triple Superphosphate) 15 kg P ha^{-1}, MP (Muriate of Potash) 60 kg K ha^{-1}, Gypsum 15 kg S ha^{-1}, Zinc oxide 2 kg Zn ha^{-1}, and Boric acid 1 kg B ha^{-1}. Chemical fertilizers were given at full doses to all treatments, including the control. All chemical fertilizers were applied during final land preparation except urea. The urea was separated into three equal portions and applied in three separate doses. Dololime, cow dung, and poultry manure were combined with soil and applied two weeks before planting crops in the first year of the experiment. The first crop received lime and manure additions, and the residual effects were assessed in subsequent harvests. T. Aman and boro rice seedlings were grown for 30–35 days in nursery beds before being carefully removed and transplanted into plots with a 20 cm $\times$ 20 cm spacing. Three seedlings were planted in each of the three hills. Intercultural activities including irrigation, weeding, and pest control were performed as needed to provide and maintain a favorable environment for regular agricultural growth and development.

2.4. Harvesting and Data Recording

When the crops were fully ripe, they were harvested. The harvested crop from each plot was collected over a 1 m^2 area and tied separately. After that, the bundles were carried to the threshing floor and threshed. Plant height, effective tillers per hill, panicle length, filled grains per panicle, and 1000-grain weight, as well as grain and straw yields, were all measured in BRRI dhan71, BARI Sorisha14, and BRRI dhan28. After drying and weighing, the yields of T. Aman and boro rice grains and straw were measured. Grain yields were determined on a 14% moisture basis, whereas straw yields were determined on a sun dry basis. Five hills were randomly selected from each plot at maturity to record the yield contributing factors. The representative grain and straw samples were dried in an oven at 65 °C for about 24 h before they were ground by a grinding machine. The prepared samples were then stored in paper bags and finally they were kept in a desiccator until analysis was done. Total N concentration in grain and straw samples was determined using the semi-micro Kjeldahl method [34] using 0.l g of oven dry ground plant samples. The plant material was digested with 2 mL 30% H_2O_2 and 3 mL H_2SO_4 and 1.1 g catalyst mixture (K_2SO_4:$CuSO_4$. $5H_2O$:Se = 100:10:1). For the determination of P, K and S, 0.5 g plant samples were digested with 10 mL of di-acid mixture (HNO_3:$HClO_4$ = 2:1) at 200 °C. After cooling, the digests were transferred into 100 mL volumetric flasks, making the volume up to the mark with distilled water. Reagent blanks were prepared in a similar manner. Concentration of N was determined with steam distillation. P concentration was determined using the colorimetric method [38], K concentration was determined using the flame photometer method, and sulfur concentration was determined using the turbidimetric method. The N, P, K, S uptake by grain and straw was determined from grain and straw yield data. The nutrient uptake was determined by the formula [39]:

$$Nutrient\ uptake\ (\text{kg/ha}) = \frac{\text{Nutrient content} \times \text{Dry mass production (kg/ha)}}{100}$$

The total system productivity of the cropping pattern was calculated by the summation of rice equivalent yield of each crop. Rice equivalent yield (REY) was calculated to compare system performance by converting the yield of non-rice crops into equivalent rice yield on a price basis, using the formula: REY = Yx (Px/Pr), where Yx is the yield of non-rice crops (kg ha^{-1}), Px is the price of non-rice crops (TK kg^{-1}), and Pr is the price of rice (TK kg^{-1}).

2.5. Statistical Analysis

A one-way analysis of variance (ANOVA) was performed using different treatments as a random variable. Before using ANOVA, the data distribution was tested for normality. Using Minitab 17 software, the data were statistically evaluated to determine the significant differences in treatment effects. Using Tukey-multiple Kamer's comparison, a post hoc test was used to distinguish differences between treatments. Unless otherwise stated, all statistical analyses were considered significant at $p < 0.05$.

3. Results

3.1. Effect of Lime and Organic Manure Amendment on Yield of T. Aman–Mustard–Boro Cropping Pattern in Two Consecutive Years

3.1.1. Grain and Straw Yield of T. Aman

In 2018, the effect of lime and organic manure amendment on grain and straw yield of T. Aman rice (BRRI dhan71) was statistically non-significant ($p = 0.954$, Table 3). Grain yields varied from 5.0 to 5.4 tons per hectare and straw yield varied from 5.1 to 5.6 tons per hectare. In 2019, grain yield of T. Aman rice responded significantly to the application of lime, cow dung and poultry manure ($p = 0.035$, Table 3), but the effect was non-significant in the case of straw yield ($p = 0.256$, Table 3). T_7 had the largest grain production (4.9 tons per hectare), whereas T_1 had the lowest (4.2 tons per hectare). The increase in grain production above control varied from 1 to 15% percent, with T_7 (15%) having the most significant increase and T_6 having the lowest (1%).

Table 3. Effect of lime and manure amendment on grain yield, straw yield and total system productivity of T. Aman–Mustard–Boro cropping pattern.

Treatment	Grain Yield (t ha^{-1})							
	T. Aman		Mustard		Boro		System Productivity (t ha^{-1})	
	2018	2019	2018	2019	2018	2019	2018	2019
T1	5.0 ± 0.29	4.2 ± 0.12 c	1.2 ± 0.07 b	1.3 ± 0.04 d	3.9 ± 0.23 b	4.2 ± 0.12 c	10.1 ± 0.58	9.7 ± 0.28 b
T2	5.1 ± 0.29	4.4 ± 0.09 bc	1.5 ± 0.08 ab	1.5 ± 0.03 abc	5.2 ± 0.30 ab	5.9 ± 0.12 ab	11.7 ± 0.68	11.8 ± 0.24 ab
T3	5.2 ± 0.30	4.4 ± 0.14 bc	1.6 ± 0.09 a	1.6 ± 0.05 ab	5.5 ± 0.32 ab	6.1 ± 0.19 ab	12.3 ± 0.71	12.1 ± 0.39 ab
T4	5.3 ± 0.30	4.4 ± 0.18 bc	1.4 ± 0.08 ab	1.3 ± 0.05 cd	4.8 ± 0.27 ab	5.2 ± 0.21 b	11.4 ± 0.66	11.0 ± 0.44 ab
T5	5.4 ± 0.31	4.8 ± 0.14 ab	1.4 ± 0.08 ab	1.4 ± 0.04 abcd	4.8 ± 0.28 ab	5.4 ± 0.16 ab	11.6 ± 0.67	11.8 ± 0.34 ab
T6	5.1 ± 0.29	4.3 ± 0.15 c	1.6 ± 0.09 a	1.6 ± 0.06 ab	5.4 ± 0.31 ab	5.8 ± 0.20 ab	12.0 ± 0.69	11.7 ± 0.41 ab
T7	5.4 ± 0.31	4.9 ± 0.14 a	1.6 ± 0.09 a	1.7 ± 0.05 ab	5.5 ± 0.32 a	6.1 ± 0.18 ab	12.6 ± 0.72	12.6 ± 0.36 a
T8	5.3 ± 0.30	4.8 ± 0.10 ab	1.6 ± 0.09 a	1.7 ± 0.03 ab	5.6 ± 0.33 a	6.1 ± 0.12 ab	12.5 ± 0.72	12.6 ± 0.26 a
T9	5.2 ± 0.30	4.6 ± 0.13 b	1.7 ± 0.10 a	1.7 ± 0.05 a	5.7 ± 0.33 a	6.2 ± 0.18 a	12.6 ± 0.73	12.6 ± 0.36 a
p-value	0.954	0.035	0.022	0	0.026	0	0.351	0.001

Treatment	Straw Yield (t ha^{-1})					
	T. Aman		Mustard		Boro	
	2018	2019	2018	2019	2018	2019
T1	5.1 ± 0.29	4.5 ± 0.13	2.9 ± 0.17	2.6 ± 0.08 d	4.8 ± 0.27	4.5 ± 0.13 c
T2	5.2 ± 0.30	4.7 ± 0.10	3.5 ± 0.20	3.4 ± 0.07 abc	6.2 ± 0.36	6.4 ± 0.13 ab
T3	5.4 ± 0.31	4.6 ± 0.15	3.7 ± 0.21	3.7 ± 0.12 abc	6.4 ± 0.37	6.7 ± 0.21 ab
T4	5.4 ± 0.31	4.7 ± 0.19	3.2 ± 0.18	2.8 ± 0.11 d	5.5 ± 0.32	5.7 ± 0.23 b
T5	5.5 ± 0.31	4.8 ± 0.14	3.4 ± 0.19	3.1 ± 0.09 bcd	5.7 ± 0.33	5.9 ± 0.17 ab
T6	5.1 ± 0.30	4.4 ± 0.15	3.7 ± 0.21	3.7 ± 0.13 abc	6.2 ± 0.36	6.4 ± 0.22 ab
T7	5.5 ± 0.32	4.9 ± 0.14	3.9 ± 0.22	3.8 ± 0.11 a	6.2 ± 0.36	6.6 ± 0.19 ab
T8	5.6 ± 0.32	4.8 ± 0.10	3.9 ± 0.22	3.8 ± 0.08 ab	6.3 ± 0.37	6.6 ± 0.13 ab
T9	5.3 ± 0.31	4.6 ± 0.13	3.9 ± 0.23	3.9 ± 0.11 a	6.5 ± 0.37	6.8 ± 0.20 a
p-value	0.904	0.256	0.051	0	0.075	0

Figures in a column having common letters do not differ significantly at 5% level of risk. Data are mean ± SE (n = 3).

3.1.2. Seed and Stover Yield of Mustard

In 2018, the residual effect of lime and organic amendment substantially impacted mustard grain production (p = 0.022, Table 3), but not stover yield (p = 0.051, Table 3). Depending on the treatments, mustard seed yields varied from 1.2 to 1.7 t ha^{-1} (Table 3). T_9 (1.7 t ha^{-1}) had the highest seed output, which was statistically equivalent to all the treatments except control while T_1 (control) had the lowest value (1.2 t ha^{-1}). The increase in seed production above control varied from 16 to 44%, with T_9 (44%) having the most significant increase and T_4 having the lowest (16%). In 2019, both seed and stover yield of mustard were significantly influenced by the residual effect of lime and organic amendments (p = 0.000 for both seed and stover yield, Table 3). Depending on the treatments, mustard seed yields varied from 1.3 to 1.7 t ha^{-1} (Table 3). The increase in seed production above control varied from 6 to 38%, with T_9 (38%) having the most significant increase and T_4 having the lowest (6%). Stover yields varied from 2.6 to 3.9 tons per hectare (Table 3). Regarding the percent increase of stover yield over control, a maximum increase (49%) was noted in $T_{9,}$ and the minimum one (8%) was found in T_4.

3.1.3. Grain and Straw Yield of Boro Rice

In 2018, the grain yield of the third crop, boro rice (BRRI dhan28) responded significantly to the residual effect of dololime, cow dung and poultry manure (p = 0.026, Table 3) but the effect was non-significant in the case of straw yield (p = 0.075, Table 3). The grain yield ranged from 3.9 to 5.7 t ha^{-1}. The highest grain yield (5.7 t ha^{-1}) was observed in T_9 which was statistically identical to all the treatments except control, whereas the lowest value (3.9 t ha^{-1}) was recorded in T_1. Except for T_1, all other treatments produced statistically similar grain yields, indicating that lime and organic manure alone or in combination exerted a beneficial role over chemical fertilizer. The increase in grain yield over control ranged from 21 to 44% where the highest increase was obtained in T_9 and the lowest one was obtained with T_4. Straw yield ranged from 4.8 to 6.5 t ha^{-1}. In 2019, the residual effect of lime and organic amendment on grain and straw yield of boro rice was more pronounced (p = 0.000 for both grain and straw, Table 3). The grain yield ranged from 4.2 to 6.2 t ha^{-1}. The highest grain yield (6.2 t ha^{-1}) was observed in T_9 which was statistically identical to all the treatments except T_4 and T_1, whereas the lowest value (4.2 t ha^{-1}) was recorded in T_1 (control). The increase in grain yield over control ranged from 25 to 50% where the highest increase was obtained in T_9 and the lowest one was obtained with T_4. Straw yield ranged from 4.8 to 6.5 t ha^{-1}. Straw yields varied from 4.5 to 6.8 tons per hectare (Table 3). In terms of percent increase in straw yield, T_9 had the highest increase (52%) while T_4 had the lowest increase (28%).

3.1.4. Total System Productivity of T. Aman–Mustard–Boro Cropping Pattern in Two Consecutive Years

The effect of the application of dololime, cow dung, and poultry manure on total system productivity was non-significant in the first year (2018) (p = 0.351, Table 3). In 2019, the total system productivity of the T. Aman–Mustard–Boro cropping pattern was significantly influenced due to the application of dololime, cow dung, and poultry manure although there was a little difference in grain yield among the treatments (p = 0.001, Table 3). The total system productivity ranged from 9.7 to 12.6 t ha^{-1} (Table 3). The highest total system productivity (12.6 t ha^{-1}) was observed in T_9, T_8, and T_7 which was statistically similar to all other treatments except T_1 (control), and the lowest value (9.7 t ha^{-1}) was recorded in T_1 (Table 3). The increase in total system productivity over control ranged from 14 to 31% where the highest increase was obtained in T_8 (31%) and the lowest one was obtained in T_4 (14%).

3.2. Effect of Lime and Organic Manure Amendment on Nutrient Uptake of T. Aman–Mustard–Boro Cropping Pattern in Two Consecutive Years

3.2.1. Nutrient Uptake by T. Aman Rice

The total absorption of the macronutrients N, P, K, and S was significantly affected by lime and organic amendment in both the years (Table 4). The amount of N taken up by T. Aman rice at different levels of lime and organic amendment ranged from 66.1 to 88.3 kg ha^{-1} in 2018 and 56.7 to 78.3 kg ha^{-1} in 2019, respectively (Table 4). In 2018, the highest increase (39%) in N uptake was observed in T_8 treatment whereas the lowest increase (14%) was noted in T_2. In 2019, the increase in N uptake ranged from 11 to 34% exhibiting the highest increase in T_9 and the lowest in T_2. T_7 had the highest P uptake in both years, while T_1 had the lowest P uptake (Table 4). The amount of K uptake by T. Aman rice ranged from 69.5 to 88.7 kg ha^{-1} in 2018 and 61.1 to 77.8 kg ha^{-1} in 2019, respectively (Table 4). S absorption varied from 22.6 to 33.2 kg ha^{-1} in 2018 and 19.5 to 29.2 kg ha^{-1} in 2019, with T_9 or T_7 having the greatest value and T_1 having the lowest uptake (Table 4).

3.2.2. Nutrient Uptake by Mustard

The residual effect of lime and manure treatment significantly impacted the total N, P, K, and S uptake by mustard in both years (Table 4). Mustard assimilation of total N varied from 40.2 to 67.4 kg ha^{-1} in 2018 and 40.9 to 67.9 kg ha^{-1} in 2019. T_9 had the highest total N uptake, while T_1 had the lowest total N uptake in both years (Table 4). Similarly, both in 2018 and 2019, T_9 had the highest P, K, and S uptake, identical to T_8 and T_7, while T_1 had the lowest value (Table 4). The uptake of P by mustard ranged from 17.3 to 29.4 kg ha^{-1} in 2018 and 17.0 to 29.5 kg ha^{-1} in 2019, respectively. Similarly, the amount of K uptake by mustard rice ranged from 44.4 to 69.3 kg ha^{-1} in 2018 and 42.0 to 69.0 kg ha^{-1} in 2019, respectively (Table 4). Likewise, S absorption varied from 22.7 to 35.7 kg ha^{-1} in 2018 and 23.1 to 36.0 kg ha^{-1} in 2019, exhibiting the highest S uptake in T_9 and the lowest uptake in T_1 (Table 4).

Table 4. Effect of lime and manure amendment on nutrient uptake by crops of T. Aman–Mustard–Boro cropping pattern.

T. Aman Rice

Treatments	Total N Uptake (kg ha^{-1})		Total P Uptake (kg ha^{-1})		Total K Uptake (kg ha^{-1})		Total S Uptake (kg ha^{-1})	
	2018	2019	2018	2019	2018	2019	2018	2019
T_1	66.1 ± 3.81 c	56.7 ± 1.64 d	16.5 ± 0.95 d	14.2 ± 0.41 e	69.5 ± 4.01 b	61.1 ± 1.76 c	22.6 ± 1.30 b	19.5 ± 0.56 d
T_2	73.3 ± 4.23 bc	64.6 ± 1.31 cd	20.0 ± 1.15 cd	17.7 ± 0.36 d	77.3 ± 4.46 ab	69.4 ± 1.41 b	25.0 ± 1.45 ab	22.2 ± 0.45 cd
T_3	77.1 ± 4.45 abc	66.2 ± 2.10 cd	21.8 ± 1.26 abc	18.7 ± 0.59 bcd	81.7 ± 4.72 ab	69.7 ± 2.22 b	26.8 ± 1.55 ab	22.9 ± 0.73 bcd
T_4	79.0 ± 4.56 abc	67.0 ± 2.71 bcd	20.2 ± 1.17 bcd	17.2 ± 0.69 d	79.0 ± 4.56 ab	67.9 ± 2.75 b	26.7 ± 1.54 ab	22.7 ± 0.92 bcd
T_5	84.3 ± 4.86 ab	74.6 ± 2.21 abc	21.7 ± 1.25 abc	19.2 ± 0.57 abcd	82.5 ± 4.76 ab	72.4 ± 2.15 ab	28.2 ± 1.63 ab	24.9 ± 0.74 bc
T_6	81.2 ± 4.69 ab	68.9 ± 2.39 abc	21.3 ± 1.23 bc	18.1 ± 0.63 cd	79.7 ± 4.60 ab	67.9 ± 2.35 b	28.5 ± 1.64 ab	24.2 ± 0.84 bc
T_7	87.6 ± 5.06 a	78.3 ± 2.26 a	24.6 ± 1.42 a	21.9 ± 0.63 a	87.8 ± 5.07 a	77.8 ± 2.25 a	32.7 ± 1.89 a	29.2 ± 0.84 a
T_8	86.7 ± 5.00 ab	78.1 ± 1.58 ab	23.5 ± 1.36 abc	20.9 ± 0.42 abc	88.7 ± 5.12 a	77.2 ± 1.57 a	32.0 ± 1.85 a	28.5 ± 0.58 a
T_9	88.3 ± 5.10 a	77.3 ± 2.24 ab	24.0 ± 1.38 ab	20.9 ± 0.61 abc	86.6 ± 5.00 a	75.3 ± 2.19 a	33.2 ± 1.92 a	29.0 ± 0.84 a
p-value	0.042	0	0.016	0	0.043	0.001	0.006	0

Mustard

Treatments	Total N Uptake (kg ha^{-1})		Total P Uptake (kg ha^{-1})		Total K Uptake (kg ha^{-1})		Total S Uptake (kg ha^{-1})	
	2018	2019	2018	2019	2018	2019	2018	2019
T_1	40.2 ± 2.32 c	40.9 ± 1.18 e	17.3 ± 1.00 c	17.0 ± 0.49 e	44.4 ± 2.57 b	42.0 ± 1.07 b	22.7 ± 1.31 b	23.1 ± 0.67 f
T_2	51.8 ± 2.99 abc	53.1 ± 1.08 cd	22.7 ± 1.31 abc	22.9 ± 0.46 cd	58.3 ± 3.36 ab	57.7 ± 1.57 ab	29.4 ± 1.69 ab	30.1 ± 0.61 bcde
T_3	58.8 ± 3.39 b	58.3 ± 1.85 bc	25.3 ± 1.46 ab	25.1 ± 0.80 bc	63.0 ± 3.64 a	62.3 ± 1.98 ab	32.4 ± 1.87 a	32.2 ± 1.02 abcd
T_4	47.6 ± 2.75 bc	45.3 ± 1.83 de	20.6 ± 1.19 bc	19.2 ± 0.78 de	53.3 ± 3.07 ab	48.6 ± 1.97 ab	27.2 ± 1.57 ab	25.8 ± 1.04 ef
T_5	51.1 ± 2.95 abc	50.3 ± 1.49 cde	22.3 ± 1.28 abc	21.5 ± 0.64 cde	56.2 ± 3.25 ab	53.1 ± 1.57 ab	28.4 ± 1.64 ab	28.0 ± 0.83 de
T_6	58.7 ± 3.39 ab	59.9 ± 2.08 abc	25.4 ± 1.47 ab	25.7 ± 0.89 bc	62.6 ± 3.62 ab	62.6 ± 2.17 ab	32.0 ± 1.85 ab	32.7 ± 1.13 abcd
T_7	63.4 ± 3.66 ab	64.5 ± 1.86 ab	27.4 ± 1.58 ab	27.7 ± 0.80 abc	65.9 ± 3.80 a	66.0 ± 1.91 a	33.9 ± 1.96 a	34.5 ± 1.00 ab
T_8	64.8 ± 3.74 ab	64.8 ± 1.31 ab	28.4 ± 1.64 a	28.2 ± 0.57 ab	66.7 ± 3.85 a	65.9 ± 1.34 a	34.3 ± 1.98 a	34.4 ± 0.70 ab
T_9	67.4 ± 3.89 a	67.9 ± 1.97 a	29.4 ± 1.70 a	29.5 ± 0.86 a	69.3 ± 4.00 a	69.0 ± 2.00 a	35.7 ± 2.06 a	36.0 ± 1.05 a
p-value	0.001	0	0.001	0	0.006	0.007	0.004	0

Boro Rice

Treatments	Total N Uptake (kg ha^{-1})		Total P Uptake (kg ha^{-1})		Total K Uptake (kg ha^{-1})		Total S Uptake (kg ha^{-1})	
	2018	2019	2018	2019	2018	2019	2018	2019
T_1	54.1 ± 3.12 e	55.5 ± 1.60 e	13.2 ± 0.76 e	13.3 ± 0.38 f	81.9 ± 4.73 d	78.7 ± 2.27 d	19.2 ± 1.11 g	19.3 ± 0.56 g
T_2	81.0 ± 4.67 cd	90.0 ± 1.83 cd	21.8 ± 1.26 bcd	23.9 ± 0.48 de	117.0 ± 6.76 bc	123.2 ± 2.50 bc	33.9 ± 1.96 de	36.9 ± 0.75 d
T_3	88.9 ± 5.13 abcd	97.5 ± 3.10 bcd	24.6 ± 1.42 abcd	26.6 ± 0.85 cd	127.6 ± 7.37 ab	134.7 ± 4.28 ab	39.5 ± 2.28 bcd	42.7 ± 1.36 c
T_4	76.4 ± 4.41 d	82.8 ± 3.35 d	18.6 ± 1.07 de	20.0 ± 0.81 e	103.0 ± 5.95 c	108.4 ± 4.38 c	28.0 ± 1.61 f	30.0 ± 1.21 f
T_5	78.0 ± 4.50 d	86.5 ± 2.56 cd	20.0 ± 1.15 cde	21.9 ± 0.65 de	111.0 ± 6.41 bc	117.0 ± 3.47 bc	30.7 ± 1.77 ef	33.3 ± 0.99 e
T_6	89.7 ± 5.18 abcd	96.2 ± 3.33 bcd	24.6 ± 1.42 abcd	26.2 ± 0.91 cd	120.9 ± 6.98 abc	126.5 ± 4.38 bc	36.0 ± 2.08 cde	38.3 ± 1.33 d
T_7	92.5 ± 5.34 abc	101.1 ± 2.92 abc	26.9 ± 1.55 abc	29.1 ± 0.84 abc	126.2 ± 7.28 ab	135.1 ± 3.90 ab	39.6 ± 2.29 abc	42.9 ± 1.24 c
T_8	97.0 ± 5.60 ab	104.2 ± 2.11 ab	29.0 ± 1.67 ab	31.0 ± 0.63 ab	133.3 ± 7.70 ab	140.4 ± 2.85 ab	43.4 ± 2.50 ab	46.2 ± 0.94 b
T_9	101.9 ± 5.88 a	110.5 ± 3.21 a	31.2 ± 1.80 a	33.6 ± 0.97 a	137.3 ± 7.93 a	145.4 ± 4.23 a	45.7 ± 2.64 a	49.1 ± 1.43 a
p-value	0	0	0	0	0.002	0	0	0

Figures in a column having common letters do not differ significantly at 5% level of risk. Data are mean ± SE (n = 3).

3.2.3. Nutrient Uptake by Boro Rice

In the third crop of the cropping pattern, the residual effect of lime and organic amendment on total nutrient uptake was more significant in both years. The residual effect of lime and manure application significantly improved total uptake of N, P, K, and S (Table 4). Boro rice's total N intake ranged from 54.1 to 101.9 kg ha^{-1} in 2018 and 55.5 to 110.5 kg ha^{-1} in 2019. T_9 had the highest total N uptake, similar to T_8 and T_7, and T_1 had the lowest N uptake (Table 4). Similarly, T_9 had the highest P, K, and S uptake, equivalent to T_8 while T_1 had the lowest (Table 4). P, K, and S total uptake ranged from 13.2 to 31.2 kg ha^{-1}, 81.9 to 137.3 kg ha^{-1}, and 19.2 to 45.7 kg ha^{-1} in 2018, and 13.3 to 33.6 kg ha^{-1}, 78.7 to 145.4 kg ha^{-1}, and 19.3 to 49.1 kg ha^{-1} in 2019, respectively (Table 4).

3.3. Effect of Lime and Manure Amendment on Soil Properties under T. Aman–Mustard–Boro Cropping Pattern

The addition of lime and manure to the soil substantially improved soil fertility and characteristics (Table 5). SOM content was 1.5% and 1.3 to 1.5% before and after the experiment, respectively, exhibiting the highest value in T_9 (Lime-2 OM-2, Dololime 2 t ha^{-1}, poultry manure 3 t ha^{-1}), which was statistically similar to T_7 (Lime-1 OM-2, Dololime 1 t ha^{-1}, Poultry manure 3 t ha^{-1}) and the lowest value in T_1 (control) (Table 5). Similarly, soil total N (STN) content was 0.11% and 0.09 to 0.18% before and after the experiment, respectively (Table 5). In the case of sole application of chemical fertilizer and lime along with chemical fertilizer, STN decreased by about 1–19% after the experiment, whereas STN increased by 37 to 68% due to sole application of manure amendment or combined application of lime and manure amendment along with chemical fertilizers (Table 5). Before the experiment, the available P level in soil was 6.9 ppm, and after the experiment, it was 6.7 to 11.3 ppm. In the case of the control, accessible P content fell by around 4% after the experiment, but solo or combination application of lime and manure amendment increased available P content by roughly 21 to 64% compared to the original state. The highest increase was observed in T_9 (Lime-2 OM-2, Dololime 2 t ha^{-1}, Poultry manure 3 t ha^{-1}) and the lowest one in T_4 (OM-1, Cow dung 5 t ha^{-1}) (Table 5). Before the experiment, the exchangeable Ca content was 5.40 cmol$_c$/kg and varied from 4.60 to 6.76 cmol$_c$/kg, after the experiment (Table 5). The increase in exchangeable Ca content in soil after the experiment varied from −10 to 56%, with the largest rise in T_9 (Lime-2 OM-2, Dololime 2 t ha^{-1}, Poultry manure 3 t ha^{-1}) and a reduction in T1 (control) compared to their pre-experiment state (Table 5).

Before and after the experiment, exchangeable Mg content was 1.33 cmol$_c$/kg and ranged from 1.19 to 2.07 cmol$_c$/kg, respectively, with the greatest value in T_9 (Lime-2 OM-2, Dololime 2 t ha^{-1}, Poultry manure 3 t ha^{-1}) and the lowest value in T1 (control) (Table 5). After the experiment, the change in exchangeable Mg content in soil varied from -10 to 53% (Table 5). Similarly, before and after the experiment, the soil pH was 4.57 and ranged from 4.02 to 6.57, respectively (Table 5). Due to the application of lime and manure amendments and chemical fertilizers, the pH of the soil improved by around −12 to 44% after the experiment (Table 5). When no lime or manure amendment was provided, the pH of the soil dropped, whereas T_9 showed the greatest rise (Lime-2 OM-2, Dololime 2 t ha^{-1}, Poultry manure 3 t ha^{-1}). The EC of the soil was 0.22 dS/m before the experiment and ranged from 0.22 to 0.46 dS/m thereafter. Due to the application of lime and manure amendments, the EC of the soil rose 1 to 106% after the experiment compared to the original state (Table 5). T_9 (Lime-2 OM-2, Dololime 2 t ha^{-1}, Poultry manure 3 t ha^{-1}) had the largest increase, whereas T_1 (control) had the lowest (Table 5). Before and after the experiment, the CEC of the soil varied from 34.32 cmol$_c$/kg and 32.52 to 45.02 cmol$_c$/kg, respectively (Table 5). The increase in exchangeable Ca content in soil after the experiment varied from −5 to 31%, with the largest rise in T_9 (Lime-2 OM-2, Dololime 2 t ha^{-1}, Poultry manure 3 t ha^{-1}) and a reduction in T_1 (control) compared to their pre-experiment state (Table 5).

Table 5. Effect of lime and manure amendment on changes of soil properties under T. Aman–Mustard–Boro cropping pattern.

Treatments	SOM Content (%)		Soil TN (%)		Available P (ppm)		Exchangeable Ca ($cmol_c$/kg)	
	Before	After	Before	After	Before	After	Before	After
T_1	1.51 ± 0.13	1.28 ± 0.11 e	0.11 ± 0.01	0.09 ± 0.02 d	6.92 ± 0.19	6.65 ± 0.14 i	5.10 ± 0.12	4.60 ± 0.11 h
T_2	1.51 ± 0.13	1.39 ± 0.12 d	0.11 ± 0.01	0.11 ± 0.02 c	6.92 ± 0.19	8.96 ± 0.12 g	5.10 ± 0.12	5.79 ± 0.12 f
T_3	1.51 ± 0.13	1.41 ± 0.10 d	0.11 ± 0.01	0.11 ± 0.03 c	6.92 ± 0.19	9.89 ± 0.12 d	5.10 ± 0.12	6.09 ± 0.14 c
T_4	1.51 ± 0.13	1.47 ± 0.12 c	0.11 ± 0.01	0.15 ± 0.03	6.92 ± 0.19	8.36 ± 0.21 h	5.10 ± 0.12	5.61 ± 0.13 g
T_5	1.51 ± 0.13	1.51 ± 0.14 b	0.12 ± 0.01	0.16 ± 0.03 b	6.92 ± 0.19	9.25 ± 0.12 f	5.10 ± 0.12	5.92 ± 0.15 e
T_6	1.51 ± 0.13	1.49 ± 0.13 bc	0.11 ± 0.01	0.16 ± 0.03 b	6.92 ± 0.19	9.73 ± 0.18 e	5.10 ± 0.12	6.01 ± 0.17 d
T_7	1.51 ± 0.13	1.54 ± 0.12 a	0.11 ± 0.01	0.18 ± 0.02 a	6.92 ± 0.19	10.23 ± 0.22 c	5.10 ± 0.12	6.05 ± 0.21 cd
T_8	1.51 ± 0.13	1.48 ± 0.11 c	0.11 ± 0.01	0.16 ± 0.03 b	6.92 ± 0.19	10.79 ± 0.23 b	5.10 ± 0.12	6.28 ± 0.26 b
T_9	1.51 ± 0.13	1.54 ± 0.11 a	0.11 ± 0.01	0.18 ± 0.03 a	6.92 ± 0.19	11.32 ± 0.32 a	5.10 ± 0.12	6.76 ± 0.33 a
p-value	-	0	-	0	-	0	-	0
Treatments	**Exchangeable Mg ($cmol_c$/kg)**		**pH**		**EC (dS/m)**		**CEC ($cmol_c$/kg)**	
	Before	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
T_1	1.33 ± 0.12	1.19 ± 0.08 h	4.57 ± 0.15	4.02 ± 0.17 g	0.22 ± 0.05	0.22 ± 0.04 g	34.32 ± 1.89	32.52 ± 1.81 d
T_2	1.33 ± 0.12	1.57 ± 0.10 f	4.57 ± 0.15	5.59 ± 0.21 e	0.22 ± 0.05	0.28 ± 0.05 f	34.32 ± 1.89	38.03 ± 1.53 bc
T_3	1.33 ± 0.12	1.67 ± 0.10 e	4.57 ± 0.15	5.94 ± 0.17 d	0.22 ± 0.05	0.33 ± 0.06 de	34.32 ± 1.89	39.27 ± 1.16 bc
T_4	1.33 ± 0.12	1.45 ± 0.11 g	4.57 ± 0.15	5.23 ± 0.21 f	0.22 ± 0.05	0.31 ± 0.05 e	34.32 ± 1.89	36.93 ± 1.27 c
T_5	1.33 ± 0.12	1.55 ± 0.12 f	4.57 ± 0.15	5.59 ± 0.22 e	0.22 ± 0.05	0.33 ± 0.04 de	34.32 ± 1.89	37.81 ± 1.65 bc
T_6	1.33 ± 0.12	1.74 ± 0.12 d	4.57 ± 0.15	5.84 ± 0.23 d	0.22 ± 0.05	0.35 ± 0.05 d	34.32 ± 1.89	39.53 ± 1.00 bc
T_7	1.33 ± 0.12	1.80 ± 0.12 c	4.57 ± 0.15	6.09 ± 0.24 c	0.22 ± 0.05	0.39 ± 0.05 c	34.32 ± 1.89	39.63 ± 1.55 bc
T_8	1.33 ± 0.12	1.90 ± 0.16 b	4.57 ± 0.15	6.24 ± 0.21 b	0.22 ± 0.05	0.42 ± 0.06 b	34.32 ± 1.89	40.81 ± 1.00 b
T_9	1.33 ± 0.12	2.07 ± 0.18 a	4.57 ± 0.15	6.57 ± 0.20 a	0.22 ± 0.05	0.46 ± 0.08 a	34.32 ± 1.89	45.01 ± 0.93 a
p-value	-	0	-	0	-	0	-	0

Figures in a column having common letters do not differ significantly at 5% level of risk. Data are mean ± SE (*n* = 3).

3.4. Correlation among Soil Properties and between Soil pH and Crop Yield in T. Aman–Mustard–Boro Cropping Pattern

Significant correlations were found between soil characteristics (Table 6). As did other chemical characteristics, soil macronutrients and soil reaction rose as SOM content (%) grew (Table 6). The soil pH had a substantial beneficial impact on nutrient availability and soil quality improvement. The availability of main and secondary macronutrients rose when soil pH increased, and the EC and CEC of the soil improved as well (Table 6). The plant nutrients (N, P, Ca, and Mg) were found to have a synergistic impact (Table 6). Increased soil EC and CEC increased the availability of exchangeable Ca and Mg.

Table 6. Relationship among soil properties as influenced by lime and manure amendment; (*n* = 27).

	SOM (%)	STN (%)	Available P (ppm)	Ca_{ex} (cmol(+)/kg)	Mg_{ex} cmol(+)/kg)	Soil pH	EC (dS/m)	CEC (cmol(+)/kg)
SOM content (%)	1							
Soil TN (%)	0.946 ***	1						
Available P (ppm)	0.795 ***	0.739 **	1					
Ca_{ex} (cmol(+)/kg)	0.820 ***	0.717 ***	0.974 ***	1				
Mg_{ex} (cmol(+)/kg)	0.766 ***	0.750 ***	0.978 ***	0.945 ***	1			
Soil pH	0.814 ***	0.721 ***	0.983 ***	0.983 ***	0.915 ***	1		
EC (dS/m)	0.841 ***	0.856 ***	0.935 ***	0.899 ***	0.950 ***	0.890 ***	1	
CEC (cmol(+)/kg)	0.738 ***	0.690 **	0.915 ***	0.927 ***	0.923 ***	0.901 ***	0.884 ***	1

r value: 0.0 to 0.2—very weak fit, 0.2 to 0.4—weak fit, 0.4 to 0.7—moderate fit, 0.7 to 0.9—strong fit, 0.9 to 1.0—very strong fit, ** indicates significant at 1% level of risk, *** indicates significant at 0.1% level of risk.

All three crops had significant but varied effects on grain and straw yields (Figure 1). The response of grain yield (R^2 =0.41) was higher than that of straw yield (R^2 =0.36) in T. Aman rice (Figure 1). In mustard, the influence of soil pH on grain and straw production was more evident than in T. Aman rice (Figure 1). Grain yield (R^2 = 0.58) had a higher response than straw yield (R^2 = 0.52) (Figure 1). Boro rice grain and straw yields had the strongest correlation to soil pH (Figure 1). The response of straw yield (R^2 = 0.67) was higher than grain yield (R^2 = 0.64) (Figure 1).

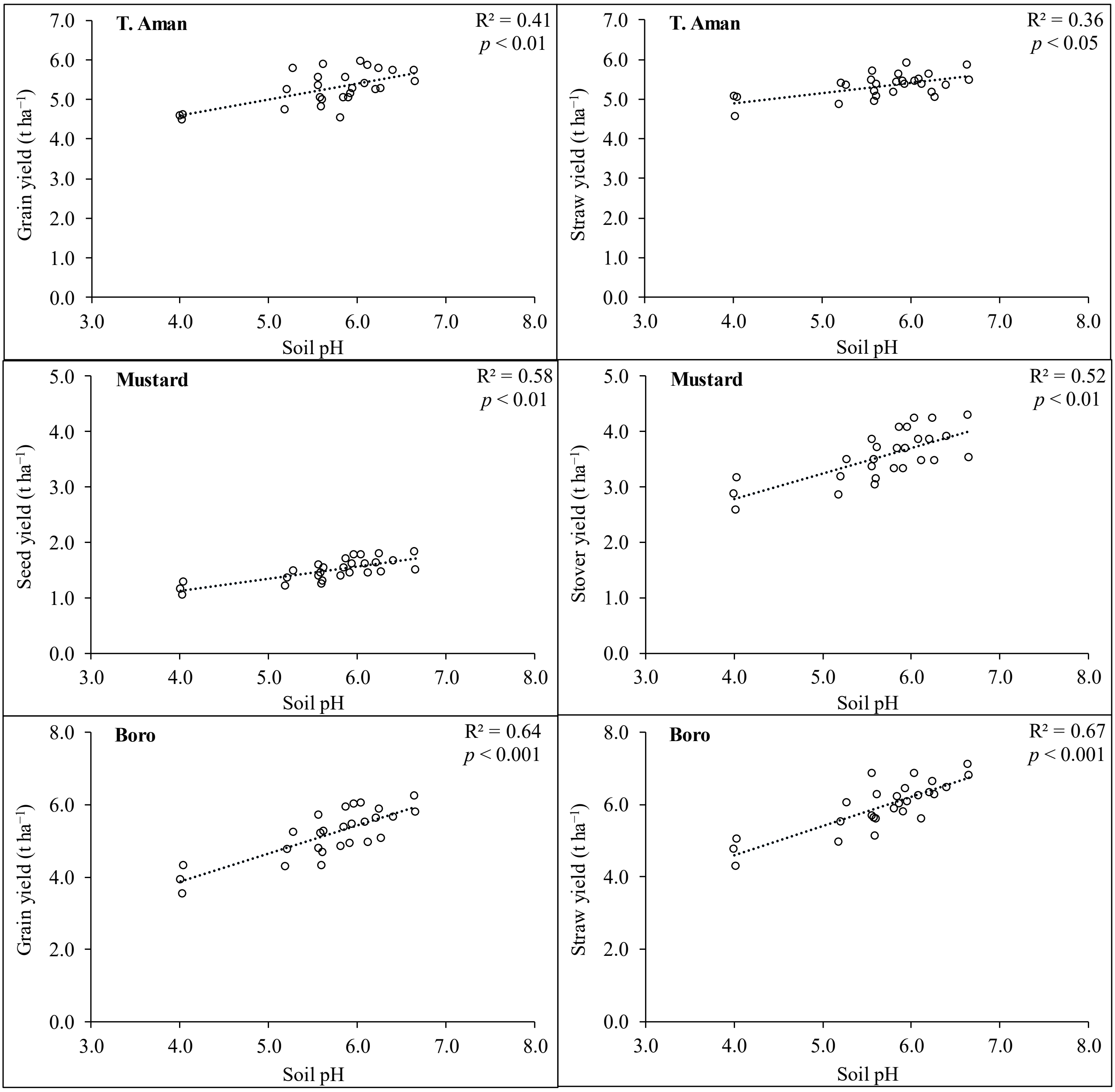

Figure 1. Relationship between soil pH and crop yield in T. Aman–Mustard–Boro cropping pattern as influenced by lime and manure amendment. Empty circle in the figure indicates the correlation point between yield and soil pH.

4. Discussion

According to our findings, lime and organic amendments raised pH by around 26% after the trial, but chemical fertilizers increased soil acidity by 4% (Table 5), consistent with Ozlu and Kumar [40]. With the addition of lime and manure, any of the following mechanisms or combinations might have produced the rise in soil pH: proton consumption by functional groups associated with biological molecules [41], decarboxylation of organic acid anions during decomposition, specific adsorption of organic molecules by ligand exchange with the release of OH [42], and the release of OH ions during reduction reactions associated with localized anaerobic microsites are all examples of proton consumption [43]. STN and available P content in soil rose due to higher soil pH [44–46]. They increased P mineralization resulting from lime and manure treatment, as Van Chuong [47] and Naher et al. [48] previously observed. Due to lime and organic amendment application, the availability of exchangeable Ca^{2+} and Mg^{2+} increased when soil pH increased, as found by Mosharrof et al. [49] and Kunhikrishnan et al. [22]. According to Yagi et al. [50] and Kisić et al. [51], higher soil pH caused by lime and manure addition also enhanced soil EC and CEC.

The impact of lime and manure amendments on three different crops in this experiment was variable. The influence of lime and manure was less noticeable in the first crop, T. Aman (BRRI dhan71) rice. Conversely, in mustard (BARI Shorisha14) and boro rice (BRRI dhan28), lime or manure, alone or in combination, had a substantial effect. This was noticeable in the yields of mustard and boro rice. The increase in grain output above control ranged from 1 to 9% in the case of BRRI dhan71. In the case of BARI Shorisha14 and BRRI dhan28, it ranged from 16 to 44% and 21 to 44%, respectively. Liming has also been linked to an increase in crop yields [52,53]. In addition, interactive effects of N and P fertilizers increases chlorophyll content, stomatal conductance and quantum yield of photosystem II resulting in higher yield of crops [54]. Crop yields of straw likewise followed a similar pattern. Rice straw yields increased after lime was added. Liming elevates the pH and decreases the acidity of the soil, allowing for better straw yields [55–57]. According to our findings, T. Aman, mustard, and boro rice grain and straw yields were highly linked with soil pH (Figure 1). All soil characteristics were strongly associated with soil pH, and grain and straw yields showed a high positive association with other soil physicochemical properties (Table 6; Figure 1).

According to Fageria and Baligar [58], applying lime at the correct rate produces a range of chemical and biological changes in the soil, many of which are favorable or helpful in improving crop development and yields on acid soils. According to Asrat et al. [59], grain output varied significantly, with the application of 5 tons of manure and 2.2 tons of lime per hectare increasing grain yield by 279%. Lime treatment on acid soil has a substantial influence on straw yield [60]. This study’s findings are consistent with those of Sukristiyonubowo et al. [61], who observed that combining manure (straw compost), lime, and mineral fertilizer raised rice grain yield. Our findings are comparable to those of Rahman et al. [19] and Halim et al. [62], who demonstrated that applying lime to acid soils in Bangladesh’s Rangpur and Dinajpur areas increased agricultural yields. Liming stimulates soil N availability and rice N assimilation, according to earlier research [17,18]. According to Liao et al. [18], liming may be used to increase rice yield and P absorption in the double rice cropping system. The factors of nutrition absorption are generally nutrient concentrations and dry matter yield. Nutrient absorption is regulated by the ionic forms of nutrients in the rhizosphere, which is influenced by soil acidity and total nutrient concentrations in the soil. Reduced soil acidity may have improved the pH and macronutrient availability, increasing crop absorption [63]. Liming aided root development by reducing the adverse effects of Al and hence increased P and K uptake, increasing rice yield [61]. Likewise, application of manure and its compost also improves yield nutrient content and nutrient uptake by rice [64]. Competitive ability of crops, especially maize with weeds, is another management strategy for improving physical properties of the seeds resulting in improved crop yield [65]. According to our findings, combining lime and organic amendment substantially increased each crop's overall output and nutrient absorption in the T. Aman–Mustard–Boro cropping pattern. In the Old Himalayan Piedmont Plain's Potato–Mungbean–Rice cropping pattern, Sultana et al. [29] reported that applying 1 t ha^{-1} dololime in combination with 3 t ha^{-1} poultry manure or 5 t ha^{-1} FYM increased agricultural productivity and nutrient efficiency.

5. Conclusions

The study's findings clearly show that adding lime and/or manure to acid soils greatly enhanced yield and nutrient uptake in the T. Aman–Mustard–Boro rice cropping patterns. Lime or manure alone improved crop yield as well as system productivity to a significant extent. Combined application of lime and manure remarkably increased the yield, system productivity, and nutrient uptake of the crops, and also improved the physicochemical properties of the soil. Based on the findings, it can be concluded that the application of dololime in conjunction with manure amendment can be used for improved crop productivity and soil quality in Madhupur Tract's acidic terrace soils. Similar research in other acid-prone areas of Bangladesh are worth considering for widespread recommendations.

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