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Combined Application of Rice Husk Biochar and Lime Increases Phosphorus Availability and Maize Yield in an Acidic Soil

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Abstract: Biochar, a pyrogenic carbon, has been receiving incremental attention for potential contribution to soil health, agricultural productivity enhancement while mitigating climate change by sequestering carbon and reducing greenhouse gas (GHG) emissions. However, it is not well-known to us how far rice husk biochar (RHB) application rates could increase phosphorus (P) bioavailability and plant performance when co-applied with P and lime. Here, we present data of a pot experiment consisting of eleven treatments to evaluate RHB, lime, and phosphorus effect on soil phosphorus availability, CO_2 emission, nutrient uptake, and yield performance of maize. Co-application of RHB (10 and 15 t ha^{-1}) and lime (100% and 75%) was made with different rates of P (100%, 75%, and 50%). Our result revealed that, at harvest, the combined application of RHB, lime, and phosphorus fertilizer significantly increased soil pH, P availability and decreased Al and Fe toxicity relative to the control while increasing maize yield. The maximum soil pH increased by 36.75%, the highest available P increased by 158.75%, whilst, the exchangeable Al content reduced by 96.84% compared to the control treatment. However, the difference in biomass production and yield among different lime, RHB, and P were minimal, with the largest grain yield (15.50 t ha^{-1}) was recorded in the T_6 treatments (75% lime + 10 t ha^{-1} RHB + 100% Triple superphosphate). The increment in biomass and grain yield could have occurred due to lime and RHB mediated changes in soil properties, including enhancement of soil pH, availability of P, and other nutrients. This increased availability then increased nutrient uptake and biomass production. Our results suggest that the combined application of lime and RHB could bring favorable changes in soil properties while sacrificing some carbon from soils.

Keywords: maize; acid soil; rice husk biochar; lime; Triple superphosphate (TSP); phosphorus availability; yield

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1. Introduction

Maize is considered a universal crop for its multipurpose uses, including food for human beings and feed for animals [1]. Therefore, it can grow globally in different weather conditions and various soil types [2]. However, soil acidity is one of the main constraints for maize cultivation. Tropical soils are generally influenced by high precipitation and temperature, leading to the loss of basic cations. Therefore, these soils are highly weathered acidic soils [3]. As a result, in this tropical and subtropical region, soil acidification is one of the major limiting factors for crop production since soil acidity reduces nutrient availability [4–6].

Several management practices are suggested to ameliorate acidic soils, while liming is considered the easiest soil amendment [7]. Lime is traditionally incorporated into the surface and sub-surface zone of soil to buffer soil pH [8]. However, the effects of lime in the soil are not sustainable since reacidification of soil has been reported due to exhaustion of the liming effects [9]. Therefore, alternative soil amendments, including organic matter addition and recently biochar, have been suggested.

Biochar is a pyrogenic carbon-rich material. It has a large surface area while it carries functional groups. Moreover, in its ash, it contains different mineral nutrients, including basic cations (Ca and Mg). Therefore, biochar can potentially buffer soil pH by adding basic cations and consuming protons with negatively charged functionals groups (e.g., carboxylic and phenolic groups) [10]. In addition, biochar can also change nutrient dynamics that can change the acidification of soil. For instance, biochar can retain ammonium which plants can take. Mineralization and uptake of ammonium (NH_4^+) do not cause acidification since mineralization-mediated hydroxyl ions (OH^-) counterbalance the proton released by the plant during NH_4^+ uptake. However, the acidification is doubled if the NH_4^+ is converted to NO_3^- and then leached [11]. Therefore, nitrate leaching from soil can be one of the major causes of soil acidification. The role of biochar in alleviating soil acidification could therefore depend on biochar properties, while it has been shown that biochar, after becoming aged in the soils, has a greater potentiality to buffer soil pH. Since biochar's residence time in the soil long ranging from decades to centuries, multiple benefits, including alleviating soil acidity, decreasing the toxic accumulation of Al and Fe concentration, crop yield improvement, and thus, environmental sustainability can be harvested for a long time [12,13]. These findings underscore the potential benefits of biochar as a soil amendment for carbon sequestration as well as having better soils. One of the most popular examples of such benefits is Terra preta soil in Brazil.

Biochar is an alternate option for alleviating soil acidity and environmental sustainability [12]. It is a carbon-rich, recalcitrant organic material obtained from the thermal degradation of biomass in different temperatures and feedstocks [14,15]. Furthermore, it is an ecologically sound soil amendment due to its quality of resistance to decompose. These attributes potentially contribute to carbon sequestration into the soil for a long [16,17]. It also helps increase soil pH, availability of nutrients, diversity of micro-organisms, and decrease the toxic accumulation of Al and Fe concentration [13,18–21].

Phosphorus (P) is an essential macronutrient for the plant, playing a vital role in many physiological processes, including photosynthesis and energy transfer [22]. However, in acid soils, the bioavailability of P is low due to the fixation of P with Al and Fe-bearing minerals [23]. There are several possible ways to increase P bioavailability in acid soils. These are: (a) an increase of soil pH, (b) intensification of competitive interactions between fixed phosphate and other negatively charged organic molecules (e.g., humic or fulvic acids), and (c) microbial cycling (e.g., mycorrhizal P association). Therefore, the application of organic matter has been shown to increase P bioavailability. Biochar, being an organic soil amendment, could increase P bioavailability in acid soils by changing soil pH (as discussed above) and intensification of competitive interactions [10,24]. However, freshly prepared biochar may be less efficient in competing with fixed phosphate since biochar is large with low negative surfaces [25,26].

Soil organic matter content of many highly weathered soils is low. Therefore, the application of pyrogenic carbon as biochar could increase the organic matter status of the soil. However, the application of biochar could alter soil carbon dynamics since biochar changes substrate pools and nutrient dynamics. For instance, an increase in soil pH can increase CO_2 gas emission considering the organic matter and soil microbes' decomposition [27], while positive, negative, and minimal responses of CO_2 emission from biochar amended soil with attribution of several potential mechanisms [28–30]. Therefore, a clear understanding of biochar-mediated impacts on carbon mineralization from acidic soil is needed for large-scale field application.

To meet the increased food demand globally, approximately 15 million tons of P chemical fertilizer provide every year to farmland [31]. However, due to lack of proper knowledge regarding the appropriate rate of P fertilizer, repeated and excess P fertilizer addition to cultivable land causes loss of P through different pathways, including leaching and runoff. As a result, water pollution occurs due to increased P concentration in the water [32]. Furthermore, phosphate fertilizers are usually produced from rock phosphate, which is projected to exhaust in the near future. Therefore, rational use of phosphate fertilizer is needed. Considering these facts, a pot trial was conducted with acidic soil having the objectives to determine the effect of RHB, lime, and phosphorus on soil phosphorus availability, nutrient uptake, and yield performance of maize and to examine the emission of soil CO_2 gas.

2. Materials and Methods

2.1. Experimental Site

The pot trial was conducted in the new glasshouse, Faculty of Agriculture, Universiti Putra Malaysia, Serdang, Selangor. The experimental site was located at 2°98′36.6″ N (north) latitude and 101°73′81.9″ E (east) longitudes with an elevation of 56.8 m from sea level at the west coast of Peninsular Malaysia. The local climate is hot, humid tropic, and the average minimum temperature was around 22 °C, and the average maximum temperature was 36 °C, relative humidity was 78.87% during the whole experiment.

2.2. Soil Collection and Preparation

The Bungor (Typic Paleudult; Order: Ultisol) soil series was collected in depth from 0–20 cm from Taman Partanian, Universiti Putra Malaysia, Puchong, Selangor (2°58′59.7″ N latitude; 101°38′47.5″ E longitude). The soil sample was air-dried, pulverized, and sieved to <2 mm before chemical characterization and prior to treatment. Thirty-two plastic containers (Height 38 cm, width 30 cm, and diameter 32 cm) were used with 20 kg of soil. Each container was drilled with three holes at the bottom to permit leachate to flow out. The moisture content was maintained using a portable moisture meter (FieldScout TDR 150 Soil Moisture Meter). Biochar and lime were incorporated with soil before two weeks of maize seeds were sowing. Four seeds were planted in 2 cm depth of soil surface in each pot and thinned to one plant per pot after 7 days of emergence based on the healthy appearance. N-P-K fertilizer was applied in each pot recommended by Pedram [33], as follows: urea (140 kg ha^{-1} N), triple superphosphate (100 kg ha^{-1} P_2O_5), and muriate of potash (120 kg ha^{-1} K_2O). The full dose of P and K fertilizer were applied as a basal dose one day before the seeds were sown. N fertilizer was applied in two equal splits on the 10th and 28th days after sowing (DAS). Based on the lime requirement test, dolomitic limestone was applied at 66 g (100%) and 49.5 g (75%) [34]. Weeding was carried out manually from each pot immediately after the emergence of weeds. The experiment was conducted from August 2020 to November 2020. The physico-chemical properties of the initial soil are shown in Table 1.

Table 1. Selected physicochemical properties of initial soil.

Properties	Soil
Textural Class	Sandy clay loam
% Sand	69.27
% Silt	2.28
% Clay	28.44
pH	4.61
CEC ($cmol_c$ kg^{-1})	5.77
Total C (%)	1.41
Total N (%)	0.07
Total S (%)	0.05
Exchangeable K ($cmol_c$ kg^{-1})	0.22
Exchangeable Ca ($cmol_c$ kg^{-1})	1.46
Exchangeable Mg ($cmol_c$ kg^{-1})	0.42
Exchangeable Al ($cmol_c$ kg^{-1})	2.49
Available P (mg kg^{-1})	5.21
Extractable Fe (mg kg^{-1})	99.44
Extractable Mn (mg kg^{-1})	4.64
NH_4^+-N (mg kg^{-1})	16.41
NO_3^--N (mg kg^{-1})	11.37

2.3. Rice Husk Biochar Collection and Characterization

Rice husk biochar (RHB) was used in this pot experiment, made from locally available feedstock in Malaysia. This biochar was obtained from Sendi Enterprise (Sungai Burong, Selangor, Malaysia) via a pyrolysis process at 300 °C. The physicochemical properties of RHB are shown below (Table 2).

Table 2. Selected physical and chemical properties of RHB.

Properties	RHB
Moisture Content (%)	6
Ash Content (%)	32.40
pH	8.15
CEC ($cmol_c$ kg^{-1})	48.12
Total C (%)	24.86
Total N (%)	1.13
Total S (%)	0.15
Exchangeable K ($cmol_c$ kg^{-1})	17.45
Exchangeable Ca ($cmol_c$ kg^{-1})	19.46
Exchangeable Mg ($cmol_c$ kg^{-1})	13.96
Available P (mg kg^{-1})	3098.40
Extractable Fe (mg kg^{-1})	43.06
Extractable Mn (mg kg^{-1})	23.51

2.4. Experimental Layout and Treatment

A single factor experiment was arranged in a randomized complete block design (RCBD) with four replications. The detailed treatments are presenting in Table 3.

Table 3. Teatments applied in the pot experiment.

Treatment Code	Description of the Treatments
T_1	Control (no treatments and fertilizer)
T_2	Recommended rate of NPK (t ha^{-1})
T_3	100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 100% TSP
T_4	100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 75% TSP
T_5	100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 50% TSP
T_6	75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 100% TSP
T_7	75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 75% TSP
T_8	75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 50% TSP
T_9	75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 100% TSP
T_{10}	75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 75% TSP
T_{11}	75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 50% TSP

TSP: Triple superphosphate.

2.5. Soil Analysis

The hydrometer method was used to determine the soil particle-size distribution [35]. Then, the textural classification was based on the United States Department of Agriculture (USDA) soil texture triangle of size classes as clay (<2 µm), silt (2–50 µm), and sand as (50–2000 µm) [36]. Finally, the bulk density of soil was determined by using a core-ring method [37].

Soil pH was measured in a 1:2.5 (weight/volume basis) soil: distilled water ratio using a glass electrode pH meter (Model: Eijkelkamp Multimeter 18.52.01) [38]. Soil CEC was determined using the ammonium acetate leaching method at pH 7. The leachate was analyzed for NH_4^+ concentration using the Auto-analyzer (AA) to determine soil CEC. Soil total carbon (TC), total nitrogen (TN), and total sulphur (TS) were measured by dry combustion method (Dumas method) using a LECO TrueSpec CNS auto analyzer (LECO Corporation, St. Joseph, MI, USA) using air dry and ground soil. The exchangeable cation Ca, Mg, and K was extracted using a 5:50 ratio of soil: ammonium acetate (NH_4OAc) buffered solution at pH 7, in which the basic cations adsorbed in soil was replaced by NH_4^+ ion [39], and concentration was determined by inductively coupled plasma optical emission spectroscopy (ICP-OES, PerkinElmer, Inc., Waltham, MA, USA). Soil exchangeable Al was extracted using 1 M KCl [40], and the extract was examined by an inductively coupled plasma optical emission spectrometry (ICP-OES). In a plastic vial, 5 g of soil was added with 50 mL of 1 M KCl, followed by shaking for 30 min, and the supernatant was separated by the Whatman no. 42 filter paper. Mehlich No. 1 double acid was used to extract the sample to examine the extractable Fe and Mn, and the concentration was determined using an atomic absorption spectrometer (AAS) [37]. Next, 2 g of soil was extracted by the extracting solution of 0.03 N ammonium fluoride (NH_4F) and 0.1 N hydrochloric acids (HCl) solution [41], and the concentration was determined by inductively coupled plasma optical emission spectroscopy (ICP-OES, PerkinElmer, Inc., Waltham, MA, USA). Soil inorganic N (NH_4^+-N and NO_3^--N) was analyzed by extracting with a 1:4 ratio of fresh soil: 2M KCl phenylmercuric acetate (KCl-PMA) mixture [42] and determined by titration against 0.01 N HCl.

2.6. Biochar Analysis

The pH of the rice husk biochar was measured using a pH meter by taking a 1:2.5 ratio of air-dried biochar sample to distilled water [43]. Total N and total C in the biochar were analyzed by a CNS analyzer (TrueMac CNS Analyser). 1 M NH_4OAc buffered solution at pH 7 was used for determining biochar CEC and exchangeable cations [39]. The extracts' K, Ca, and Mg were measured by atomic absorption spectrophotometry (PerkinElmer, Inc., Waltham, MA, USA). For total P determination, the dry ashing method followed by ICP-OES was used. A dry combustion method was used to measure the ash content of rice husk biochar. Five g of RHB sample was taken in a crucible and heated at 500 °C for

8 h [44]. After cooling the crucible to room temperature, it was reweighed. The ash content percentage was then calculated as:

$$\text{Ash content } (\%) = \frac{\text{Weight of ash (g)}}{\text{The dry mass of biochar (g)}} \times 100, \quad (1)$$

2.7. Plant Material Analysis

In this experiment, the maize variety, F_1 Hybrid Sweet Corn, was used as a test crop collected from a local market. It is a common variety that Malaysian farmers regularly use. Plant height was determined using a measuring tape at harvest (75 DAS) by taking the average plant height from the base to the tip of the longest leaf [45]. The leaf chlorophyll content was measured using a portable chlorophyll meter (SPAD-502 Konica Minolta, Inc., Tokyo, Japan). The SPAD readings were taken from fully expanded leaves of each plant and averaged for each pot [46]. After harvest, the plant parts (stem and leaves) were placed into envelopes and dried in an oven at 60 °C for 72 h [47]. The dried plant parts were ground using a blender, and 0.25 g was used for the digestion process. The single dry ashing method [48] was used to extract the macro elements of the plant tissues. The concentrations of P, K, Ca, and Mg were determined using an atomic absorption spectrometer (AAS PerkinElmer PinAAcle, 900T, Waltham, MA, USA). Total N of the plant was determined by the TrueMac CNS analyzer (LECO Corporation, St. Joseph, MI, USA). The maize nutrient uptake was calculated by multiplying with the respective dry weight (oven-dry weight) of the plant part with the nutrient content [49].

$$\text{Uptake} = \text{Total nutrient concentration} \times \text{biomass}, \quad (2)$$

A number of yield components such as fresh biomass (g), dry biomass (g), cob length (cm), no. of grain per cob, fresh cob weight (g), root length (cm), etc., were measured. Phosphorus use efficiency was calculated by the following equation [50]:

$$\text{Phosphorus use efficiency (PUE), (kg ha}^{-1}\text{)} = (\text{YF} - \text{Yo})/\text{F}, \quad (3)$$

where YF denotes the P uptake under fertilized treatment (kg ha^{-1}); Yo denotes the P uptake under control treatment (kg ha^{-1}), and F indicates the rate of P applied in that particular treatment (kg ha^{-1}).

2.8. Soil CO_2 Flux Emission Measurement

A portable LI-8100 automated soil CO_2 flux system (LI-COR Biosciences, Lincoln, NE, USA) was used to measure Soil CO_2 gas flux on days 1, 2, 3, 4, 5, 6, 7, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, and 75. Each day, the data was taken between 9.00 a.m. to 11.00 a.m. [51]. To minimize the soil surface disturbance, a polyvinyl chloride (PVC) pipe (11.5 cm in height and 20 cm inner diameter) was inserted 7 to 8 cm into the soil on the previous day of the first measurement. All the PVC collars were kept fixed during the whole experiment. The cumulative soil CO_2 flux measurement was calculated by linear interpolation [52].

2.9. Percent Relative Data

The relative data of the value were expressed as percentages, relative to control for each element recommended by Ashraf et al. [53]:

$$\text{Relative data } (\%) = \frac{\text{Treatment value} - \text{control value}}{\text{control value}} \times 100 \quad (4)$$

where the treatment value was the rice husk biochar and lime amended treatment, and the control value was without amendment.

2.10. Statistical Analysis

All data were analyzed using the analysis of variance (ANOVA) procedure, and means were separated by Tukey's Honestly Significant Difference (HSD) test at a 5% level of confidence using Statistical Analysis System, version: SAS 9.4 software (SAS Institute Inc., Cary, NC, USA). In addition, linear regression and principal component analysis were also performed to understand the relationships and contribution of different factors on the yield of maize.

3. Results

3.1. Effect of Treatments on Changes in Nutrients of the Post-Harvest Soil

The effect of RHB, dolomitic limestone, and different doses of P application on soil nutrient availability of maize are presented in Table 4. The addition of treatments significantly altered soil pH. The soil pH noted ranged from 4.49 to 6.14. The lowest pH (4.49) was observed from the control treatment. The treatment with 100% lime + 10 t ha^{-1} RHB + 100% TSP (T_3) showed the highest soil pH, which was increased by 1.65 units compared to control (6.14-4.49), although T_3 and T_5 led the same statistical value.

It was observed that soil available P after harvest of the maize crop was significantly increased using RHB, lime, and P application (Table 4). The available P examined ranged from 5.43 to 14.05 mg kg^{-1} soil. The maximum P content found from T_9 (75% lime + 15 t ha^{-1} RHB + 100% TSP), followed by T_3 (100% lime + 10 t ha^{-1} RHB + 100% TSP) and T_6 (75% lime + 10 t ha^{-1} RHB + 100% TSP) and the minimum found from control treatment (T_1). The highest increment of available P was 158.75% from T_3 compared to the control. The application of soil amendments significantly increased soil exchangeable K shown in Table 4. The highest K content (1.49 cmol$_c$ kg^{-1}) observed from T_9 (75% lime + 15 t ha^{-1} RHB + 100% TSP), followed by T_6 (75% lime + 10 t ha^{-1} RHB + 100% TSP). The lowest K content (0.34 cmol$_c$ kg^{-1}) was analyzed from Control (T_1). The maximum increment of exchangeable K was noted 338.24% from T_6 compared over control treatment.

It was observed that soil exchangeable Ca was significantly increased using RHB, lime, and P application (Table 4). The maximum exchangeable Ca 4.15 cmol$_c$ kg^{-1} found from T_9 (75% lime + 15 t ha^{-1} RHB + 100% TSP), followed by T_{10} (75% lime + 15 t ha^{-1} RHB + 75% TSP) and the minimum exchangeable Ca 1.43 cmol$_c$ kg^{-1} found from control treatment (T_1). The exchangeable Ca was highest increased by 190.21% from T_9 compared to the untreated soil. The exchangeable Mg of soil under this study was significantly influenced by the amendments represented in Table 4. The highest Mg content (1.47 cmol$_c$ kg^{-1}) observed from T_3 (100% lime + 10 t ha^{-1} RHB + 100% TSP), followed by T_9 (75% lime + 15 t ha^{-1} RHB + 100% TSP). The lowest Mg content (0.44 cmol$_c$ kg^{-1}) was analyzed from Control (T_1). The maximum increment of exchangeable Mg was 234.09% from T_3 compared to the control treatment.

The exchangeable Al in soil was significantly influenced by the treatments presented in Table 4. The value of exchangeable Al ranged from 0.08 to 2.53 cmol$_c$ kg^{-1} soil. T_3 (100% lime + 10 t ha^{-1} RHB + 100% TSP) noted the lowest value (0.08 cmol$_c$ kg^{-1}), followed by T_5 (100% lime + 10 t ha^{-1} RHB + 50% TSP). The highest value (2.53 cmol$_c$ kg^{-1}) was found from the control treatment. It was observed that soil-extractable Fe was significantly decreased using RHB, lime, and P application in maize crops (Table 4). The value of extractable Fe was significantly different, with the values ranging from 43.36 to 80.05 mg kg^{-1}. The lowest value (43.36 mg kg^{-1}) of Fe was noted from T_7 (75% lime + 10 t ha^{-1} RHB + 75% TSP), and this value decreased by 45.83% compared to the control. The highest value (80.05 mg kg^{-1}) was observed by the control (T_1) treatment. The extractable Mn of soil under this study was significantly influenced by the amendments represented in Table 4. T_3 (100% lime + 10 t ha^{-1} RHB + 100% TSP) showed the highest Mn content (6.58 mg kg^{-1}), followed by T_9 (75% lime + 15 t ha^{-1} RHB + 100% TSP). The control treatment (T_1) showed the lowest Mn content (4.67 mg kg^{-1}). The maximum increment of extractable Mn was 40.90% from T_3 compared to control.

Table 4. Effect of treatments on changes in nutrients of the post-harvest soil.

Treatment	pH	Available P (mg kg^{-1})	Exchangeable K (cmol$_c$ kg^{-1})	Exchangeable Ca (cmol$_c$ kg^{-1})	Exchangeable Mg (cmol$_c$ kg^{-1})	Exchangeable Al (cmol$_c$ kg^{-1})	Extractable Fe (mg kg^{-1})	Extractable Mn (mg kg^{-1})
T_1	4.49 ^{e} ± 0.036	5.43 ^{h} ± 0.017	0.34 ^{e} ± 0.022	1.43 ^{g} ± 0.013	0.44 ^{g} ± 0.012	2.53 ^{a} ± 0.013	80.05 ^{a} ± 1.56	4.67 ^{f} ± 0.041
T_2	4.55 ^{e} ± 0.039	5.85 ^{g} ± 0.015	0.47 ^{d} ± 0.025	1.60 ^{f} ± 0.013	0.55 ^{g} ± 0.025	2.48 ^{a} ± 0.021	84.09 ^{a} ± 1.31	4.71 ^{f} ± 0.016
T_3	6.14 ^{a} ± 0.023	13.56 ^{b} ± 0.206	1.37 ^{bc} ± 0.015	4.05 ^{b} ± 0.013	1.47 ^{a} ± 0.015	0.08 ^{f} ± 0.011	51.66 ^{bc} ± 1.14	6.58 ^{a} ± 0.016
T_4	5.91 ^{d} ± 0.013	11.41 ^{c} ± 0.078	1.34 ^{c} ± 0.019	3.97 ^{bc} ± 0.015	1.31b ^{cd} ± 0.019	0.18 ^{d} ± 0.015	47.25 ^{cd} ± 1.01	6.11 ^{c} ± 0.025
T_5	6.10 ^{ab} ± 0.013	8.74 ^{e} ± 0.029	1.35 ^{bc} ± 0.018	3.96 ^{cd} ± 0.021	1.19 ^{f} ± 0.016	0.09 ^{ef} ± 0.018	55.03 ^{b} ± 1.06	5.84 ^{e} ± 0.021
T_6	5.93 ^{cd} ± 0.015	13.44 ^{b} ± 0.048	1.43 ^{ab} ± 0.018	3.84 ^{e} ± 0.023	1.33 ^{bc} ± 0.013	0.24 ^{d} ± 0.019	45.86 ^{d} ± 0.70	6.27 ^{b} ± 0.022
T_7	6.02 ^{cb} ± 0.019	11.01 ^{d} ± 0.065	1.38 ^{bc} ± 0.015	4.05 ^{b} ± 0.017	1.26 ^{de} ± 0.019	0.12 ^{ef} ± 0.017	43.36 ^{d} ± 1.50	6.08 ^{c} ± 0.015
T_8	5.95 ^{cd} ± 0.017	8.05 ^{f} ± 0.035	1.39 ^{bc} ± 0.013	3.81 ^{e} ± 0.022	1.22 ^{ef} ± 0.024	0.17 ^{de} ± 0.018	54.46 ^{b} ± 1.48	5.95 ^{de} ± 0.019
T_9	5.90 ^{d} ± 0.015	14.05 ^{a} ± 0.033	1.49 ^{a} ± 0.017	4.15 ^{a} ± 0.011	1.46 ^{a} ± 0.013	0.39 ^{bc} ± 0.016	46.49 ^{cd} ± 1.28	6.48 ^{a} ± 0.019
T_{10}	5.87 ^{d} ± 0.026	11.33 ^{cd} ± 0.043	1.34 ^{c} ± 0.018	4.14 ^{a} ± 0.013	1.34 ^{b} ± 0.019	0.44 ^{b} ± 0.016	47.21 ^{cd} ± 1.28	6.27 ^{b} ± 0.022
T_{11}	5.92 ^{cd} ± 0.013	8.73 ^{e} ± 0.042	1.39 ^{cb} ± 0.016	3.88 de ± 0.026	1.28 ^{cd} ± 0.019	0.34 ^{c} ± 0.024	53.46 ^{b} ± 0.78	6.05 cd ± 0.018
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Means within the same column followed by the same letter are not significantly different at $p \leq 0.05$; (Tukey's HSD test). The column represents the mean values ± standard error. T_1 = No treatments and fertilizer (Control), T_2 = Recommended rate of NPK (t ha^{-1}), T_3 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 100% TSP, T_4 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 75% TSP, T_5 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 50% TSP, T_6 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 100% TSP, T_7 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 75% TSP, T_8 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 50% TSP, T_9 = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 100% TSP, T_{10} = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 75% TSP, T_{11} = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 50% TSP.

The incorporation of RHB, lime, and P fertilizer contribute to a greater reduction in soil exchangeable acidity compared with the control represented in Figure 1. The lowest value (0.12 $cmol_c$ kg^{-1}) of exchangeable acidity was noted from T_3 (100% lime + 10 t ha^{-1} RHB + 100% TSP), which decreased by 95.20%. The maximum soil exchangeable acidity (2.50 $cmol_c$ kg^{-1}) was observed from the control.

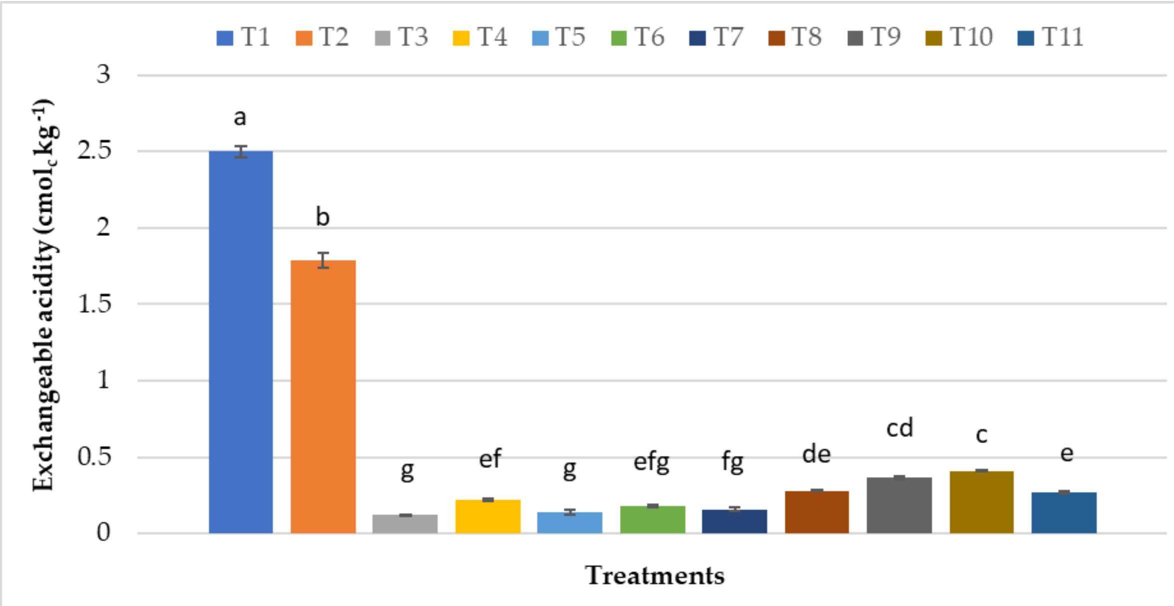

Figure 1. Effect of treatments on changes in soil exchangeable acidity of the post-harvest soil. Bar errors show ± standard error of four replications. T_1 = No treatments and fertilizer (Control), T_2 = Recommended rate of NPK (t ha^{-1}), T_3 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 100% TSP, T_4 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 75% TSP, T_5 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 50% TSP, T_6 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 100% TSP, T_7 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 75% TSP, T_8 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 50% TSP, T_9 = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 100% TSP, T_{10} = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 75% TSP, T_{11} = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 50% TSP.

3.2. Effect of Treatments on Changes in Plant Growth and Yield Contributing Characters

Maize plant height, dry biomass, root length, and leaf chlorophyll content (SPAD value) were significantly increased by adding RHB, lime, and P fertilizers at harvest, presented in Table 5. For example, T_9 (75% lime + 15 t ha^{-1} RHB + 100% TSP) showed the highest plant height of 230.45 cm, while T_1 exhibited the lowest height of 179.20 cm; though T_3 to T_{11} led to the same statistical difference.

There was a significant alteration in dry biomass, root length, and SPAD value of maize after applying the treatments compared to the unamended soil (Table 5). The maximum dry biomass of 84.31 g was noted from T_6 (75% lime + 10 t ha^{-1} RHB + 100% TSP), while the lowest dry biomass (22.32 g) was found from the control treatment (T_1). The highest root length of 79.61 cm was from T_7 (75% lime + 10 t ha^{-1} RHB + 75% TSP). In contrast, the lowest root length (46.94 cm) was revealed from the control (T_1). T_5 (100% lime + 10 t ha^{-1} RHB + 50% TSP) showed the highest SPAD value of 52.03, while the lowest (40.70) was from untreated soil (T_1). Although, T_3 to T_{11} revealed the same statistical differences in terms of dry biomass, root length, and leaf chlorophyll content. The highest increase in the SPAD value was 27.84% from T_5 (100% lime + 10 t ha^{-1} RHB + 50% TSP) compared to control.

The maize cob length, fresh cob weight, no. of grain per cob, and yield were significantly changed (Table 6) by combined application of RHB, lime, and P fertilizer (T_3 to T_{11}) compared to that of untreated soil (T_1 and T_2). The highest cob length (23.75 cm), fresh cob weight (290.60 g), and no. of grain per cob (635) showed by T_6 (75% lime + 10 t ha^{-1} RHB + 100% TSP), while the control treatment showed the lowest of all. However, from T_3 to T_{11} noted as statistically similar in cob length and no. of grain per cob; T_3, T_4, T_5, T_6, T_7, T_8, T_{10}, and T_{11} showed the same statistical value of fresh cob weight. The highest yield of 15.50 t ha^{-1} was exhibited by T_6 (75% lime + 10 t ha^{-1} RHB + 100% TSP) followed by T_4 (100% lime + 10 t ha^{-1} RHB + 75% TSP); although T_3, T_4, T_5, T_6, T_7, T_8, T_{10}, and T_{11} showed the similar statistical value. The control treatment found a minimum crop yield of 9.22 t ha^{-1}.

Table 5. Effect of treatments on plant growth.

Treatment	Plant Height (cm)	Dry Biomass (g)	Root Length (cm)	SPAD Value
T_1	179.20 ^{c} ± 1.86	22.32 ^{c} ± 1.82	46.94 ^{b} ± 1.21	40.70 ^{c} ± 0.684
T_2	195.07 ^{b} ± 1.53	39.37 ^{b} ± 2.21	53.65 ^{b} ± 1.00	43.70 ^{bc} ± 0.62
T_3	225.66 ^{a} ± 2.86	84.01 ^{a} ± 1.90	73.01 ^{a} ± 1.67	50.45 ^{a} ± 0.924
T_4	224.52 ^{a} ± 4.06	79.23 ^{a} ± 1.93	76.16 ^{a} ± 1.25	49.03 ^{a} ± 0.578
T_5	225.30 ^{a} ± 2.89	80.03 ^{a} ± 1.84	77.18 ^{a} ± 1.61	52.03 ^{a} ± 0.657
T_6	222.26 ^{a} ± 2.53	84.31 ^{a} ± 1.82	77.35 ^{a} ± 1.94	50.75 ^{a} ± 1.372
T_7	223.92 ^{a} ± 2.20	81.87 ^{a} ± 2.05	79.61 ^{a} ± 4.09	50.68 ^{a} ± 1.148
T_8	224.86 ^{a} ± 1.98	75.37 ^{a} ± 2.09	75.23 ^{a} ± 2.35	48.95 ^{ab} ± 1.383
T_9	230.45 ^{a} ± 2.22	78.91 ^{a} ± 1.77	71.95 ^{a} ± 1.84	49.78 ^{a} ± 1.193
T_{10}	226.07 ^{a} ± 1.81	81.62 ^{a} ± 1.95	73.24 ^{a} ± 2.26	49.63 ^{a} ± 1.497
T_{11}	222.91 ^{a} ± 1.81	77.45 ^{a} ± 2.15	76.90 ^{a} ± 2.06	50.88 ^{a} ± 1.13
p-value	<0.0001	<0.0001	<0.0001	<0.0001

Means within the same column followed by the same letter are not significantly different at $p \leq 0.05$; (Tukey's HSD test). The column represents the mean values ± standard error. T_1 = No treatments and fertilizer (Control), T_2 = Recommended rate of NPK (t ha^{-1}), T_3 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 100% TSP, T_4 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 75% TSP, T_5 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 50% TSP, T_6 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 100% TSP, T_7 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 75% TSP, T_8 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 50% TSP, T_9 = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 100% TSP, T_{10} = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 75% TSP, T_{11} = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 50% TSP.

Table 6. Effect of treatments on yield contributing characters.

Treatment	Cob Length (cm)	Fresh Cob Weight (g)	No. of Grain per Cob	Yield (t ha^{-1})
T_1	18.28 ^{a} ± 0.559	172.98 ^{c} ± 1.69	323 ^{d} ± 5.82	9.22 ^{c} ± 0.090
T_2	19.50 ^{b} ± 0.507	183.15 ^{c} ± 2.33	480 ^{c} ± 4.19	9.77 ^{c} ± 0.126
T_3	23.18 ^{a} ± 0.332	286.68 ^{ab} ± 2.31	624 ^{ab} ± 5.18	15.29 ^{ab} ± 0.122
T_4	22.50 ^{a} ± 0.492	290.03 ^{a} ± 2.27	622 ^{ab} ± 4.19	15.47 ^{a} ± 0.119
T_5	22.48 ^{a} ± 0.496	286.73 ^{ab} ± 3.39	628 ^{ab} ± 4.21	15.29 ^{ab} ± 0.181
T_6	23.75 ^{a} ± 0.247	290.60 ^{a} ± 2.21	635 ^{a} ± 3.86	15.50 ^{a} ± 0.119
T_7	23.15 ^{a} ± 0.184	279.45 ^{ab} ± 2.53	630 ^{ab} ± 5.21	14.90 ^{ab} ± 0.136
T_8	22.45 ^{a} ± 0.403	279.43 ^{ab} ± 2.05	611 ^{b} ± 5.05	14.90 ^{ab} ± 0.110
T_9	23.10 ^{a} ± 0.381	276.80 ^{b} ± 1.64	622 ^{ab} ± 5.74	14.77 ^{b} ± 0.080
T_{10}	22.90 ^{a} ± 0.443	287.75 ^{ab} ± 1.48	616 ^{ab} ± 3.38	15.35 ^{ab} ± 0.08
T_{11}	23.25 ^{a} ± 0.366	282.45 ^{ab} ± 1.90	618 ^{ab} ± 4.91	15.07 ^{ab} ± 0.101
p-value	<0.0001	<0.0001	<0.0001	<0.0001

Means within the same column followed by the same letter are not significantly different at $p \leq 0.05$; (Tukey's HSD test). The column represents the mean values ± standard error. T_1 = No treatments and fertilizer (Control), T_2 = Recommended rate of NPK (t ha^{-1}), T_3 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 100% TSP, T_4 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 75% TSP, T_5 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 50% TSP, T_6 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 100% TSP, T_7 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 75% TSP, T_8 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 50% TSP, T_9 = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 100% TSP, T_{10} = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 75% TSP, T_{11} = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 50% TSP.

3.3. Effect of Treatments on Changes in Plant Nutrient Concentration and Uptake

There was a significant difference in plant nutrient concentration and uptake of maize, represented in Tables 7 and 8. With T_1 and T_2, the concentration and total uptake of N, P, K, Ca, and Mg taken up by the maize plant were statistically lower than those of biochar and lime amended treatments (T_3 to T_{11}). The highest uptake of N (2027.66 mg plant^{-1}) and Ca (526.94 mg plant^{-1}) obtained from T_6 (75% lime + 10 t ha^{-1} RHB + 100% TSP); the highest P (250.98 mg plant^{-1}) noted from T_{10} (75% lime + 15 t ha^{-1} RHB + 75% TSP); but T_6, T_9, and T_{10} have the same statistical value. The maximum K uptake (1986.84 mg plant^{-1}), and Mg uptake (273.03 mg plant^{-1}) are shown from T_3 (100% lime + 10 t ha^{-1} RHB + 100% TSP). Figure 2 shows the maximum (145.64%) phosphorus use efficiency (PUE) noted from T_{10} (75% lime + 15 t ha^{-1} RHB + 75% TSP) followed by T_6 (133.37%) and T_9 (131.75%).

Table 7. Effect of treatments on changes in plant nutrient concentration.

Treatment	N Concentration (%)	P Concentration (%)	K Concentration (%)	Ca Concentration (%)	Mg Concentration (%)
T_1	0.80 ^{g} ± 0.013	0.11 ^{e} ± 0.009	0.55 ^{f} ± 0.017	0.09 ^{f} ± 0.006	0.10 ^{g} ± 0.006
T_2	1.30 ^{f} ± 0.013	0.18 ^{d} ± 0.009	1.04 ^{e} ± 0.011	0.11 ^{f} ± 0.009	0.13 ^{g} ± 0.008
T_3	2.25 ^{bc} ± 0.016	0.26 ^{bc} ± 0.008	2.37 ^{a} ± 0.006	0.54 ^{cd} ± 0.009	0.33 ^{b} ± 0.006
T_4	2.16 ^{cd} ± 0.022	0.28 ^{ab} ± 0.006	2.26 ^{d} ± 0.006	0.50 ^{de} ± 0.005	0.26d ^{ef} ± 0.006
T_5	2.30 ^{b} ± 0.022	0.24 ^{c} ± 0.008	2.28 ^{cd} ± 0.009	0.58 ^{bc} ± 0.009	0.28 ^{de} ± 0.003
T_6	2.41 ^{a} ± 0.021	0.28 ^{ab} ± 0.006	2.25 ^{d} ± 0.006	0.63 ^{a} ± 0.010	0.23 ^{f} ± 0.011
T_7	2.25 ^{bc} ± 0.021	0.23 ^{c} ± 0.008	2.31 ^{bc} ± 0.008	0.60 ^{ab} ± 0.009	0.38 ^{a} ± 0.004
T_8	2.14 ^{d} ± 0.013	0.24 ^{c} ± 0.006	2.26 ^{d} ± 0.004	0.54 ^{cd} ± 0.009	0.25 ^{ef} ± 0.006
T_9	2.02 ^{e} ± 0.028	0.29 ^{ab} ± 0.006	2.33 ^{ab} ± 0.004	0.60 ^{ab} ± 0.013	0.29 ^{cd} ± 0.012
T_{10}	2.18 ^{cd} ± 0.020	0.31 ^{a} ± 0.008	2.37 ^{a} ± 0.013	0.54 ^{cd} ± 0.006	0.32 ^{bc} ± 0.006
T_{11}	2.30 ^{b} ± 0.019	0.28 ^{ab} ± 0.005	2.33 ^{ab} ± 0.005	0.48 ^{e} ± 0.013	0.24 ^{f} ± 0.009
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Means within the same column followed by the same letter are not significantly different at $p \leq 0.05$; (Tukey's HSD test). The column represents the mean values ± standard error. T_1 = No treatments and fertilizer (Control), T_2 = Recommended rate of NPK (t ha^{-1}), T_3 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 100% TSP, T_4 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 75% TSP, T_5 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 50% TSP, T_6 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 100% TSP, T_7 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 75% TSP, T_8 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 50% TSP, T_9 = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 100% TSP, T_{10} = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 75% TSP, T_{11} = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 50% TSP.

Table 8. Effect of treatments on changes in plant nutrient uptake.

Treatment	N (mg Plant^{-1})	P (mg Plant^{-1})	K (mg Plant^{-1})	Ca (mg Plant^{-1})	Mg (mg Plant^{-1})
T_1	178.56 ^{g} ± 2.88	24.00 ^{e} ± 1.91	123.32 ^{i} ± 3.91	20.83 ^{g} ± 1.08	21.21 ^{f} ± 1.44
T_2	511.81 ^{f} ± 5.08	71.42 ^{d} ± 3.43	408.46 ^{h} ± 4.36	44.09 ^{g} ± 3.37	50.20 ^{f} ± 2.95
T_3	1886.02 ^{b} ± 13.06	216.33 ^{b} ± 6.30	1986.84 ^{a} ± 5.42	451.55 ^{c} ± 7.18	273.03 ^{a} ± 5.42
T_4	1711.37 ^{d} ± 17.42	217.32 ^{b} ± 5.19	1786.64 ^{f} ± 5.11	394.17 ^{ef} ± 3.79	229.77 ^{bc} ± 10.23
T_5	1840.69 ^{bc} ± 17.59	190.08 ^{c} ± 6.00	1826.69 ^{de} ± 6.83	462.17 ^{bc} ± 6.83	221.43 ^{cd} ± 3.14
T_6	2027.66 ^{a} ± 17.72	231.86 ^{ab} ± 5.44	1892.76 ^{c} ± 5.44	526.94 ^{a} ± 8.78	191.81 ^{de} ± 9.35
T_7	1844.12 ^{bc} ± 17.49	186.26 ^{c} ± 6.14	1889.15 ^{c} ± 6.14	491.22 ^{b} ± 7.47	272.22 ^{a} ± 6.99
T_8	1615.59 ^{e} ± 9.40	177.12 ^{c} ± 4.87	1703.36 ^{g} ± 3.08	408.88 ^{de} ± 6.44	186.69 ^{e} ± 4.85
T_9	1590.04 ^{e} ± 22.43	229.33 ^{ab} ± 4.29	1838.63 ^{d} ± 3.22	473.46 ^{bc} ± 10.19	224.18 ^{c} ± 9.90
T_{10}	1781.36 ^{cd} ± 16.45	250.98 ^{a} ± 6.12	1934.39 ^{b} ± 10.54	440.75 ^{cd} ± 4.71	257.10 ^{ab} ± 5.27
T_{11}	1777.48 ^{cd} ± 15.00	219.28 ^{b} ± 3.65	1802.65 ^{ef} ± 3.71	371.77 ^{f} ± 10.00	176.20 ^{e} ± 6.61
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Means within the same column followed by the same letter are not significantly different at $p \leq 0.05$; (Tukey's HSD test). The column represents the mean values ± standard error. T_1 = No treatments and fertilizer (Control), T_2 = Recommended rate of NPK (t ha^{-1}), T_3 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 100% TSP, T_4 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 75% TSP, T_5 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 50% TSP, T_6 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 100% TSP, T_7 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 75% TSP, T_8 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 50% TSP, T_9 = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 100% TSP, T_{10} = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 75% TSP, T_{11} = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 50% TSP.

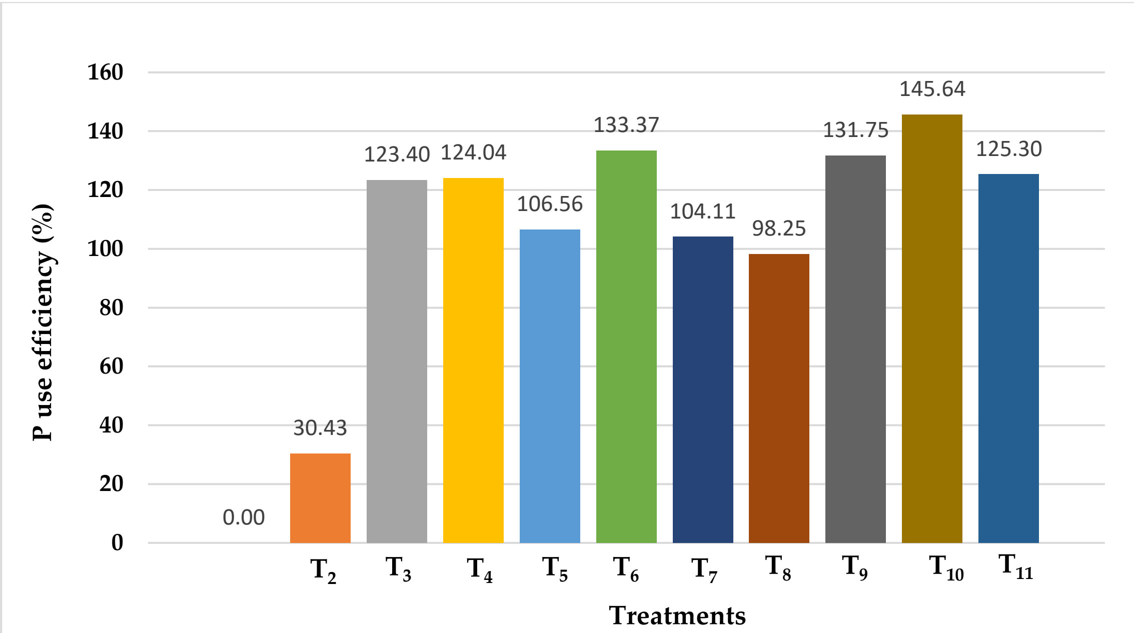

Figure 2. Effect of treatments on phosphorus use efficiency. T_1 = No treatments and fertilizer (Control), T_2 = Recommended rate of NPK (t ha^{-1}), T_3 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 100% TSP, T_4 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 75% TSP, T_5 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 50% TSP, T_6 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 100% TSP, T_7 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 75% TSP, T_8 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 50% TSP, T_9 = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 100% TSP, T_{10} = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 75% TSP, T_{11} = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 50% TSP.

3.4. Effect of Treatments on Changes in Soil CO_2 Emission

Results for the measured CO_2 emissions from the treatments are presented in Figure 3, and their cumulative emission dynamic is shown in Figure 4. In this study, CO_2 emissions were relatively higher with the co-application of biochar and lime rather than unamended soil. The emission of CO_2 was highest on day 5 compared to all other days, from all the treatments except T_1 and T_2. Among the biochar and lime amended treatments, T_8 (75% lime + 10 t ha^{-1} RHB + 50% TSP) emitted the lower CO_2 gas, and its cumulative emission was 151.04 µmol CO_2 m^{-2}; even though there was no statistically significant difference for T_6, T_7, T_8, T_9, and T_{10}. The highest cumulative CO_2 flux (160.70 µmol CO_2 m^{-2}) was observed from T_3 (100% lime + 10 t ha^{-1} RHB + 100% TSP) followed by T_4 (157.23 µmol CO_2 m^{-2}), and T_5 (156.87 µmol CO_2 m^{-2}), in contrast, the lowest cumulative CO_2 flux (62.25 µmol CO_2 m^{-2}) was from the control treatment (T_1). From Figures 3 and 4, it is clear that the amount of CO_2 emission was very close from all the amended treatments, and the more lime rate, the more CO_2 gas emission. The cumulative emission of CO_2 was significantly increased by 158.15% from T_3 (100% lime + 10 t ha^{-1} RHB + 100% TSP), whereas, 142.63% by T_8 (75% lime + 10 t ha^{-1} RHB + 50% TSP) compared over control treatment. The cumulative CO_2 emission was in the order of $T_3 > T_4 > T_5 > T_9 > T_7 > T_6 > T_{10} > T_{11} > T_8 > T_2 > T_1$.

3.5. Relationship between Plant Parameters, Nutrients Uptake, Soil pH, and Nutrients

Pearson's correlation analysis was performed to evaluate the relationship among the soil nutrients, plant parameters, plant nutrient uptake, and CO_2 emission (Table 9). Grain yield was significantly and positively correlated with soil pH (r = 0.98), Soil available P (r = 0.74), exchangeable K, Ca, Mg (r = 0.97, 0.98, and 0.0.95, respectively), extractable Mn (r = 0.93), plant biomass (r = 0.97), root length (r = 0.91). Furthermore, CO_2 flux was correlated with soil pH (r = 0.99), available P (r = 0.76), exchangeable K, Ca, Mg (r = 0.99.

0.99, and 0.97 respectively), extractable Mn (r = 0.95), plant biomass (r = 0.97), root length (r = 0.90) and grain yield (r = 0.99).

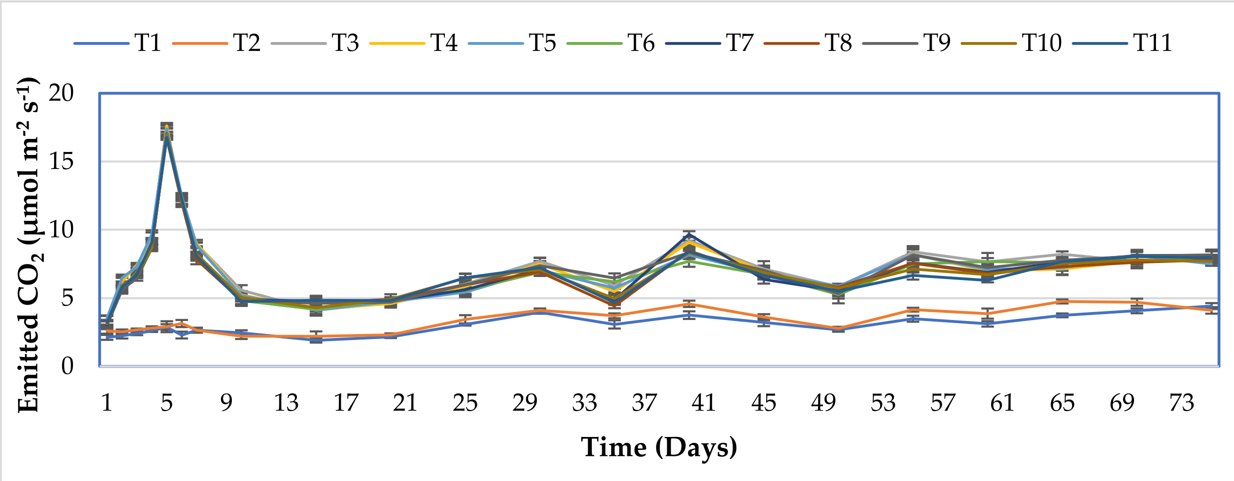

Figure 3. Effect of Treatments on soil CO_2 flux emission in a maize field. Bar errors show ± standard error of four replications. T_1 = No treatments and fertilizer (Control), T_2 = Recommended rate of NPK (t ha^{-1}), T_3 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 100% TSP, T_4 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 75% TSP, T_5 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 50% TSP, T_6 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 100% TSP, T_7 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 75% TS P, T_8 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 50% TSP, T_9 = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 100% TSP, T_{10} = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 75% TSP, T_{11} = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 50% TSP.

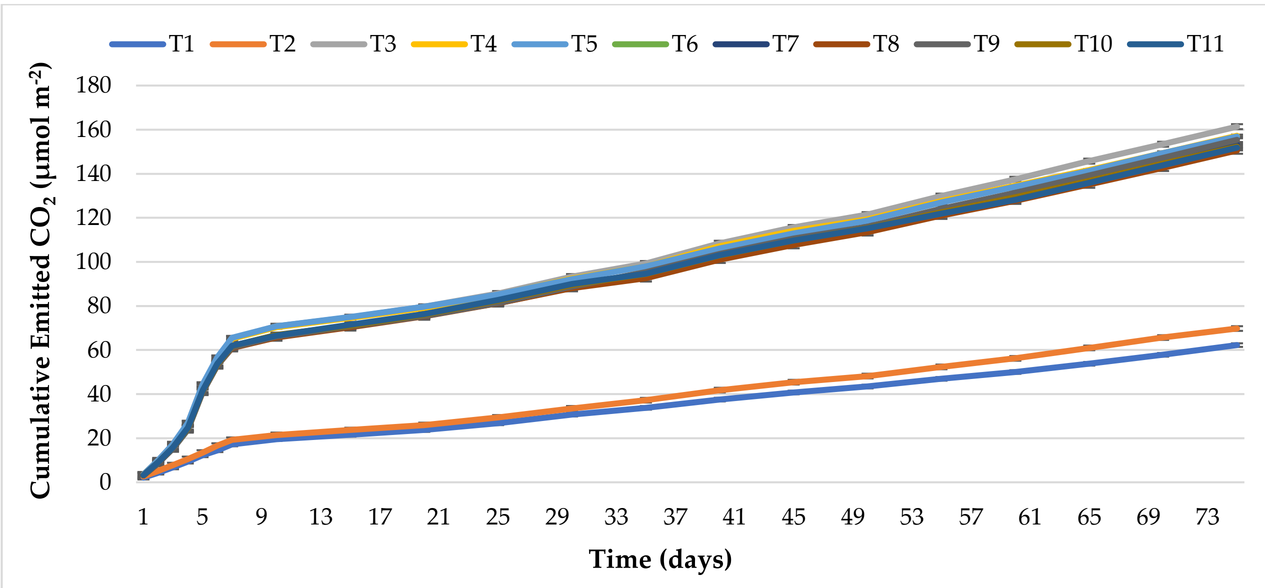

Figure 4. Effect of Treatments on cumulative soil CO_2 flux emission. Bar errors show ± standard error of four replications. T_1 = No treatments and fertilizer (Control), T_2 = Recommended rate of NPK (t ha^{-1}), T_3 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 100% TSP, T_4 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 75% TSP, T_5 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 50% TSP, T_6 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 100% TSP, T_7 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 75% TSP, T_8 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar + 50% TSP, T_9 = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 100% TSP, T_{10} = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 75% TSP, T_{11} = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar + 50% TSP.

Table 9. The correlation coefficient among maize plant parameters, nutrients uptake, soil pH, and nutrients (all relations were significant).

Correlation	pH	Av. P	Exch. K	Exch. Ca	Exch. Mg	Exch. Al	Exct. Fe	Exct. Mn	Exch. Acidity	Plant Biomass	Root Length	Grain Yield	N Uptake	P Uptake	K Uptake	Ca Uptake	Mg Uptake	CO_2 Emission
pH	1.00																	
Av. P	0.73	1.00 *																
Exch. K	0.97 *	0.77 *	1.00 *															
Exch. Ca	0.98 *	0.77 *	0.99 *	1.00 *														
Exch. Mg	0.95 *	0.86 *	0.97 *	0.97 *	1.00 *													
Exch Al	−0.99 *	−0.72 *	−0.98 *	−0.98 *	−0.94 *	1.00 *												
Exct. Fe	−0.92 *	−0.82 *	−0.94 *	−0.95 *	−0.92 *	0.93 *	1.00 *											
Exct. Mn	0.93 *	0.90 *	0.95 *	0.96 *	0.99 *	−0.92 *	−0.93 *	1.00 *										
Exch. acidity	−0.98 *	−0.72 *	−0.97 *	−0.97 *	−0.94 *	0.98 *	0.90 *	−0.91 *	1.00 *									
Plant biomass	0.96 *	0.78 *	0.97 *	0.97 *	0.95 *	−0.96 *	−0.92 *	0.93 *	−0.98 *	1.00 *								
Root length	0.91 *	0.63 *	0.91 *	0.90 *	0.84 *	−0.91 *	−0.88 *	0.82 *	−0.93 *	0.90 *	1.00 *							
Grain yield	0.98 *	0.74 *	0.97 *	0.98 *	0.95 *	−0.98 *	−0.93 *	0.93 *	−0.98 *	0.97 *	0.91 *	1.00 *						
N uptake	0.97 *	0.75 *	0.96 *	0.96 *	0.94 *	−0.97 *	−0.92 *	0.92 *	−0.98 *	0.97 *	0.92 *	0.98 *	1.00 *					
P uptake	0.90 *	0.81 *	0.94 *	0.95 *	0.96 *	−0.90 *	−0.91 *	0.94 *	−0.92 *	0.93 *	0.82	0.94 *	0.93 *	1.00 *				
K uptake	0.98 *	0.79 *	0.98 *	0.99 *	0.97 *	−0.98 *	−0.94 *	0.96 *	−0.98 *	0.98 *	0.91 *	0.99 *	0.99 *	0.96 *	1.00 *			
Ca uptake	0.96 *	0.81 *	0.97 *	0.96 *	0.94 *	−0.96 *	−0.95 *	0.93 *	−0.95 *	0.96 *	0.88 *	0.96 *	0.97 *	0.91 *	0.97 *	1.00 *		
Mg uptake	0.92 *	0.78 *	0.89 *	0.94 *	0.92 *	−0.91 *	−0.90 *	0.91 *	−0.91 *	0.91 *	0.83 *	0.91 *	0.91 *	0.87 *	0.94 *	0.91 *	1.00 *	
CO_2 emission	0.99 *	0.76 *	0.99 *	0.99 *	0.97 *	−0.99 *	−0.94 *	0.95 *	−0.98 *	0.97 *	0.90 *	0.99 *	0.97 *	0.93 *	0.99 *	0.96 *	0.92 *	1.00 *

Av. P: available P; Exch. K: exchangeable K; Exch. Ca: exchangeable Ca; Exch. Mg: exchangeable Mg; Exch. Al: exchangeable Al; Exct. Fe: extractable Fe; Exct. Mn: extractable Mn; Exch. Acidity: exchangeable Acidity; * $p < 0.05$.

4. Discussion

4.1. Impact of Treatments on Changes in Nutrients of the Post-Harvest Soil

In this study, the soil pH, at the end of the study, significantly increased due to different soil amendments. Among the treatment combinations, the pH was relatively higher, except in treatment T_4, when 100% lime was applied, than all other treatments. When 75% of the recommended rate of biochar was applied along with different rates of biochar, soil pH was higher when biochar was applied at higher application rates. These results suggest that biochar buffered soil pH possibly through basic cation additions and H^+ consumption on its negative functional groups (Table 2). Biochar mediating an increase in soil pH has been reported by Abdulrahman et al. [54], while organic amendments mediating (H^+) exchange has also been reported [55]. Our result was in line with the study by Ch'ng et al. [56], where they reported an increase of 0.99 units of soil pH after applying chicken litter biochar.

Soil available P significantly increased by using the different treatments compared to the unamended soil. The largest increment was observed in the T_9, i.e., when biochar was applied at 15 t ha^{-1} along with 100% recommended rate of P and 75% of the lime requirement. Moreover, the available P was relatively larger when the 100% P was applied irrespective of biochar and lime addition than other P treatments. Under 75% P addition, biochar (15 t ha^{-1}) along with 75% lime performed equally with T_4 (100% lime, and 10 t biochar ha^{-1}), suggesting a clear biochar effect. This is plausible since biochar amendment significantly increased soil pH that might have increased the bioavailability of P. Our presumption is supported by a significant correlation between soil pH and available soil P (Table 9 and Figure 5) [57]. Besides, freshly prepared biochars with large surface areas perform as an adsorbent of phosphate and help to increase the P bioavailability of soil [31]. Our result was similar to the findings of Panhwar et al. [58]. By applying rice husk biochar and bio-fertilizer, they revealed 99.82% increased soil available P.

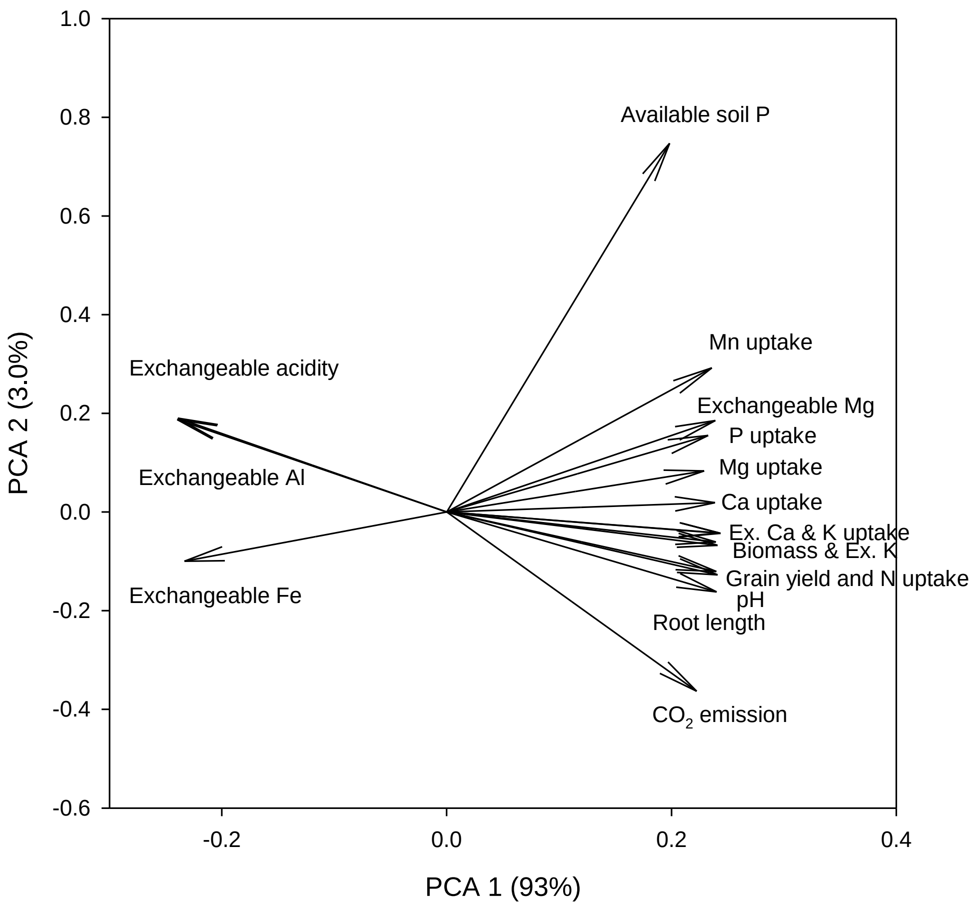

Figure 5. Principal component analysis of different variables.

A significant increase in base cations (Ca^{2+}, Mg^{2+}, K^+) was recorded after applying biochar and lime treatments compared to unamended soil. Our result was well supported by Maru et al. [23], where they found increased exchangeable bases by using 5 t ha^{-1} chicken litter biochar in tropical acid soil. Soil exchangeable bases are raised by the exchange reaction between the organic amendment's base cations and soil exchangeable Al^{3+} and H^+. Apart from this, the lime application is another source of soil exchangeable Ca and Mg. Therefore, these treatments ameliorate soil acidity and provide nutrients in acid soil [59].

All the treatments except T_1 and T_2 significantly decreased exchangeable acidity, exchangeable Al, and extractable Fe after biochar and lime were applied compared to unamended soil. Our result revealed that the exchangeable acidity, Al, and Fe concentration reduced by 95.20%, 96.84%, and 45.83%, respectively. This reduction is partially related to the increased soil pH [56]. Soluble Al and Fe content precipitated as insoluble hydroxides of Al and Fe on the surface of the organic amendments due to the increase in soil pH. Thus, Al and Fe content was reduced [56]. In addition, exchangeable acidity decreased due to the increased soil pH. Besides, exchangeable acidity is reduced by lowering the exchangeable Al [60]. Our findings align with Kamran et al. [61], noting that exchangeable acidity was reduced by using chicken manure biochar.

4.2. Impact of Treatments on Plant Growth and Yield Contributing Characters

There were significant changes in the growth performance of maize plants when grown in the amended soils compared to unamended soil. In terms of yield, all the amended soils performed equally except for T_9. These results suggest that biochar application along with reduced lime and P (up to 50%) can provide a yield similar to their 100% recommendation. This yield was possibly manifested by a better plant performance in terms of yield contributing characters under these treatments (Figure 5). The first component in the principal component analysis explained most of the variation (93%) in the variables, while the second component explained only 3% of the variations. Among the variables analyzed, all variables had positive loading in the first component except exchangeable acidity, exchangeable Al, and Fe. However, the values of the loading were almost similar for all variables estimating at +0.22 and −0.22. In the second component, the variation in loading was much prominent ranging from −0.4 for CO_2 emission to +0.78 for soil available P. Altogether, our PCA analysis showed that grain yield was positively associated with soil pH, root length, plant N, P, Ca, and Mg uptake. In contrast, it was negatively associated with exchangeable acidity, exchangeable Al, and Fe. Specifically, the better performance of maize in terms of yield and yield components was possibly occurred due to an increase in soil pH that helps to make the plant nutrients available. A greater availability of nutrients including N, P, K, and others promoted plant growth through a larger nutrient uptake. For instance, available P was higher in these treatments, and there was a significant relationship between grain yield and available P (Figure 6). Similar trends were also observed for other nutrients (Table 9). Moreover, incorporating biochar into the soil might have minimized the leaching loss of nutrients, thereby influencing plants' growth [62]. Similar results have also been reported in the literature. For instance, an increased soil pH has been shown as the vital growth factor of maize plants [63,64]. According to Mehmood et al. [65], reduced exchangeable acidity increased soil pH, and a sufficient amount of nutrients present in the soil due to biochar addition are considered an enhancement of plant growth. Our findings are also in line with Masud et al. [59], where they used poultry litter biochar to increase maize production in acid soil. Co-application of biochar and lime is supportive to nutrient release and also enhancement of nutrient retention to boost the yield of maize [62].

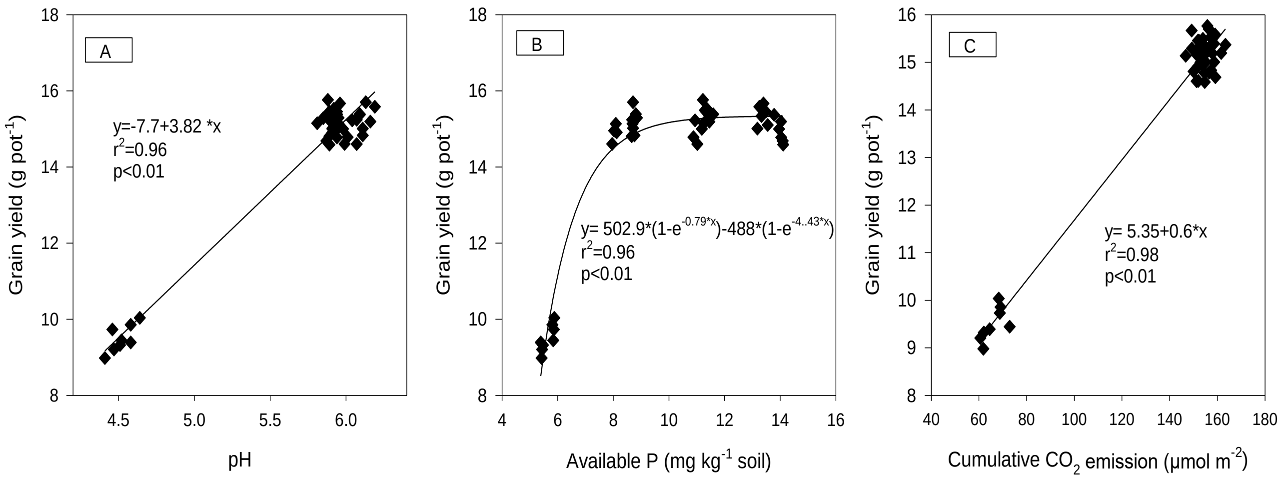

Figure 6. Relationship between soil pH, soil available P, and cumulative CO_2 emission against grain yield (**A**–**C**), respectively.

4.3. Impact of Treatments on Plant Nutrient Concentration and Uptake

Our study showed that nutrient concentration and total uptake were highly significantly increased with the co-application of biochar and lime-treated soil compared to untreated soil. This result is similar to the study by Rabileh et al. [49], where they found increased nutrient uptake treated with biochar and lime. In addition, our study revealed that the application of biochar and lime reduces Al and Fe content from the soil by increasing soil pH, which helps to reduce the Al toxicity of roots and resulted in increased nutrient uptake of maize [56]. A meta-analysis conducted by Biederman et al. [66] reported that the amount of P and K raised in plants by adding biochar over fertilizer due to increased nutrient availability by increasing retention capacity and soil liming.

4.4. Impact of Treatments on Changes in Soil CO_2 Emission

The co-application of biochar with lime and different doses of P fertilizer significantly influenced the emission rate of CO_2. In this present study, applied high lime rate contributes to an increase of 158.15% from T3 (100% lime + 10 t ha^{-1} RHB + 100% TSP), while, 142.63% by T8 (75% lime + 10 t ha^{-1} RHB + 50% TSP) compared to untreated soil CO_2 emission. It seems that, for increased CO_2 emissions, carbon dissociation is not the only liable fact; whereas, CO_2 is emitted due to the prompt activities of microbial communities [67]. In the initial stage of our pot study, the emission of CO_2 flux was highest on day 5 from all the amended soil due to the speedy mineralization of soil organic carbon [68]. This result is consistent with the findings of Mosharrof et al. [69]. According to Fidel et al. [70], the daily emission of CO_2 was changed because of the variation of density of root and biomass of plants, resulting in the labile soil organic carbon variation.

Generally, the application of biochar into the soil may reduce the emission of CO_2 gas from the soil by the labile carbon absorbed on the biochar's surface or into the biochar's pore space [71]. Furthermore, the recalcitrant characteristic of biochar, which helps to decompose slowly and resulted in reduced microbial respiration, is another cause of decreased CO_2 flux emission [72]. In contrast, biochar contains volatile organic carbon, contributing to enhancing the soil CO_2 emission [73].

5. Conclusions

In tropical acidic soil, amending with the combined application of different rates of RHB, dolomitic limestone, and chemical P fertilizer can enhance nutrients availability to the plant by increasing soil pH, available P, base cations, and reducing exchangeable acidity while reducing the toxicity of Al and Fe. Compared to control and NPK treatments, combined application of lime and RHB increased P bioavailability with the largest increase in the greater P application rate. However, the difference between different RHB and lime treatments (i.e., application rates) was minimal. Finally, our results indicate that treatments with 75% lime + 10 t ha^{-1} RHB with different doses of P fertilizer (T_6, T_7 and T_8) are recommended, which can significantly increase available P in soil, dry biomass, and yield of maize, instead of 100% lime or 15 t ha^{-1} RHB. This approach will help reduce economic cost, environmental benefits, and gain more profit to farmers; concurrently, reduced soil CO_2 gas may reduce the threat of various earth ecosystems. However, further research is needed to evaluate the agronomical values at a framers field scale.

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