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Combined Application of Biochar and Lime Increases Maize Yield and Accelerates Carbon Loss from an Acidic Soil

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Abstract: Biochar, an ecologically friendly soil amendment, is suggested for large-scale field application for its multiple potential benefits, including carbon sequestration, crop yield improvement, and the abatement of greenhouse gas emissions. However, it is unknown how effective it is in changing soil properties and its associated yield improvement when biochar is co-applied with lime in acidic soil. Here, we examined the effects of two different biochars, i.e., rice husk biochar (RHB) and oil palm empty fruit bunches biochar (EFBB), and lime on nutrient availability, the yield of maize, and soil CO_2 emission of acid soil. Biochars were applied at two different rates (10 and 15 t ha^{-1}) in combination with two rates of lime (100% and 75%), while the recommended rate of NPK fertilizers, 100% lime, and without any amendments (control) were also included. Hybrid sweet corn was grown in pots with 20 kg soils for 75 days. Plant performance and soil analyses were performed before and after crop maize cultivation while CO_2 emission was recorded. Compared to the control, combined RHB biochars with lime significantly buffered soil pH and increased nutrient availability (e.g., P by 137%), while reducing Al and Fe concentration at harvest. These changes in soil properties significantly increased maize yield (by 77.59%) and nutrient uptake compared to the control. Between the two biochars, RHB was relatively more effective in making these changes than EFBB. However, this treatment contributed to a greater carbon loss as CO_2 (209% and 145% higher with RHB and EFBB) from soil than the control. We believe that biochar-mediated buffering of soil pH is responsible for this change. Our results suggest that combined biochar application could bring desirable changes in soil properties and increase crop performance, although these effects can be short-lived.

Keywords: acid soil; biochar; lime; carbon dioxide; soil nutrients; maize yield

1. Introduction

Soil acidification is one of the main constraints for crop production in tropical and subtropical regions [1,2]. Around 3950 million hectares of lands have been assessed to be influenced by acidity, involving almost 30% of the worldwide land surface [3] and representing roughly half of the worldwide arable land [4]. Acidification of soil occurs due to multiple reasons, including the presence of acidifying minerals and soil management practices. For instance, acidification is often intensified with agricultural practices (e.g., mineral N fertilization). It can accelerate the leaching of exchangeable bases and imbalance soil reaction due to excessive uptake of positively charged cations from the applied inorganic fertilizers [5]. Therefore, managing soil acidity is one of the stressing needs to increase and maintain soil productivity.

Several management practices, including lime application and organic amendments, are suggested to ameliorate soil acidity. These days, the most well-known and effective technique for reducing soil acidity is the addition of lime ($CaCO_3$) [6]. When lime is applied, the soil pH increases since it provides basic cations such as Ca and Mg, and thus, the Al toxicity reduces [7]. Moreover, lime application can help to increase soil microbial activity with changes in soil bacterial and fungal colonization [8,9]. Despite these benefits of lime application, it has some disadvantages. For instance, the application of lime in agricultural soil for a long period can cause re-acidification and may increase physical firmness [10], while it may cause leaching loss of mineral nutrients such as Mg^{2+} and NO_3^- [11].

Recently, organic amendments, including biochar, a form of pyrogenic carbon, have been suggested for increasing crop productivity in diverse soils, including acidic soils. Biochar, being resistant to microbial decomposition, is considered a natural and eco-friendly soil amendment since it carries out these roles for a longer period [12–14]. Biochar can help to remediate soil acidity in several ways. The carboxylic and phenolic functional groups in the biochar surface can buffer soil pH, while the intrinsic basic cations in the biochar can also help to minimize soil pH. The latter effect may be short-lived, while the earlier effect will promote with time [15]. In addition, biochar can improve soil microbial functions, including symbiotic association with mycorrhiza that helps to acquire nutrients under acidic conditions. For example, by applying paddy straw-derived biochar into the sandy soil, the soil pH increased by 4.5 units compared to the control under a field study [16]. The toxicity of Al has been reported to decrease in an Alfisol by raising the biochar rate [14]. Ch'ng et al. [17] reported a similar increase in soil pH that decreased exchangeable Al and Fe when the soil was amended with chicken litter biochar. Biochar has also been found to increase soil CEC, although the increment can vary with feedstocks. According to Tomczyk et al. [14], the CEC of an Anthrosol increased by 190% compared to control by applying biochar produced from wood.

Biochar can also improve plant nutrition and yield since it is the source of nutrient elements such as nitrogen (N), phosphorus (P), potassium (K), and other trace elements [18,19]. Moreover, biochar can increase the bioavailability of nutrients in soil such as K, Ca, Mg, and P [20], and soil aeration, water-holding capacity, bulk density of soil, and microorganisms increased with the addition of biochar [21]. In an ecological farming system, biochar increased crop yield by 25% in tropical soils [22]. Mensah and Frimpong [23] reported that biochar addition in two soil types significantly increased biomass and yield of maize. Moreover, adding biochar to soil, with or without chemical fertilizer, has been reported to supply sufficient macro- and micro-nutrients to plants [24,25].

In recent years, for economic sustainability, soil fertility, and mitigating GHG emissions, the use of biochar has emerged as an environmentally friendly strategy [26]. When applied to soil, biochar increases soil organic carbon and acts as a C sequester since its mineralization rate is quite low [27,28]. However, the application of biochar has been shown to alter the emission of soil CO_2 with diverse effects for different biochars and their residence in the soil. For example, He et al. [29] reported an increased CO_2 flux (22.14%) due to the addition of biochar because of the volatile organic C contained in the biochar [30]. In contrast, the reduction of soil CO_2 flux emission occurs due to the very slow decomposition of biochar, which helps to reduce microbial activity [31]. Thus, the inconsistent results from the previous researchers mark the demand of its further investigation, specifically including different kinds of biochars and in different soil types.

Globally, maize is one of the leading cereal crops, providing food and feed for humans and animals, along with diverse raw materials for agricultural industries [32]. Many different foods and feed items are prepared from maize, providing multiple nutrients and vitamins [33]. In our study, biochar addition with lime might support nutrient availability, growth, and yield of maize, as well as being economically and environmentally feasible. This approach may also contribute to food security, especially in developing countries. However, the production of maize in acidic soils is often relatively low, which can be improved if proper management strategies are implemented. Although there are many biochar-related publications, there is still a knowledge gap on how different rates of biochar could ameliorate soil acidity when co-applied with different levels of lime [34,35]. Considering these facts, a pot trial was conducted with two different biochars (rice husk and empty fruit bunch biochar) at two different rates (10 and 15 t ha^{-1}) with varying amounts of lime to examine whether biochar can reduce the lime requirement and improve maize yield, its nutrient uptake, and soil CO_2 emission in acid soil.

2. Materials and Methods

2.1. Collection and Characterization of Soil Sample

An acidic soil sample was collected from Taman Partanian, Universiti Putra Malaysia, Puchong, Selangor (2°58′59.7″ N latitude; 101°38′47.5″ E longitude). The soil sample was taken at a depth of 0–20 cm, air-dried, and ground to pass through a 2 mm sieve. The soil sample was characterized for its physical and chemical properties (Table 1). The hydrometer method was used to analyze the soil's particle size [36]. The soil was classified as sandy clay loam texture by the United States Department of Agriculture (USDA) soil classification system, and it belongs to the Bungor Series (fine, kaolinitic, isohyperthermic, typic Paleudult). A glass electrode pH meter was used to determine soil pH in a 1:2.5 (weight/volume basis) ratio of soil and water, respectively [37]. The soil was analyzed for total carbon (TC), total nitrogen (TN), and total sulfur (TS) using a CNS auto-analyzer (LECO Corporation, St. Joseph, MI, USA) by the dry combustion method. Mineral N concentration (NH_4^+-N and NO_3^- N) was determined after extraction of the soil with 2 M KCl phenylmercuric acetate (KCl-PMA, KCl Purity min 99.5%; M = 74.56 g/mol) mixture (1:4, w/m) and titrated against 0.01 N HCl (HCl Purity min 36.5% to 38%; M = 36.46 g/mol) [38]. The ammonium acetate leaching method at pH 7 was used to determine the cation exchange capacity (CEC) of the soil. Specifically, ammonium acetate (NH_4OAc purity min 98%; M = 77.08 g/mol) solution at pH 7 was used to extract exchangeable K, Ca, and Mg using the leaching method [39]. Later, the collected leachate was determined by inductively coupled plasma optical emission spectroscopy (ICP-OES, Perkin Elmer, Boston, MA, USA). The Bray and Kurtz II method was used to determine available P [40], where 2 g of soil was extracted by the extracting solution of 0.03 N ammonium fluoride (NH_4F, Purity min 95%; M = 37.04 g/mol) and 0.1 N hydrochloric acids (HCl) solution, and ICP-OES was used to analyze the concentration. One M KCl was used to extract soil exchangeable Al [41], and afterwards, as determined by the ICP-OES, the extractable Fe and Mn were extracted by Mehlich No. 1 double acid, and an atomic absorption spectrometer (AAS) was used to determine the concentration [42]. All the analyses were conducted in quadruplicates.

2.2. Collection and Characterization of Biochar

The rice husk biochar (RHB) used in this study was collected from Sendi Enterprise (Sungai Burong, Selangor, Malaysia), and was pyrolyzed at 300 °C, and oil palm empty fruit bunches biochar (EFBB) was purchased from Parkar Go Green Sdn Bhd (Sri Kenari, Kajang, Malaysia), in medium thermal condition at 300–350 °C, through pyrolysis. Some physical and chemical properties of biochar are shown in Supplementary Table S1. A pH meter was used to determine the pH of the biochar at the ratio of 1:2.5 of the air-dried biochar sample and distilled water, respectively [43]. The TrueMac CNS analyzer was used to determine the total C and total N of the biochar, and CEC and base cations were determined by 1 M NH_4OAc buffered solution at pH 7 [41]. Atomic absorption spectrophotometry (AAS, PerkinElmer, Inc., Waltham, MA, USA) was used to determine the extraction of K, Ca, and Mg. The dry ash method followed by ICP-OES was used to analyze the total P of biochar [44]. The ash content of biochar was measured by the dry combustion method, and the percentage was calculated as:

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

where the weight of ash was the weight of biochar before it is heated, and the dry mass of biochar was the weight of biochar after it was heated. Both types of biochar were used at 5.0 g in a crucible and heated at 500 °C for 8 h [45]; at room temperature, the crucible was cooled and then reweighted, followed by calculating the above equation.

Table 1. Selected physical and chemical properties of experimental soil.

Properties	Soil
Textural Class	Sandy clay loam
% Sand	69.27
% Silt	2.28
% Clay	28.44
pH	4.61 ± 0.017
CEC ($cmol_c\ kg^{-1}$)	5.77 ± 0.013
Total C (%)	1.41 ± 0.009
Total N (%)	0.07 ± 0.004
Total S (%)	0.05 ± 0.004
Exchangeable K ($cmol_c\ kg^{-1}$)	0.22 ± 0.016
Exchangeable Ca ($cmol_c\ kg^{-1}$)	1.46 ± 0.013
Exchangeable Mg ($cmol_c\ kg^{-1}$)	0.42 ± 0.018
Exchangeable Al ($cmol_c\ kg^{-1}$)	2.49 ± 0.021
Available P (mg kg^{-1})	5.21 ± 0.019
Extractable Fe (mg kg^{-1})	99.44 ± 1.48
Extractable Mn (mg kg^{-1})	4.64 ± 0.422
NH_4-N (mg kg^{-1})	16.41 ± 0.50
NO_3-N (mg kg^{-1})	11.37 ± 0.86

The column represents the mean values ± standard error.

2.3. Experimental Design and Treatment

An experiment was conducted in a randomized complete block design (RCBD) with nine treatments and four replications. The detailed treatments were as follows:

T_1 = No treatments and fertilizer (Control)
T_2 = Recommended rate of NPK (t ha^{-1})
T_3 = 100% dolomitic limestone
T_4 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar
T_5 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar
T_6 = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar
T_7 = 100% dolomitic limestone + 10 t ha^{-1} oil palm empty fruit bunches biochar
T_8 = 75% dolomitic limestone + 10 t ha^{-1} oil palm empty fruit bunches biochar
T_9 = 75% dolomitic limestone + 15 t ha^{-1} oil palm empty fruit bunches biochar

2.4. Pot Trial

A pot experiment was carried out in a glasshouse at the Faculty of Agriculture, Universiti Putra Malaysia, Selangor (2°98′36.6′ N latitude; 101°73′81.9′ E longitude). Hybrid sweet corn was used as a test crop in the study. The pots were 38 cm in height, 30 cm in width, and 32 cm in diameter. Pots were filled with 20 kg of experimental soil, while the N, P, and K fertilizers were applied following the recommendation of Pedram [46]. Urea, triple superphosphate (TSP), and muriate of potash (MoP) were used at 140 kg ha^{-1} N, 100 kg ha^{-1} P_2O_5, and 120 kg ha^{-1} K_2O, respectively. Based on the recommended rates, urea, TSP, and Mop were applied at 2.17, 1.55, and 1.43 g. On the previous day of seed sowing, the full dose of P and K fertilizer was used as a basal dose, and N fertilizer was incorporated in two equal splits at 10 and 28 days after sowing (DAS). Biochar was applied in the pot at 71.42 g (10 t ha^{-1}) and 107.10 g (15 t ha^{-1}). Dolomitic limestone was applied at 66 g (100%) and 49.5 g (75%) based on the lime requirement test [47]. The RHB, EFBB, and dolomitic limestone were applied to the soil, mixed thoroughly, and moistened with water at 60% water-holding capacity 14 days before sowing the maize seeds. Before sowing, the maize seeds were soaked with water for 10 to 12 h for good germination. Three seeds were sown in each pot at 3–4 cm depth and, after seven days, thinned to one. The maize plants were observed and harvested at 75 DAS.

2.5. Measurement of Soil CO_2 Flux Emission

Soil CO_2 flux was measured with a portable LI-8100 automated soil CO_2 flux system (LI-COR Biosciences, Lincoln, NE, USA) on days 1, 2, 3, 4, 5, 6, 7, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, and 75. The polyvinyl chloride (PVC) pipe was 11.5 cm in height and 20 cm inner diameter, installed 7–8 cm into the soil in each pot one day before the first measurement. All the PVC collars were left in the soil until the end of the experiment. The soil around the external side of all PVC collars was firmly compacted to avoid gas leakage. The measurement of soil CO_2 flux was taken from 9.00 a.m. to 11.00 a.m. [48]. Cumulative soil CO_2 emission was calculated by linear interpolation [49].

2.6. Biomass Production Measurement and Nutrient Analysis in Plant and Soil

After harvesting the maize, the plant was cut 0.1 m from the soil surface of each pot to analyze the plant biomass. After that, the stem and leaves were partitioned, washed with distilled water, and oven-dried at 60 °C until they reached constant weight. A measuring scale that measured plant height, root length, cob length, and cob diameter was measured by a vernier caliper scale. Fresh biomass, dry biomass, and cob were weighed with a digital weighing machine. The single dry ash method was used to extract P, K, Ca, and Mg of the stem and leaves of the plant [44], and the leachate was analyzed using AAS (AAS, PerkinElmer PinAAcle 900T, Waltham, MA, USA). The total N of the plant was determined by the TrueMac CNS analyzer (LECO Corporation, St. Joseph, MI, USA). The plant nutrient uptake was calculated using the following formula [50]:

$$\text{Uptake} = \text{Total nutrient concentration} \times \text{biomass}, \tag{2}$$

where the nutrient concentration was found using AAS, and the biomass was the plant's respective dry weight. After harvesting the maize plant, the soil sample was taken and ground to pass through a 0.2 mm sieve for analysis of soil pH, base cations (K, Ca, and Mg), available P, exchangeable Al, extractable Fe, and Mn, as described in a previously mentioned procedure.

2.7. Percent Relative Data

The relative data of the values were expressed as percentages, relative to control for each element recommended by Ashraf et al. [51],

$$\text{Relative data } (\%) = \frac{\text{Treatment value} - \text{ control value}}{\text{control value}} \times 100 \tag{3}$$

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

2.8. Statistical Analysis

One-way analysis of variance (ANOVA) was performed to identify the treatment effects, while Tukey's Honestly Significant Difference (HSD) test was used to separate the means using Statistical Analysis System Software, SAS, version 9.4 ($p \leq 0.05$). A repeated measure ANOVA was used on the CO_2 to determine the overall effects of treatments. In addition, we performed a paired *t*-test to identify whether there was any significant difference between the two biochars. 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 Nutrients of the Post-Harvest Soil

At the end of the experiment, soil pH increased significantly for different treatments compared to the control treatment ($p \leq 0.05$, Table 2). The highest pH value was 6.16 from T_4 (100% lime + 10 t ha^{-1} RHB), followed by T_5 (75% lime + 10 t ha^{-1} RHB) and T_6 (75% lime + 15 t ha^{-1} RHB), and the lowest soil pH was shown by the non-amendment treatment T_1 (control). The maximum soil pH increased with treatment T_4 (100% lime + 10 t ha^{-1} RHB) by 1.62 pH units (6.16–4.54) compared to the control.

The available P of the post-harvest soil significantly increased with the biochar- and lime-treated soil compared to the unamended soil, as presented in Table 2. The highest soil available P was 12.58 mg kg^{-1} from T_6 (75% lime + 15 t ha^{-1} RHB), followed by T_5 (75% lime + 10 t ha^{-1} RHB). The lowest available P was shown by the non-amendment treatment T_1 (control). The highest available P was increased by 136.91% from T_6 (75% lime + 15 t ha^{-1} RHB) compared to the control treatment.

Results showing the effects of biochar and lime addition on soil exchangeable K are presented in Table 2. Compared to the control treatment, the combined application of these amendments significantly increased the exchangeable K. The maximum (1.42 cmol$_c$ kg^{-1}) exchangeable K content was observed from 75% lime + 10 t ha^{-1} RHB (T_5), followed by 100% lime + 10 t ha^{-1} RHB (T_4) from the post-harvest soil and minimum exchangeable K (0.27 cmol$_c$ kg^{-1}) found from the unamended soil, T_1. Although, there were no statistical differences among T_4, T_5, T_6, T_7, and T_9. The maximum exchangeable K was increased by 425.93% from T_5 (100% lime + 10 t ha^{-1} RHB) compared to the control. There was a significant effect of RHB, EFBB, and dolomitic limestone addition on post-harvest soil of exchangeable Ca, as shown in Table 2. Soil exchangeable Ca was highest (4.21 cmol$_c$ kg^{-1}) in soil amended with 100% lime + 10 t ha^{-1} RHB (T_4), followed by T_6 (4.07 cmol$_c$ kg^{-1}) and T_5 (4.06 cmol$_c$ kg^{-1}). The lowest soil exchangeable Ca was found in the control, T_1 (1.41 cmol$_c$ kg^{-1}), followed by T_2 (1.54 cmol$_c$ kg^{-1}) and T_3 (3.23 cmol$_c$ kg^{-1}). The highest exchangeable Ca was increased by 198.58% from T_4 (100% lime + 10 t ha^{-1} RHB) compared to the control. Application of organic materials with lime significantly ($p \leq 0.05$) changed exchangeable Mg in post-harvest soil (Table 2). The highest exchangeable Mg (1.61 cmol$_c$ kg^{-1}) with the biochar and lime amendment was observed from T_7 (100% lime + 10 t ha^{-1} EFBB), but no statistical significance was observed between T_7 and T_4. The lowest (0.41 cmol$_c$ kg^{-1}) was found from the control treatment. The relative data of exchangeable Mg were increased by 292.68% from T_7 (100% lime + 10 t ha^{-1} EFBB) compared to the control.

The significant changes of treatment combinations with RHB, EFBB, and dolomitic limestone on exchangeable Al are shown in Table 2. The lowest value (0.08 cmol$_c$ kg^{-1}) was observed from T_5 (75% lime + 10 t ha^{-1} RHB), followed by T_4 (100% lime + 10 t ha^{-1} RHB) and T_9 (75% lime + 15 t ha^{-1} EFBB), and the highest value (2.49 cmol$_c$ kg^{-1}) was found from control treatment of the post-harvest soil. There was the same statistical difference of exchangeable Al between T_4 and T_5. The exchangeable Al was maximally decreased by 96.79% from T_5 (75% lime + 10 t ha^{-1} RHB) compared to the control.

The significant effect of dolomitic limestone and different types of biochar on extractable Fe of post-harvest soil is presented in Table 2. The extractable Fe significantly decreased due to lime and biochar treatments. The lowest value (45.93 mg kg^{-1}) of Fe was found from T_6 (75% lime + 15 t ha^{-1} RHB), and this value decreased by 41.77% compared to the control treatment. Although, T_4, T_5, and T_6 showed the same statistical value. The highest value (78.88 mg kg^{-1}) was revealed by the control (T_1) treatment.

Table 2. Effect of treatments on nutrients of the post-harvest soil.

Treatment	pH	P (mg kg^{-1})	K (cmol$_c$ kg^{-1})	Ca (cmol$_c$ kg^{-1})	Mg (cmol$_c$ kg^{-1})	Al (cmol$_c$ kg^{-1})	Fe (mg kg^{-1})	Mn (mg kg^{-1})
T_1	4.54 ^{f} ± 0.02	5.31 ^{f} ± 0.04	0.27 ^{e} ± 0.02	1.41 ^{g} ± 0.02	0.41 ^{e} ± 0.01	2.49 ^{a} ± 0.02	78.88 ^{a} ± 1.67	4.58 ^{e} ± 0.01
T_2	4.58 ^{f} ± 0.03	5.66 ^{e} ± 0.04	0.42 ^{d} ± 0.03	1.54 ^{f} ± 0.02	0.44 ^{e} ± 0.01	2.45 ^{a} ± 0.02	78.71 ^{a} ± 1.57	4.66 ^{e} ± 0.02
T_3	5.50 ^{e} ± 0.02	5.93 ^{e} ± 0.03	0.56 ^{c} ± 0.02	3.23 ^{e} ± 0.02	1.28 ^{d} ± 0.02	0.84 ^{b} ± 0.01	54.73 ^{c} ± 1.63	5.06 ^{d} ± 0.02
T_4	6.16 ^{a} ± 0.01	11.03 ^{b} ± 0.06	1.41 ^{a} ± 0.03	4.21 ^{a} ± 0.02	1.55 ^{ab} ± 0.01	0.13 ^{ef} ± 0.01	46.10 ^{d} ± 1.15	6.05 ^{a} ± 0.03
T_5	6.11 ^{ab} ± 0.02	11.04 ^{b} ± 0.07	1.42 ^{a} ± 0.02	4.06 ^{bc} ± 0.02	1.51 ^{bc} ± 0.02	0.08 ^{f} ± 0.01	47.48 ^{d} ± 1.74	6.08 ^{a} ± 0.03
T_6	6.06 ^{bc} ± 0.02	12.58 ^{a} ± 0.11	1.37 ^{ab} ± 0.02	4.07 ^{b} ± 0.02	1.47 ^{c} ± 0.03	0.17 ^{e} ± 0.01	45.93 ^{d} ± 1.20	6.18 ^{a} ± 0.02
T_7	6.03 ^{bc} ± 0.02	7.75 ^{d} ± 0.04	1.30 ^{ab} ± 0.03	4.00 ^{bc} ± 0.02	1.61 ^{a} ± 0.01	0.25 ^{d} ± 0.01	57.24 ^{bc} ± 1.39	5.46 ^{c} ± 0.03
T_8	5.71 ^{d} ± 0.02	8.01 ^{d} ± 0.04	1.26 ^{b} ± 0.02	3.84 ^{d} ± 0.02	1.46 ^{c} ± 0.01	0.34 ^{c} ± 0.01	63.36 ^{b} ± 0.78	5.53 ^{c} ± 0.03
T_9	6.00 ^{c} ± 0.01	8.82 ^{c} ± 0.06	1.33 ^{ab} ± 0.02	3.97 ^{c} ± 0.03	1.50 ^{bc} ± 0.02	0.16 ^{e} ± 0.01	54.37 ^{c} ± 0.99	5.79 ^{b} ± 0.04
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 columns represent 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, T_4 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar, T_5 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar, T_6 = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar, T_7 = 100% dolomitic limestone + 10 t ha^{-1} oil palm empty fruit bunches biochar, T_8 = 75% dolomitic limestone + 10 t ha^{-1} oil palm empty fruit bunches biochar, T_9 = 75% dolomitic limestone + 15 t ha^{-1} oil palm empty fruit bunches biochar.

Results regarding extractable Mn of soil treated with different types of biochar with lime are presented in Table 2. The results indicated that the extractable Mn significantly increased upon the application of biochar- and lime-amended soil. Soil extractable Mn was highest (6.18 mg kg^{-1}) in soil amended with 75% lime + 15 t ha^{-1} RHB (T_6), followed by T_5 (6.08 mg kg^{-1}) and T_4 (6.05 mg kg^{-1}). It is noted that there were no significant differences among these three treatments. The lowest soil extractable Mn was found from control, T_1 (4.58 mg kg^{-1}), followed by T_2 (4.66 mg kg^{-1}) and T_3 (5.06 mg kg^{-1}). The exchangeable Mn was 34.93% higher from T_6 (75% lime + 15 t ha^{-1} RHB) than that of the control treatment. RHB had a better effect than EFBB on soil pH, available P, exchangeable K, Ca, Al, Fe, and Mn, but not Mg (Supplementary Table S2).

3.2. Effect of Treatments on Maize Plant Growth and Yield Contributing Characteristics

There were significant differences ($p \leq 0.05$) in plant height, stem diameter, root length, and dry biomass of maize when applying RHB, EFBB, and lime at 75 DAS (Table 3). The plant height of maize ranged from 172.65 to 228.11 cm, which was not significantly different in T_4 to T_9. The plant height of T_1 (control) was significantly lower compared with all other treatments, and the longest plant height was observed from T_4 (100% lime + 10 t ha^{-1} RHB). RHB had a better effect on root length, plant biomass, grain yield, and also N, P, K, Ca, and Mg nutrients' uptake (Supplementary Table S3) compared to EFBB.

Results showed a significant change in the stem diameter and root length of maize grown on soils amended with RHB and EFBB with combined application of lime, compared with the untreated soil (Table 3). The highest stem diameter (2.77 cm) and root length (89.05 cm) were found from T_6 (75% lime + 15 t ha^{-1} RHB) and T_5 (75% lime + 10 t ha^{-1} RHB) correspondingly, but statistically significant differences were not found among T_4 up to T_9 in regards to root length. The control treatment (T_1) showed the lowest values of stem diameter (1.50 cm) and root length (49.44 cm). The dry biomass of the maize plants at 75 DAS ranged from 24.45 to 90.90 g plant^{-1} (Table 3). This was a 272.11% increase compared to that of the control treatment.

The maize cob length, fresh cob weight, number of grains per cob, and yield were significantly increased (Table 3) by treatments with organic amendments (T_4 to T_9) compared to that of untreated soil (T_1 to T_3). The highest cob length (23.75 cm), fresh cob weight (292.75 g), and number of grains per cob (620.75) were shown by T_6 (75% lime + 15 t ha^{-1} RHB), and maximum yield was shown by T_4, although T_3 to T_9 showed the same statistical difference in terms of cob length and T_4 to T_6 showed the same statistical difference in terms of fresh cob weight and number of grains per cob and yield.

3.3. Effect of Treatments on Maize Plant Nutrients' Concentration and Total Uptake

Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) concentration (Table 4) and total uptake (Table 5) by maize plant were also significantly ($p \leq 0.05$) influenced by RHB and EFBB with combined application of lime. The highest values of N (2232.22 mg plant^{-1}), P (265.71 mg plant^{-1}), K (2133.19 mg plant^{-1}), Ca (498.33 mg plant^{-1}), and Mg (277.57 mg plant^{-1}) uptake were produced by T_6 (75% lime + 15 t ha^{-1} RHB) compared to the control treatment. There was statistically lower nutrient uptake from T_1, T_2, and T_3 than from biochar- and lime-treated soil (T_4 to T_9).

Table 3. Effect of treatments on maize plant growth characteristics.

Treatment	Plant Height (cm)	Stem Diameter (cm)	Root Length (cm)	Dry Biomass (g)	Cob Length (cm)	Fresh Cob Weight (g)	No. of Grains per Cob	Cob Yield (t ha^{-1})
T_1	172.65 ^{c} ± 1.95	1.50 ^{f} ± 0.06	49.44 ^{c} ± 2.44	24.45 ± 1.88	17.25 ^{b} ± 0.39	164.75 ^{e} ± 2.78	312.25 ^{f} ± 6.61	8.79 ^{e} ± 0.148
T_2	184.08 ^{bc} ± 2.18	1.98 ^{e} ± 0.03	55.55 ^{c} ± 2.03	41.50 ^{d} ± 1.74	17.68 ^{b} ± 0.45	176.25 ^{e} ± 1.75	356.25 ^{e} ± 7.66	9.40 ^{e} ± 0.094
T_3	193.75 ^{b} ± 3.33	2.26 ^{d} ± 0.02	63.11 ^{bc} ± 3.14	58.79 ^{c} ± 0.57	22.95 ^{a} ± 0.41	263.75 ^{d} ± 2.66	458.25 ^{d} ± 7.22	14.07 ^{d} ± 0.142
T_4	228.11 ^{a} ± 1.61	2.62 ^{b} ± 0.02	80.41 ^{a} ± 4.00	86.63 ^{a} ± 2.37	23.35 ^{a} ± 0.39	283.75 ^{ab} ± 2.66	607.25 ^{a} ± 4.80	15.14 ^{ab} ± 0.141
T_5	227.44 ^{a} ± 3.75	2.52 ^{bc} ± 0.03	89.05 ^{a} ± 2.13	90.90 ^{a} ± 2.57	23.08 ^{a} ± 0.43	285.25 ^{ab} ± 2.66	614.25 ^{a} ± 3.57	15.21 ^{ab} ± 0.142
T_6	226.83 ^{a} ± 2.26	2.77 ^{a} ± 0.02	85.56 ^{a} ± 3.66	87.31 ^{a} ± 1.60	23.75 ^{a} ± 0.25	292.75 ^{a} ± 2.02	620.75 ^{a} ± 3.59	15.61 ^{a} ± 0.107
T_7	218.23 ^{a} ± 1.96	2.55 ^{bc} ± 0.02	79.61 ^{a} ± 4.09	74.04 ^{b} ± 1.04	22.98 ^{a} ± 0.30	276.00 ^{bc} ± 2.08	538.75 ^{c} ± 4.11	14.72 ^{bc} ± 0.112
T_8	221.29 ^{a} ± 3.93	2.45 ^{c} ± 0.03	77.66 ^{ab} ± 3.45	79.27 ^{b} ± 1.36	22.20 ^{a} ± 0.29	266.00 ^{cd} ± 2.35	481.00 ^{d} ± 5.82	14.19 ^{cd} ± 0.124
T_9	217.26 ^{a} ± 1.78	2.59 ^{b} ± 0.02	79.03 ^{a} ± 3.13	72.85 ^{b} ± 1.02	22.83 ^{a} ± 0.48	283.75 ^{ab} ± 2.43	573.00 ^{b} ± 4.26	15.14 ^{ab} ± 0.130

Means within the same column followed by the same letter are not significantly different at $p \leq 0.05$ (Tukey's HSD test). The columns represent 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, T_4 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar, T_5 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar, T_6 = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar, T_7 = 100% dolomitic limestone + 10 t ha^{-1} oil palm empty fruit bunches biochar, T_8 = 75% dolomitic limestone + 10 t ha^{-1} oil palm empty fruit bunches biochar, T_9 = 75% dolomitic limestone + 15 t ha^{-1} oil palm empty fruit bunches biochar.

Table 4. Effect of treatments on maize plant nutrients' concentration.

Treatment	N (%)	P (%)	K (%)	Ca (%)	Mg (%)
T_1	$0.75^{i} \pm 0.013$	$0.138^{ef} \pm 0.009$	$0.32^{i} \pm 0.004$	$0.10^{f} \pm 0.008$	$0.053^{f} \pm 0.005$
T_2	$1.24^{f} \pm 0.011$	$0.160^{e} \pm 0.009$	$0.83^{h} \pm 0.008$	$0.12^{ef} \pm 0.005$	$0.060^{ef} \pm 0.004$
T_3	$1.03^{g} \pm 0.006$	$0.123^{f} \pm 0.005$	$0.98^{g} \pm 0.009$	$0.13^{e} \pm 0.005$	$0.070^{e} \pm 0.004$
T_4	$2.25^{b} \pm 0.006$	$0.270^{b} \pm 0.004$	$2.20^{b} \pm 0.005$	$0.39^{b} \pm 0.004$	$0.265^{c} \pm 0.003$
T_5	$2.14^{c} \pm 0.004$	$0.243^{c} \pm 0.003$	$1.88^{d} \pm 0.005$	$0.37^{b} \pm 0.004$	$0.288^{b} \pm 0.003$
T_6	$2.56^{a} \pm 0.003$	$0.305^{a} \pm 0.003$	$2.44^{a} \pm 0.005$	$0.57^{a} \pm 0.004$	$0.318^{a} \pm 0.003$
T_7	$2.07^{d} \pm 0.005$	$0.263^{bc} \pm 0.005$	$1.84^{e} \pm 0.006$	$0.21^{d} \pm 0.003$	$0.243^{d} \pm 0.003$
T_8	$2.14^{c} \pm 0.004$	$0.208^{d} \pm 0.003$	$1.60^{f} \pm 0.004$	$0.24^{c} \pm 0.003$	$0.248^{d} \pm 0.003$
T_9	$1.85^{e} \pm 0.005$	$0.288^{ab} \pm 0.005$	$1.97^{c} \pm 0.006$	$0.23^{cd} \pm 0.003$	$0.253^{cd} \pm 0.003$

Means within the same column followed by the same letter are not significantly different at $p \leq 0.05$ (Tukey's HSD test). The columns represent 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, T_4 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar, T_5 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar, T_6 = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar, T_7 = 100% dolomitic limestone + 10 t ha^{-1} oil palm empty fruit bunches biochar, T_8 = 75% dolomitic limestone + 10 t ha^{-1} oil palm empty fruit bunches biochar, T_9 = 75% dolomitic limestone + 15 t ha^{-1} oil palm empty fruit bunches biochar.

Table 5. Effect of treatments on maize 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	$182.50^{i} \pm 3.36$	$34.04^{g} \pm 1.42$	$77.93^{i} \pm 1.22$	$24.73^{i} \pm 0.98$	$13.02^{i} \pm 0.75$
T_2	$514.56^{h} \pm 4.30$	$66.41^{f} \pm 2.58$	$344.56^{h} \pm 1.21$	$49.88^{h} \pm 1.09$	$26.12^{h} \pm 0.73$
T_3	$604.24^{g} \pm 3.12$	$73.12^{f} \pm 1.78$	$576.033^{g} \pm 0.99$	$77.81^{g} \pm 1.05$	$40.96^{g} \pm 0.74$
T_4	$1905.44^{c} \pm 5.43$	$227.16^{b} \pm 2.27$	$1866.50^{b} \pm 1.20$	$331.58^{c} \pm 0.82$	223.61 ± 0.98
T_5	$1945.95^{b} \pm 3.18$	$220.87^{b} \pm 1.85$	$1704.59^{c} \pm 0.78$	$337.00^{b} \pm 0.85$	$261.98^{b} \pm 0.88$
T_6	$2232.22^{a} \pm 2.82$	$265.71^{a} \pm 1.72$	$2133.19^{a} \pm 1.56$	$498.33^{a} \pm 0.92$	$277.57^{a} \pm 0.43$
T_7	$1531.46^{e} \pm 3.95$	$194.78^{d} \pm 1.87$	$1353.03^{e} \pm 1.28$	$151.24^{f} \pm 0.87$	$178.41^{f} \pm 0.59$
T_8	$1695.06^{d} \pm 3.38$	$164.93^{e} \pm 1.68$	$1265.99^{f} \pm 1.13$	$187.80^{d} \pm 0.87$	$196.78^{d} \pm 1.06$
T_9	$1345.91^{f} \pm 3.48$	$208.08^{c} \pm 2.04$	$1426.88^{d} \pm 1.26$	$163.42^{e} \pm 1.09$	$183.00^{e} \pm 0.86$

Means within the same column followed by the same letter are not significantly different at $p \leq 0.05$ (Tukey's HSD test). The columns represent 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, T_4 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar, T_5 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar, T_6 = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar, T_7 = 100% dolomitic limestone + 10 t ha^{-1} oil palm empty fruit bunches biochar, T_8 = 75% dolomitic limestone + 10 t ha^{-1} oil palm empty fruit bunches biochar, T_9 = 75% dolomitic limestone + 15 t ha^{-1} oil palm empty fruit bunches biochar.

3.4. Effect of Treatments on Soil CO_2 Emission in Maize Field

As shown in Figure 1, soil CO_2 emission was significantly affected by biochar and lime. The CO_2 flux emission was relatively higher by using organic amendment and lime compared to untreated soil. The average CO_2 emission rate across all measured dates was significant among the treatments (Figure 2). The combined application of biochar and lime increased the CO_2 rate from the soil. The highest average CO_2 emission was found in T_7 and T_9. The lowest average CO_2 emission was observed in T_1 and T_2. The effect of biochar and lime on the cumulative CO_2 emission from the soil is delineated in Figure 3. The CO_2 flux sharply increased on day 4 from all the treatments except T_1 and T_2; after that, it decreased. Although, there were no statistically significant differences in cumulative CO_2 emission among T_3, T_7, T_8, and T_9. No significant differences were observed in the cumulative CO_2 emission of T_4, T_5, and T_6. The lowest cumulative CO_2 emission (60.95 μmol CO_2 m^{-2}) was found from the unamended treatment (T_1). In contrast, the highest magnitude (19.37 μmol CO_2 m^{-2} s^{-1}) and cumulative CO_2 flux (188.38 μmol CO_2 m^{-2}) were noted from T_7 (100% lime + 10 t ha^{-1} EFBB), followed by T_9 (179.15 μmol CO_2 m^{-2}) and T_8 (173.72 μmol CO_2 m^{-2}). A moderate amount of CO_2 emission was noticed from all the treatments from 15 DAS, and it continued up to the last measurement. The Figure 3 shows that the cumulative CO_2 emission was higher from EFBB

(T_7, T_8, and T_9) than from RHB (T_4, T_5, and T_6). The cumulative CO_2 emission significantly increased by 209.43% and 146.69% from EFBB and RHB respectively, compared to the control. The order of the cumulative CO_2 emission was $T_7 > T_9 > T_8 > T_3 > T_4 > T_5 > T_6 > T_2 > T_1$. Note that the higher the amount of lime used, the higher the emission of CO_2 from soil.

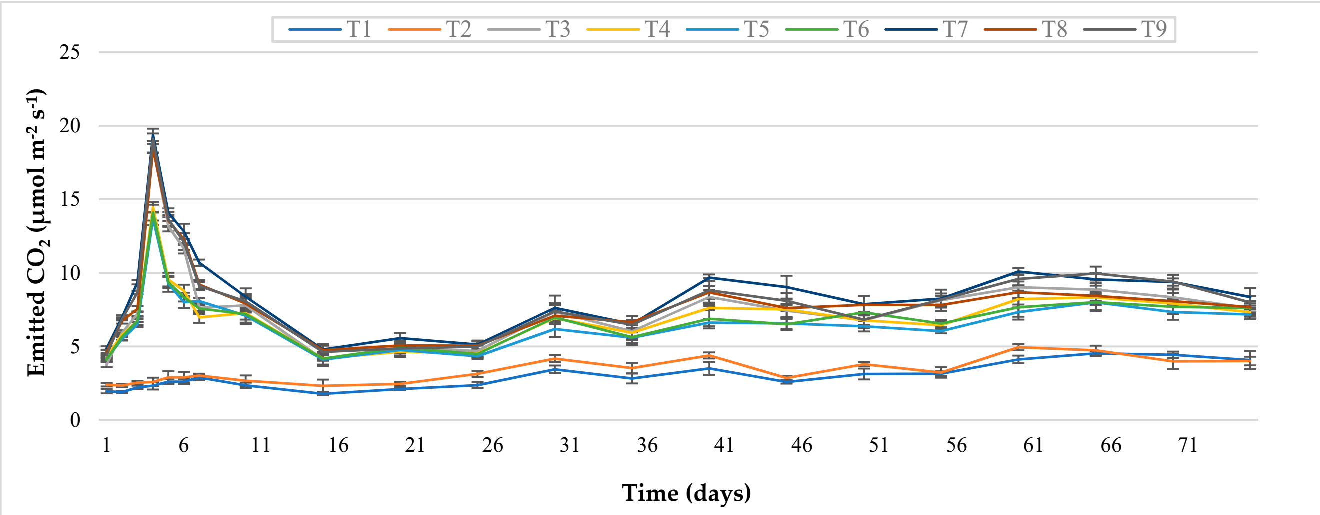

Figure 1. Effect of treatments on soil CO_2 flux emission in a maize field. Bar errors show ± standard error of four replications.

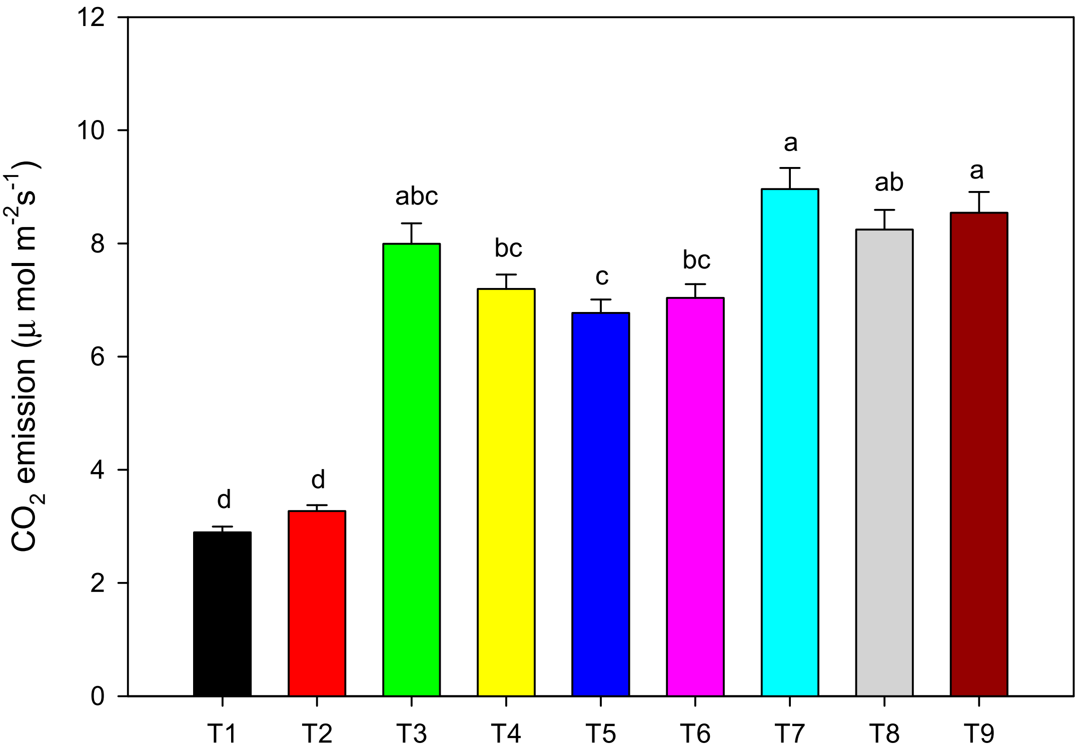

Figure 2. Average CO_2 emission rate across all measured dates. Same letters are not significantly different above bar at $p \leq 0.05$. T_1 = No treatments and fertilizer (Control), T_2 = Recommended rate of NPK (t ha^{-1}), T_3 = 100% dolomitic limestone, T_4 = 100% dolomitic limestone + 10 t ha^{-1} rice husk biochar, T_5 = 75% dolomitic limestone + 10 t ha^{-1} rice husk biochar, T_6 = 75% dolomitic limestone + 15 t ha^{-1} rice husk biochar, T_7 = 100% dolomitic limestone + 10 t ha^{-1} oil palm empty fruit bunches biochar, T_8 = 75% dolomitic limestone + 10 t ha^{-1} oil palm empty fruit bunches biochar, T_9 = 75% dolomitic limestone + 15 t ha^{-1} oil palm empty fruit bunches biochar.

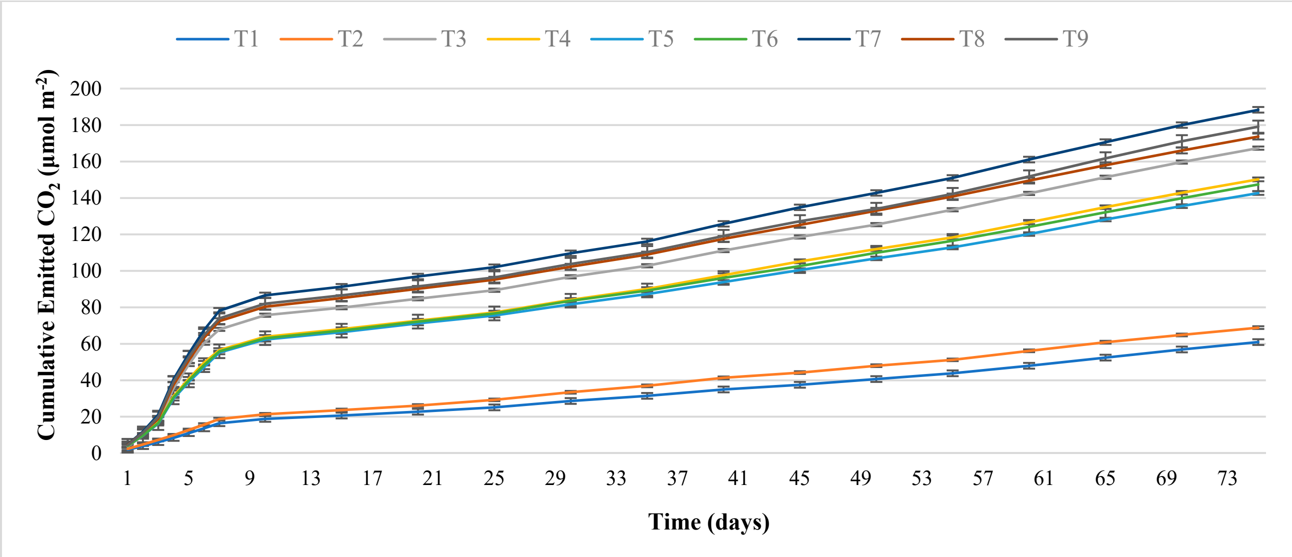

Figure 3. Effect of treatments on cumulative soil CO_2 flux emission. Bar errors show ± standard error of three replications.

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

Pearson's correlation analysis was performed significantly to determine the relationship between plant parameters, nutrient uptake, soil pH, and nutrients (Table 6). CO_2 flux was correlated with exchangeable K, Ca, Mg, Fe, and grain yield (r = 0.05, 0.09, 0.02, 0.33, and 0.20, respectively). Grain yield was correlated significantly and positively with available P, exchangeable Ca, plant biomass, and root length (r = 0.09, 0.31, 0.44, and 0.36, respectively.) Exchangeable Al was correlated significantly and positively with exchangeable K (r = 0.060). The results in Figure 4 showed that biomass production significantly increased with the increased soil pH, soil available P, and decreased Al concentration (r2 = 0.87, 0.88, and 0.81, respectively; $p < 0.01$).

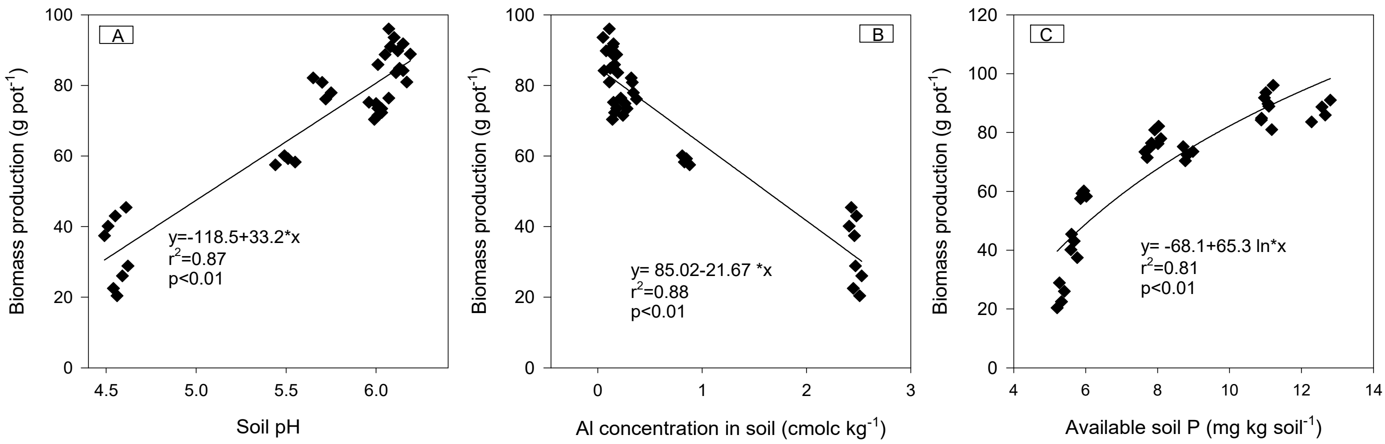

Figure 4. Relationship between soil pH and biomass production (**A**), exchangeable Al concentration in soil and biomass production (**B**), and available soil P and biomass production (**C**). The asterisk stands for multiplication sign.

Table 6. The correlation coefficients among maize plant parameters, nutrient uptake, soil pH, and nutrients (all relations were significant).

Parameters	pH	Av. P	Exch. K	Exch. Ca	Exch. Mg	Exch. Al	Exct. Fe	Exct. Mn	Plant Biomass	Root Length	Grain Yield	N Uptake	P Uptake	K Uptake	Ca Uptake	Mg Uptake	CO_2
pH																	
Av. P	−0.10																
Exch. K	0.02	0.06															
Exch. Ca	0.20	0.05	0.25														
Ex. Mg	0.15	−0.05	−0.06	0.52													
Exch. Al	−0.18	−0.37	0.06	−0.14	−0.43												
Exct. Fe	−0.26	0.21	0.18	−0.12	−0.08	0.07											
Exct. Mn	−0.08	0.16	−0.02	0.37	−0.69	−0.42	−0.19										
Plant biomass	−0.14	0.08	0.36	−0.44	0.48	0.04	−0.14	0.40									
Root length	0.05	0.26	0.20	−0.02	0.16	0.33	−0.07	0.31	−0.16								
Grain yield	−0.03	0.09	−0.27	0.31	−0.40	−0.36	−0.08	−0.38	0.44	0.36							
N uptake	−0.22	−0.51	−0.08	0.46	−0.36	−0.22	0.14	−0.47	0.56	0.44	−0.32						
P uptake	0.07	−0.01	0.21	−0.22	−0.04	0.00	−0.16	−0.29	−0.03	0.40	0.00	−0.36					
K uptake	0.17	0.53	0.12	0.01	0.21	0.39	−0.01	0.39	−0.23	−0.59	0.16	0.73	0.69				
Ca uptake	0.01	0.77	−0.36	−0.20	0.17	0.38	−0.34	−0.03	−0.13	−0.13	0.10	0.47	−0.16	−0.19			
Mg uptake	0.11	0.16	0.34	−0.36	0.19	−0.25	0.20	0.35	−0.43	−0.22	0.08	0.70	0.44	−0.54	0.08		
CO_2	−0.26	−0.80	0.05	0.09	0.02	−0.50	0.33	0.03	−0.08	0.20	0.20	−0.33	0.15	0.37	0.62	−0.08	

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.

4. Discussion

4.1. Biochar and Lime Treatment Affects Soil Properties

After soil application of different treatments, soil pH changed significantly, with the highest soil pH ~ 6.16 (Table 2) in T_4 (100% dolomitic limestone + 10 t ha^{-1} RHB), while across lime treatments, soil pH was significantly higher in the rice husk biochar than the empty fruit branch biochar (Supplementary Table S1). These results suggest that rice husk biochar was more effective in neutralizing soil pH. We believe that the neutralization mostly occurred with its larger basic cation addition since the total basic content was higher in the RHB than the EFBB [52,53]. As the biochar is alkaline in nature, it releases OH^- by its basic cations (Ca^{2+}, K^+, and Mg^{2+}) during the hydrolysis process, that may increase soil pH [54]. Although biochar's surface functional groups (i.e., CEC) could contribute to buffering soil pH, it seems that it was surpassed by basic cation addition because the CEC of RHB was slightly lower than EFBB (48 vs. 57 cmol kg biochar^{-1}).

Application of lime and biochar could increase the availability of soil P. In this study, the highest available P (12.58 mg kg^{-1}) was observed from T_6 (75% lime + 15 t ha^{-1} RHB), a 136.91% increase compared to the control. Moreover, the available soil P was also higher in the pots receiving RHB than EFBB. The availability of P in the soil may have increased due to an increased soil pH, while a relatively larger total P in the RHB would have also contributed to the soil P, because the total P in RHB and EFBB was around 3100 and 1900 mg kg^{-1}, respectively. In acid soils, the competitive interactions between soil minerals (Fe/Al hydro-oxides) and negatively charged biochar could increase the availability of soil P [55,56]. This mechanism is less important for this study since freshly prepared biochars with larger particle sizes were applied. Our result was in line with Panhwar et al. [57], where they found 99.82% increased available P using biochar and bio-fertilizer.

The application of the amendments positively influenced the K contents of the studied soil (Table 2). The highest exchangeable K (1.42 cmol$_c$ kg^{-1}) was found from T_5, while it was relatively higher in the RHB than the EFBB. We believe this increased K concentration in the soil resulted from the applied K with the biochar's ash. Many researchers have also reported similar results [32,58,59]. For instance, in tropical acid soil, soil exchangeable K increased using 5 t ha^{-1} chicken litter biochar [60]. In a study with Nepalese silty loam soil, Gautam et al. [61] reported that biochar contained a high amount of ash, which is responsible for increased exchangeable K, which stimulates for quick discharge of mineral nutrients to the soil [62] along with restraining the loss of K leaching [63].

The combined application of lime and biochar has increased Ca and Mg concentration in soils since both amendments contain Ca and Mg [50,64]. Our result showed that exchangeable Ca increased by 318%, which was similar to what was found by Rabileh et al. [50]. They found that exchangeable Ca increased by 411% using oil palm EFB biochar at 20 t ha^{-1} incorporation with dolomitic limestone. In the pyrolysis process, organic materials do not lose nutrient content such as Ca. Therefore, having a higher C content in biochar helps to increase exchangeable Ca in soil [65]. After applying the soil amendment, the exchangeable Mg of soil improved by using biochar and lime. The maximum soil exchangeable Mg (1.61 cmol$_c$ kg^{-1}) was shown from T_5. This result was similar to the findings of Masud et al. [66], where they found a significant increase of 226% exchangeable Mg by using poultry litter biochar, observed with maize crop. Biochar's ash holds high amounts of cations. After applying biochar, it increases soil exchangeable bases [67]. Besides, lime acts as a source of Mg content in the soil [7].

Lime and biochar treatments can reduce Al and Fe toxicity when applied in acidic soils. The exchangeable Al^{3+} decreased significantly ($p < 0.05$) with the biochar and lime addition in all soils except the control treatment. Our results were well-supported by those of Ch'ng et al. [17], where they explained that, by using chicken litter biochar, soil pH increased by 0.88 units, which caused the reduction of exchangeable Al. Biochar's ash contains oxides that react with H^+ and Al monomeric and cause the decrease of exchangeable Al [68]. The liming effect of biochar is also responsible for reduced exchangeable Al content [69]. They also explained the mechanism of reducing Al content, whereby a higher surface area of biochar serves as an absorbent of Al's negatively charged carboxylic and phenolic groups [17,69]. The current study results showed that the lowest extractable Fe of 45.93 mg kg^{-1} was observed from T_6 (75% lime + 15 t ha^{-1} RHB) of post-harvest soil. This result is in line with the study by Ch'ng et al. [17], where they found that by applying biochar, extractable Fe reduced by 44.49%. Biochar released organic acid, which is responsible for immobilization of Fe via chelation. Thus, Fe content decreased [17,70].

4.2. Combined Application of Biochar and Lime Increased Crop Performance

Co-application of lime and biochar increased biomass and grain production of maize, along with other yield contributing factors, while across all lime treatments, RHB was more effective than EFBB. We believe that soil pH is one of the most important factors contributing to yield enhancement [71], because soil pH was much higher in these treatments (~8.0) than in the control, while there was a significant correlation between biomass/grain production and soil pH (Figure 4). An increase in soil pH might have favored nutrient uptake, while the toxicity of Al and Fe was also reduced (Figure 4). Our PCA supported (Figure 5) this argument. The plant was also supported with greater nutrient availability through enhanced microbial activity, since the CO_2 release rate (a proxy of microbial activities) was higher in this treatment. According to Masulili et al. [70], reducing Al and Fe content due to increased soil pH may be an essential factor in improving plant growth. Our result is also in agreement with those of Pandit et al. [64]. Cob length, fresh cob weight, and number of grains per cob were significantly higher upon biochar with lime addition. The combination of organic amendments and lime (T_4 to T_9) is favorable because it enhances the nutrient release and decreases the nutrient (N, P, K) losses, which results in the higher yield of maize [72]. The reduction of soil acidity, Al and Fe toxicity, and plant nutrient availability enhanced the maize cob and yield parameters [17].

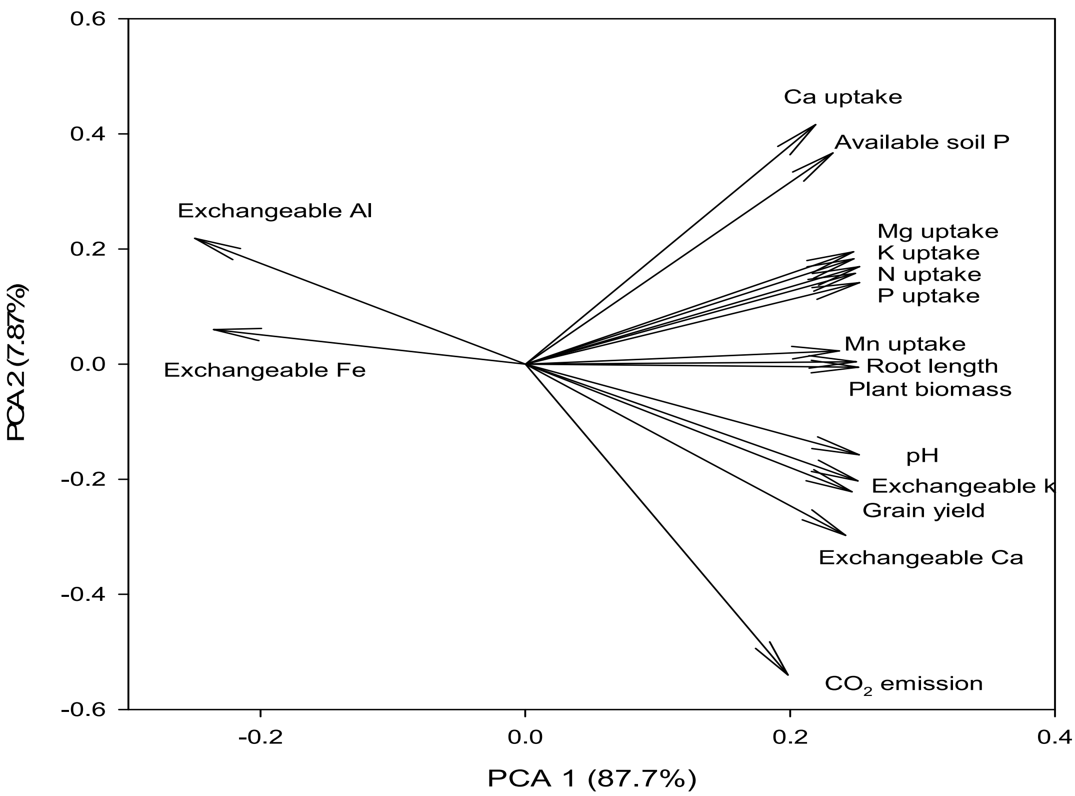

Figure 5. Principal component analysis (PCA) of different variables.

4.3. Combined Application of Biochar and Lime Increased Nutrient Uptake

The nutrient uptake was significantly higher in organic amended soil with lime application in maize plants compared with the treatments without the organic amendments (T_1, T_2, and T_3). Across lime treatments, the nutrient uptake was higher in RHB than EFBB. These results suggest that RHB was more effective in enhancing nutrient acquisition in maize. We believe that intrinsic nutrients in biochar and biochar-mediated changes in soil properties, especially changes in soil pH, contributed to the enhanced nutrient uptake. This is in tandem with the result of Ch'ng et al. [17], where they found increased nutrient uptake using biochar. In this study, the soil pH increased, resulting in decreased exchangeable Al and extractable Fe content due to biochar and lime application. This is favorable to reduce root Al toxicity, which might be the reason for better root growth of maize plants. As a result, the nutrient uptake in maize increased [17]. Our findings are in agreement with the result obtained by Van Zwieten et al. [73], who revealed the significant increase of N uptake in maize plants by applying biochar. They explained that the plant growth performance was increased by adding biochar because the bioavailability of nutrients increased in the soil and inspired a huge amount of nutrient uptake by plants.

4.4. Combined Application of Biochar and Lime Accelerated Soil CO_2 Emission

Soil amendment with organic matter and lime could affect soil respiration and CO_2 release from soil. In this pot experiment, it was observed that the soil CO_2 emission was influenced by the rate of dolomitic limestone, RHB, and EFBB. The higher CO_2 emission was noted with a higher rate of lime application. The larger CO_2 emission could have occurred due to an acceleration of microbial activities that resulted from the lime-mediated (pH increase) enhancement of nutrient availability [74]. Similar results are reported in the previous literature [75,76] and indirectly prompt microbial respiration [77].

Treatments with RHB with lime (T_4, T_5, and T_6) showed lower CO_2 flux from the soil than EFBB with lime (T_7, T_8, and T_9)-amended soil. These results might be due to less carbon content in RHB than EFBB [78], while the nature of organic C in the biochar (aromaticity) might also be responsible. Generally, RHB biochar is rich in ash, and thus, it is possible that the aromatic core is less condensed, suggesting that a part of the RHB carbon could have also mineralized [31]. Moreover, the available N in the EFBB was lower than the RHB, inferring a lower C:N ratio, resulting in slow mineralization of C. It is noted that biochar application may accelerate the CO_2 flux resulting from the volatile organic C presented in biochar [30]. However, the application of biochar may decelerate the emission of CO_2 flux by the sorption of labile carbon on the biochar's surface or into the biochar's pore space [79].

The result suggests that the lime-C was more decreased from the combined application of RHB with lime than the lime-only treatment (T_3), or co-application of EFBB and lime treatments (T_7, T_8, and T_9), which might be associated with the enhancement of lime-C sequestration into the soil [80]. It can be observed that in the initial stage of our study (on day 4), the CO_2 flux was highest from all the treated soils. This result is in line with the studies of Kong et al. [81] and Wang et al. [82]. The plausible mechanism was the decomposable soil organic carbon's rapid mineralization [83]. A significant alteration in daily CO_2 flux was due to the differences in density of roots or biomass, which causes the variation of labile soil organic carbon [84].

5. Conclusions

The combined application of biochar with lime changed soil properties and, thus, increased crop performance and nutrient uptake. Compared to the control, combined application of biochars with lime significantly buffered soil pH, with the largest increment shown in pots receiving rice husk biochar with 75% of the lime. Across all lime treatments, the pH was higher in pots receiving the rice husk biochar than the empty fruit branch biochar. These changes in soil pH also brought a significant change in soil nutrient availability. Availability of P, N, K, and other major cations increased in lime treatments, irrespective of biochar addition. As a result, the yield and yield contributing characteristics were shown to be greater in these treatments. Between the two biochars, RHB was relatively more effective in making these changes than EFBB. However, these treatments contributed to a greater carbon loss as CO_2 (209% and 145% higher with RHB and EFBB) from soil compared to the control. Our results suggest that the combined application of biochar could bring desirable changes in soil properties and increase crop performance, although these effects can be short-lived. Specifically, our findings advanced our understanding of function-specific biochar application in relation to its liming capacity, which is a pre-requisite for any large-scale soil amendment.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agronomy11071313/s1, Table S1: Some physico-chemical properties of RHB and EFBB, Table S2: Effect of different amendments on the nutrient concentration in acid soils (mean ± SE), Table S3: Effect of different amendments on the yield and nutrient concentration in maize plants (mean ± SE).

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