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Research Article

Examining the Effect of Combined Biochar and Lime Rates on Selected Soil Physicochemical Properties of Acid Soils in Gimbi District, Western Ethiopia

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The physicochemical properties of Western Ethiopian soils were negatively threatened with continuous cultivation crop lands. Soil amendments with biochar and lime facilitate and improve soil physicochemical properties directly and indirectly and enhance crop productivity. A field experiment was conducted in Gimbi District, Western Ethiopia, to examine the effects of combined coffee husk biochar (CHB) and soil test value-based lime (STV) rate application on physicochemical properties of acid soils. The trial included eight treatments, including control, 100% STV, 10 ton of CHB, and CHB + STV rates at 10 ton + 75%, 10 ton + 50%, 7.5 ton + 75%, 7.5 ton + 50%, and 5 ton + 75% ha^{-1}on two farm fields. The fields were laid out in RCBD with three replications. The treatments had substantial effects on $P < 0.05$) on the soil's physicochemical characteristics. The application of biochar and lime in Farms-1 and 2 reduced soil BD from 1.21 and 1.41 $g{\cdot}cm^{-3}$ to 1.15 and 1.12 to 0.90 and 0.97 $g{\cdot}cm^{-3}$, respectively. The soil pH level was increased from 5.10 to a range of 5.58 to 6.11 in Farm-1, and in Farm-2, from 4.64 to a range of 4.64 to 6.22 levels. The application of 10 ton of CHB + 75% of STV in Farms-1 and 2 resulted in the highest SOC of 7.44% and 7.68%, respectively. The application of 10 ton of CHB + 75% of STV in Farms-1 and 2 resulted in 4.86 $mg{\cdot}kg^{-1}$ and 6.96 $mg{\cdot}kg^{-1}$ available P, respectively. Available P was positively correlated with pH (0.62), SOC (0.63), and CEC (0.66). Exchangeable acidity was decreased from 4.64 $cmol_{(+)}kg^{-1}$ to a range from 3.19 to 0.98 $cmol_{(+)}kg^{-1}$ in Farm-1 and from 5.00 $cmol_{(+)}kg^{-1}$ to a range from 3.38 to 1.10 $cmol_{(+)}kg^{-1}$ in Farm-2. Therefore, amending the strongly acidic to very strongly acidic soil with a combined CHB (7.5 to 10 ton ha^{-1}) and STV (50 to 75% ha^{-1}) rates had improved the soil physicochemical properties of agricultural lands. To make a firm conclusion, research on soil analysis after crop harvest and economic benefit is required.

1. Introduction

In actuality, tropical soils have lower fertility and nutritional deficits. Several factors are contributing to the deterioration of soil attributes [1–4], while depletion of soil nutrients and a lack of suitable management to restore the soils are major obstacles to food security [5, 6]. Most soils in sub-Saharan African regions range in strength from strong to very strong acid soils; these soils often have unsuitable soil properties for crop production [7, 8]. Losses of important soil nutrients, in particular, soil phosphorus and mineral nitrogen are common in such acidic soils. The use of a combination ameliorant could be an alternative option to improve the soil fertility. In such regions of a serious problematic soil fertility issue, integrated soil fertility management was therefore suggested and has already been implemented by agricultural users in Kenya, Rwanda, Ethiopia, and Malawi [3, 5, 9, 10].

The soils in western Ethiopia region have a high potential for producing a variety of crops; however, soil acidity is the main problem that reduces soil fertility and crop output [7, 11]. Imbalanced agricultural input use and high levels of nutrient leakage are the cause of deteriorating soil fertility

[5, 12, 13]. Increasing agricultural yield is feasible when using the only appropriate soil fertility management techniques [1, 14, 15].

Since lime has shown a positive synergy with crop output, it is permitted for use in combination with a mineral fertilizer to help boost agricultural productivity [16, 17]. It improves soil's pH level, cation exchange capacity, and percentage base saturation. It promotes the breakdown of soil organic matter, verifies the nutrients in the soil, and removes contaminants from the soil. In addition, lime enhances soil physical qualities and can be used for more than three years [7, 18–20]. In general, lime is valuable, but it has some drawbacks, including high transport costs, potential restrictions on practical applications, and negative effects on trace element shortages [21, 22]. Additionally, in the western region of Ethiopia, there is a gap in the lime recommendations based on the particular crop kinds and soil conditions [18]. Therefore, it is important to find additional alternative inputs that can be combined with lime to minimize its use rate, maintain soil fertility, achieve the best crop yields, and reap associated economic benefits.

Organic fertilizers have been proven to greatly improve soil properties and plant biomass, mostly, when used in combination with other fertilizers [23–25]. This is in contrast to the use of a mere fertilizer or lime. Particularly, after combining organic input with lime experiment led, the crop response and soil healthy enhancement under organic fertilizer treatments has been approved [26, 27]. Therefore, seeking for locally accessible resources such as compost, manure, and biochar may be an option for soil fertility rather than utilizing a simple mineral fertilizer or/and lime.

Biochar is a carbon-rich biochar made by pyrolysis of biomasses [28–31]. Applying biochar to acidic soils directly enhances the biological, physical, and chemical characteristics of the soil [29, 32]. As a result, biochar can be thought of as a soil facilitator for nutrient transport and cycling, plant growth and impact on soil toxicity, soil's density, and soil nutrient release [25, 33]. However, the material and pyrolysis temperature have the greatest influence on the effects of biochar [25]. Although biochar has a significant potential for improving soil qualities, regarding its benefit, there is only very little information available in Ethiopia [30, 34].

There are excess local resources, particularly for coffee husks and others in Ethiopia, including the western part of the country that can be used as the raw materials for biochar production [5, 35, 36]. In Ethiopia, very limited amount of the coffee products produced in facilities for coffee processing are suitable for commercial use, whereas most of these coffee byproducts are burned in large stacks or dumped into streams [37, 38], which poses greater environmental risks [39]. However, turning these coffee waste products into biochar through pyrolysis could aid in addressing the country's western region's soil acidity issue.

Various scholars have long argued on the reduction of soil acidity in uses of lime and biochar in the agricultural systems of developed nations [12, 30, 40, 41]. The benefits of this biochar are not widely recognized in tropical countries, especially in Western Ethiopia. However, Gimbi District is one of those areas among the Western Ethiopia, with a lot of rainfall, where agricultural soils are physically deteriorated and essential nutrients were long-term leached and caused the development of soil acidity [7, 14]. In fact, the agricultural soils in this study area were deteriorated by this soil's acidity, which ranges from strong to extremely strong acidic level [14, 35, 42, 43]. Exceptionally high concentrations of toxic elements are suggested by the region's rich, rust-red soil or Nitisols [7, 14, 35, 43, 44]. However, utilizing a combination ameliorant for acid soils could be a viable alternative for enhancing soil fertility and may assist to resolve the difficulties in gaining access to supplies of fertilizer. The availability of raw materials for organic inputs such as biochar in the study area and the growing issues with soil acidity further emphasize the necessity for integrated fertilizer research in crop production to feed the present and future populations [7, 14, 35]. The role that ameliorants should play in this scenario and the appropriate amount of input to be added at what rate to condition the soil remain unknown, and should also be determined. As a result, the objective of this study was to examine the effects of combined coffee husk biochar and soil test value-based lime rates on selected physicochemical properties of acid soils in Gimbi District, Western Ethiopia.

2. Materials and Methods

2.1. Description of the Study Area. The examination was conducted in Gimbi District, Western Ethiopia, which is 441 km west of Addis Ababa (Figure 1). It is surrounded by the Benishangul-Gumuz region in the north, East Welega in the east, Lalo Asabi District in the west, Homa District in the southwest, Haru District in the south, and an exclaved Benishangul-Gumuz area in the southwest [45]. The mean annual temperatures in the studied areas range from 10 to 30°C, and these locations are distinguished by a unimodal rainfall pattern with an average annual rainfall of 1,700 mm and the height spans from 1,200 to 2,222 m.a.s.l.

There are three agroecological zones: lowland, midland, and highland, where 70% is highland, 10% is midland, and 20% is lowland [13, 45, 46]. Mostly, surface lands' entire topography is a reflection of previous geological and erosional processes [43]. The local population relied on trees and crops for revenue and fences, shade, food, and fodder for cattle [45, 46]. Since the early 1950s, smallholder farmers of Ethiopia, including western areas, have mostly used mineral fertilizers and rarely lime to increase crop yield. Currently, leaching and degradation to their agricultural soils became defaulted everywhere in the study area [13].

2.2. Experimental Materials and Preparation

2.2.1. Experimental Field. Depending on the uniformity of the site, two experimental sites (Farm-1, Wondimu Tasisa, and Farm-2, Girma Burayu) were specifically chosen from Gimbi District, Western Ethiopia. A composite soil sample made up of five subsamples was obtained using the zigzag method by auger at a depth of 20 cm from each site in order to determine the soil acidity (soil pH of 7) before initiating the experiment. Independent undisturbed samples were also

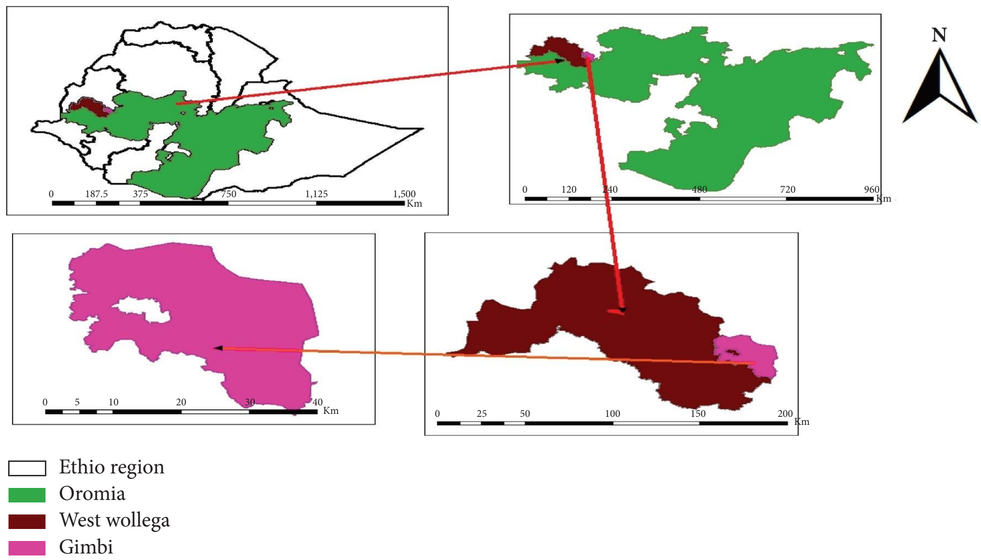

Figure 1: Map of the Gimbi district, western Ethiopia.

collected using a core sampler for BD determination. In a soil laboratory, the soil was examined for a number of parameters, and the results are shown in Table 1.

2.2.2. Biochar Material. Coffee husk from the dry pulping station found close to Gimbi town was used to make coffee husk biochar (CHB). The gathered biochar materials were dried by air in the sun to produce biochar. Soil pit kilns with dimensions of 150 cm in diameter and 90 cm in depth and a side wall with an approximate slope angle of 63.5 degrees were created for the manufacture of biochar. Dry feedstock was positioned in the center of the pit, and fire was ignited on top of them to create a blaze for layer-by-layer charring in accordance to methodology of Pandit et al. [47]. To reduce oxygen and aid the pyrolysis process, the dry feedstock was placed into a pit kiln after the fire was extinguished with earth and left for 24 hours (Figure 2). To achieve the same particle size as the topsoil used for the experiment, the produced biochar material was crushed and sieved through a 2 mm square-mesh sieve [47–50]. From the subsample of coffee husk biochar taken for each biochar product, a composite sample was created and evaluated for specific chemical parameters as shown in table (Table 1).

2.2.3. Lime Material. The lime, soil test value-based lime (STV), which contained the equivalent of 98% calcium carbonate in powder form ($CaCO_3$), was brought to the experiment site and put to use. The exchangeable acidity (EA) concentration-based equation and the BD were used to determine how much lime was required at the research location [51]. Farm-1's soil BD and EA were 1.26 $g{\cdot}cm^{-3}$ and 4.46 $cmol_{(+)}kg^{-1}$, respectively, but they were 1.41 $g{\cdot}cm^{-3}$ and 5.13 $cmol_{(+)}kg^{-1}$ for Farm-2. Accordingly, Farms-1 and 2 required 4.22 ton and 5.43 ton of soil test value-based lime (lime), respectively.

2.3. Experimental Treatments, Design, and Management. Three replications of the treatment were set up in a randomized complete block design [52]. Two farmer's fields in distinct kebeles (Chuta Georgis and Chuta Gochi) in Gimbi District, Western Ethiopia, were chosen for the study based on their availability, soil acidity, regularity of the land plot, and management. The experiment was carried out during the 2022 rainy season, with the soil samples from the treatment being taken on May 3, 2022 or incubation, and on June 3, 2022 for analysis of the effect of lime rate and biochar on soil physicochemical properties after incubation for a month.

After a month of application, the effects of ameliorant rate on soil properties were assessed using treatments that were purposefully chosen from biochar and lime rate, including the control, 100% of STV ha^{-1}, 10 ton of CHB, 10 ton of CHB + 75% of STV ha^{-1}, 10 ton of CHB + 50% of STV ha^{-1}, 7.5 ton of CHB + 75% of STV ha^{-1}, and 5 ton of CHB + 75% of STV ha^{-1}. Blocks and plots were separated by 1 and 0.5°m, respectively. Each experimental plot measured 3.20°m × 3.80°m (12.16 m^2) in size. The total area of each plot was 10.80 m^2, with the net plot size being 3.00 m × 3.60°m. To avoid the border effect, the first 10 cm of each side's width and length was left uncut in order to designate the border. In accordance with the plan, a field was laid out and prepared.

Table 1: Mean values of selected physicochemical properties of soil of preplanting of the study area and biochar produced from coffee husk (CHB).

Parameters	BD ($g\cdot cm^{-3}$)	Clay (%)	Silt (%)	Sand (%)	TC	MC (%)	Po (%)	pH-H_2O (1 : 2.5)	Ca^{2+} ($cmol_{(+)}$ kg^{-1})	Mg^{2+} ($cmol_{(+)}$ kg^{-1})	K^+ ($cmol_{(+)}$ kg^{-1})	Na^+ ($cmol_{(+)}$ kg^{-1})	BS (%)	CEC ($cmol_{(+)}$ kg^{-1})	OC (%)	OM (%)	C/N	Total N (%)	Total P ($mg\cdot kg^{-1}$)	Available P ($mg\cdot kg^{-1}$)	NH_4-N ($mg\cdot kg^{-1}$)	NO_3-N ($mg\cdot kg^{-1}$)	EA ($cmol_{(+)}$ kg^{-1})	EAl ($cmol_{(+)}$ kg^{-1})
Soil of Farm-1	1.26	23	30	47	Loam	30.5	52.2	5.2	4.1	0.4	0.7	0.2	51.77	10.43	1.89	3.26	8.38	0.11	2.93	1.14	12.89	32.9	4.46	4.31
Soil of Farm-2	1.41	12	27	61	Sandy loam	23.6	46.7	4.63	1.94	0.2	0.4	0.3	31.35	9.06	1.55	2.67	11.11	0.09	1.19	0.91	15.89	38.6	5.13	4.92
Coffee husk biochar (CHB)	—	—	—	—	—	—	—	10.61	58.3	7.77	3.1	4.47	91.94	80.1	31.26	53.89	15.39	2.03	138.01	16.8	—	—	—	—

Bulk density (BD), soil texture class (TC), porosity (Po), moisture content (MC), potential of hydrogen (pH), exchangeable calcium (Ca^{2+}), exchangeable magnesium (Mg^{2+}), exchangeable potassium (K^+), exchangeable sodium (Na^{2+}), base saturation (BS), organic carbon (OC), organic matter (OM), nitrogen (N), carbon-to-nitrogen ratio (C/N), available phosphorous (available P), cation exchange capacity (CEC), exchangeable acidity (EA), exchangeable aluminum (EAl), ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), and total mineral nitrogen (TMN).

h= 90 cm; r=75 cm; $v = \frac{1}{3}\pi h^2 (3r-h)$ = 1.145 m^3, whereas, v: volume; h: height of pit; r: radius of spherical cap form of soil pit

Figure 2: Model of a spherical cap-shaped soil pit helping biochar production.

Next, lime and biochar were carefully and uniformly placed across the similar experimental plots and hoed into the soil. All plots received the same treatment with regard to all management measures, including protecting against animal tracks, erosion, and the through-flow of other waste products.

2.4. Data Collection and Analysis

2.4.1. Soil Sampling. To ascertain the impact of mixed biochar and lime on acid soil physicochemical properties, soil samples were collected from each experimental plot one month after the treatments were applied. Five soil subsamples, one from each plot, were collected using the zigzag method by auger at a depth of 20 cm to create the composite soil sample [52]. Additionally, a core sampler was used to acquire separate samples of undisturbed soil at a distance of twenty centimeters (cm) in order to determine the BD [53]. Moreover, as per the sample of soils, ice box was used to engage the soil sample for analysis of ammonium nitrogen (NH_4-N) and nitrate nitrogen (NO_3-N) [54].

The sampling depth, intensity per unit area of the site, and the design were typically taken into consideration when creating the soil sampling protocols to account for variations in soil property parameters. Samples of representative soil were kept contaminant-free. Finally, soil samples were air-dried, crushed, thoroughly mixed, and sieved with a mesh size of 2 mm. They were then made ready, correctly labeled, packed in a plastic bag, and engaged separately in an ice box for analysis of NH_4-N and NO_3-N. After that, a soil sample was taken to a laboratory for examination.

2.4.2. Soil Physicochemical Analysis. Bulk density (BD), soil porosity (Po), and soil moisture content (MC) were analyzed to determine the effect of different treatments on them. The soil BD ($g{\cdot}cm^{-3}$) was determined by the core method after drying a defined volume of soil in an oven at 105°C for 24 hours [55]. The Po was determined by [56] method. Soil MC (%) was measured after drying in an oven at 105°C for 24 hours and dried to a constant weight, according to Gardner [57]. Water content was calculated using the formula $(W_1 - W_2)/W_2 * 100$, where W_1 is the beginning weight and W_2 is the oven-dried weight of the soil. Soil sample was pretreated with H_2O_2 (30%) to remove any organic material and sodium hexametaphosphate to disperse clay. The density of the soil suspension was determined by the hydrometer (Bouyoucos) method to read in grams of solids per liter after the sand settles out and again after the silt settles. A correction was made for the density and temperature of soil-water suspension and was identified for the percentage of particle size classes according to the USDA textural triangle [58].

To estimate the effect of different treatments on chemical properties of soil, the soil pH level, organic carbon (SOC), organic matter (SOM), total nitrogen percent (TN%), carbon-to-nitrogen ratio (C/N), cation exchangeable capacity (CEC), and available phosphorous (available P), exchangeable acidity (EA), exchangeable aluminum (EAl), ammonium nitrogen (NH_4-N), and nitrate nitrogen (NO_3-N) were analyzed. Soil pH (1 : 2.5 H_2O) was extracted by the soil:water ratio of 1 : 2.5 and determined by the potentiometric method [59]. Soil OC percent was extracted by wet oxidation (Walkley-Black) and determined by the titration method [60]. Soil organic matter percent was calculated by using the Van Bemmelen factor of 1.724. The TN% was calculated by the Kjeldahl method and analyzed by the titration method [61]. The carbon-to-nitrogen ratio was determined from the carbon and nitrogen estimated. The distillation-titration method was used to extract CEC ($cmol_{(+)}kg^{-1}$) from ammonium acetate at 7 pH level [62]. Available P ($mg{\cdot}kg^{-1}$) was extracted by the Bray II method and determined using the spectrophotometric method [63]. The EA, Al^+, and H^+ ($cmol_{(+)}kg^{-1}$) were extracted by KCl and determined by the titration method [64]. Exchangeable bases (Ca^{2+}, Mg^{2+}, K^+, and Na^+) were estimated by ammonium acetate at pH level of 7. The K^+ and Na^+ were determined using flame photometry, while Ca^{2+} and Mg^{2+} were determined using the AAS [65] technique. Nitrate nitrogen (NO_3-N) was extracted by phenoldisulphonic acid and analyzed by the spectrophotometric method [66], whereas the NH4-N was extracted by copper sulfate and analyzed by the distillation-titration method [67].

2.4.3. Biochar Chemical Properties' Analysis. After shaking the biochar for 30 minutes, the pH was measured in distilled water at a 1 : 10 biochar to water mass ratio as described in [68]. According to Chintala et al. [69], the OC content of biochar was measured using the Walkley-Black method and the total nitrogen (TN) content was measured using the Kjeldahl method. The Olsen extraction method was used to calculate the amount of available P as described in the study by Bayu et al. [68]. After leaching the biochar with ammonium acetate, the percentage base saturation was calculated. Atomic absorption spectrometry (AAS) was used to measure the Ca and Mg concentrations of the biochar in the leachate. Flame photometry was used to determine the levels of K and Na. In order to estimate the CEC titrimetrically by ammonium distillation that was displaced by sodium, the CEC was first evaluated at soil pH 7 after displacement using the 1°N ammonium acetate method in accordance to the method described by Chintala et al. [69].

2.5. Data Analysis. The statistical analysis system software, version 9.3 [70], general linear model (GLM) approach, and analysis of variance (ANOVA) were used to analyze the data of the selected soil properties parameters. To distinguish statistical significance of changes due to the different applied treatments, the least significant difference (LSD) test was performed at 5 percent probability level. Simple correlation analysis was also carried out using the Pearson's correlation coefficient to determine the magnitudes and directions of relationships between studied soil characteristics parameter at the 5% level.

3. Results and Discussion

3.1. The Preincubation Soil Physicochemical Properties of the Study Area. The soil properties of the study area before treatment application are indicated in Table 1. In Farms 1 and 2, the soil texture class composition consisted of 47 and 61% sand, 30 and 27% silt, and 23 and 12% clay, respectively. The farm of Farm-1 (Wondimu Tasisa) had soils resembling loam, whereas the Farm-2 (Girma Burayu) had sandy loam. Therefore, in the current experiment, Farm-1 and Farm-2 received different amounts of lime at various rates. According to Wogi et al. [71], loam and sandy loam soils have varying buffering capacities, which can potentially affect how much lime is needed for a given soil.

The BD was found to be 1.26 $g \cdot cm^{-3}$ for Farm-1 and 1.41 $g \cdot cm^{-3}$ for Farm-2. Farm-1 soils have surface mineral soils that were not well-compacted, while Farm-2 soils are known for their hindering of root growth and a wide range of clay characteristics. Farms-1 and 2 had MCs that were 30.5 and 23.6%, respectively. The two primary variables that determine soil MC are SOM and BD; thus, low MC of the soil may be brought on by low SOM and high BD [6].

The soil pH level revealed the acidity of the soil. The features of the soil pH values (H_2O) of the Farms-1 and 2 during preincubation, which were 5.2 and 4.63 level, respectively, are very acidic soil (Farm-1; pH value of 5.1 to 5.5) and very strongly acidic soil (Farm-2; pH level of less 5), respectively. Regarding Farm-1, the Ca^{2+} (4.1 $cmol_{(+)}kg^{-1}$), Mg^{2+} (0.4 $cmol_{(+)}kg^{-1}$), and Na^{+} (0.2 $cmol_{(+)}kg^{-1}$) were all low in content, with the exception of K (0.7 $cmol_{(+)}kg^{-1}$), which was high. Likewise, Farm-2 has medium levels of K^{+} (0.4 $cmol_{(+)}kg^{-1}$) and Na^{+} (0.3 $cmol_{(+)}kg^{-1}$), very low levels of Ca^{2+} (1.94 $cmol_{(+)}kg^{-1}$) and Mg^{2+} (0.2 $cmol_{(+)}kg^{-1}$). Low content of CEC (5–15 $cmol_{(+)}kg^{-1}$) was found in both Farm-1 (10.43) and Farm-2 (9.06), which are within the range for CEC provided by Wogi et al. [71]. The results indicate that the soil in both of the research area's farms (Farms-1 and 2) has low fertility because of their low basic cation content.

The C/N ratios in Farms-1 and 2 were 8.38 and 11.11, respectively, indicating that the soil OC and total N levels were in the middle range. Farm-1 (1.14 $mg \cdot kg^{-1}$) and Farm-2 (0.91 $mg \cdot kg^{-1}$) found very little phosphorous that was readily available. The soil exchangeable acid results for Farms-1 and -2 were 4.46 and 5.13 $cmol_{(+)}kg^{-1}$, respectively. This severe acidity of the soil may destroy the basic cations and increase the likelihood of Al poisoning. According to Bolan et al. [72], the exchangeable Al and H in such soils were not entirely limited. As a result, additional options for reclaiming the soils are required; integrating soil fertility management options may be the answer.

3.2. Biochar Chemical Composition. Table 1 contains the results of the chemical characteristics investigation of coffee biochar. The biochar was extremely strongly alkaline with a pH-H_2O of 10.61. The exchangeable bases, exchangeable Ca^{2+} (58.30 $cmol_{(+)}kg^{-1}$), exchangeable K^{+} (3.10 $cmol_{(+)}kg^{-1}$), and exchangeable Na^{+} (4.47 $cmol_{(+)}kg^{-1}$), were all very high in content, with the exception of Mg^{2+} (7.77 $cmol_{(+)}kg^{-1}$), which was ranged in high content. This has led to the extremely high base saturation (91.91%) being noted. Tested biochar has extremely high CEC (80.10 $cmol_{(+)}kg^{-1}$) and TN (2.03%) as well as high SOC. It is true that the alkalinity of biochar is confirmed by different authors [17, 25, 29–32].

The C/N ratio was 15.39. Naturally, the nitrogen content occurs in organic molecules [32, 33] and these author's facts confirm that biochar contains nitrogen. Furthermore, only 16.8 $mg \cdot kg^{-1}$ of the accessible phosphorous (available P) out of the total phosphorous of 138.01 $mg \cdot kg^{-1}$ was collected, and it had a low extractable p content. Phosphorous retention in biochar is a mechanism to provide vital indication for the effective management of P to boost crop production and sustain soil [29, 40]. This might be caused by the biochar's high alkalinity. This conclusion from a chemical examination of biochar demonstrates that it has great potential for amending acidic soils.

3.3. Effect of Combined Biochar and Lime Rates on Physical Properties of Acid Soils. The study found that applying combination biochar and lime rates resulted in a substantial ($P < 0.01$) variation in the physical parameters of the soil. For Farms-1 and -2, the positive benefits of biochar and/or lime on soil performance have been rather fully observed, as the same experiment was conducted. However, there were differences between Farms-1 and -2, because Farm-1 had previously had strongly acidic soil, whereas Farm-2 had a very strongly acidic soil. Previously, the soils in each of the farms under study were unsuitable for growing crops. This investigation made it clear that adding biochar and/or lime to the soil could enhance acid soil physical characteristics. Crop growth is encouraged on the treated soil with the addition of organic inputs and an improvement of the soil's physical attributes [32, 40, 73, 74].

3.3.1. Soil Bulk Density. In Figure 3 and Table 2, the effects of applying biochar and/or lime on the BD of acidic soils are depicted. The mean squares of the analysis of variance for BD are shown in Table 3. Treatments amended with biochar and/or lime at ($P < 0.05$ demonstrated substantially lower BD compared to controls at both study sites. Similarly, a different study justified that the application of biochar and/or lime affected soil physical properties [40, 72].

In Farm-1, the BD of the soil treated with biochar and/or lime was lower than the control treatment by 4.96 to 25.62%. The control treatment had the highest BD (1.21 $g \cdot cm^{-3}$), which is statistically equivalent to (1.15 $g \cdot cm^{-3}$) when treated with 100% lime at ($P < 0.01$). The BD of the soil treated by sole 10°t of CHB (0.90 $g \cdot cm^{-3}$) and 10°t of CHB + 75% of STV ha^{-1} were decreased by 25.62% from control one. The BD decreased from 20.57 to 28.37% compared to the control treatment in Farm-2's soil that had been modified with biochar and/or lime. The control sample (1.41 $g \cdot cm^{-3}$) had

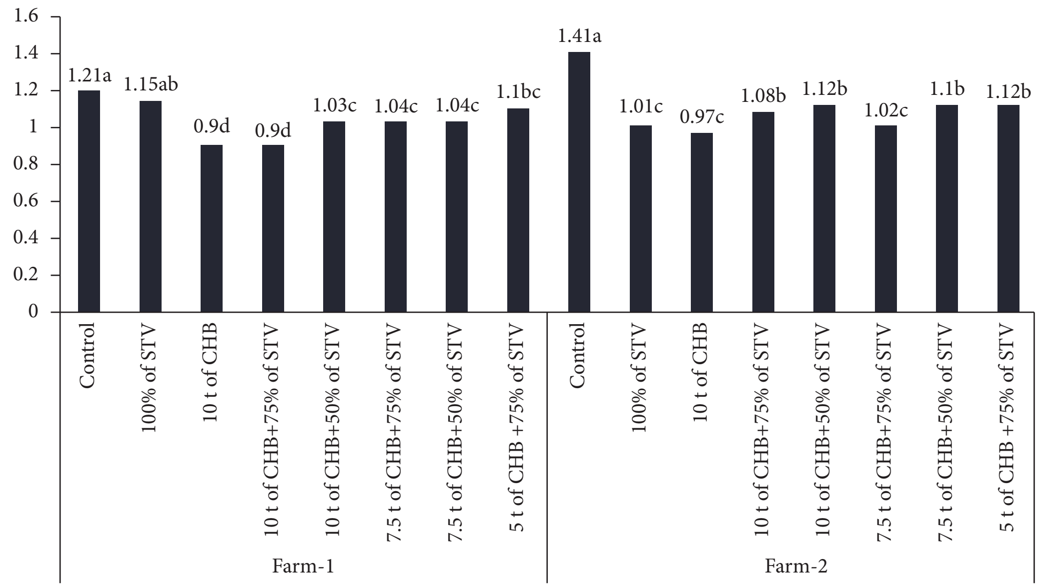

Figure 3: The effect of coffee husk biochar (CHB) and soil test value-based lime (STV) rates on bulk density (BD) of acidic soils.

Table 2: Effect of coffee husk biochar (CHB) and soil test value-based lime (STV) rates on bulk density (BD), porosity (Po), and moisture content (MC) in acidic soils.

Factor ha^{-1}	BD (g cm^{-3})	Po (%)	MC (%)
Farm-1			
Control	1.21^{a}	54.34^{d}	25.79^{d}
100% of STV	1.15^{ab}	56.35^{cd}	34.63^{ab}
10 ton of CHB	0.90^{d}	64.65^{a}	31.76^{bc}
10 ton of CHB + 75% of STV	0.90^{d}	65.78^{a}	37.92^{a}
10 ton of CHB + 50% of STV	1.03^{c}	60.88^{b}	38.70^{a}
7.5 ton of CHB + 75% of STV	1.04^{c}	60.75^{b}	27.66^{cd}
7.5 ton of CHB + 50% of STV	1.04^{c}	60.63^{b}	36.46^{ab}
5 ton of CHB + 75% of STV	1.10^{bc}	58.49^{bc}	32.93^{b}
CV (%)	3.92	2.59	8.57
LSD (0.05)	0.07**	2.72**	4.98**
Farm-2			
Control	1.41^{a}	46.79^{c}	21.56^{h}
100% of STV	1.01^{c}	61.76^{a}	36.15^{d}
10 ton of CHB	0.97^{c}	63.27^{a}	39.61^{b}
10 ton of CHB + 75% of STV	1.08^{b}	59.24^{b}	33.02^{e}
10 ton of CHB + 50% of STV	1.12^{b}	57.61^{b}	42.83^{a}
7.5 ton of CHB + 75% of STV	1.02^{c}	62.13^{a}	23.93^{g}
7.5 ton of CHB + 50% of STV	1.10^{b}	58.24^{b}	38.13^{c}
5 ton of CHB + 75% of STV	1.12^{b}	57.61^{b}	28.11^{f}
CV (%)	2.69	1.92	1.36
LSD (0.05)	0.05**	1.96**	0.78**

ns: non-significant, **: significant ($P < 0.05$), **: highly significant ($P < 0.01$).

the highest bulk density (Figure 3). This finding revealed that the amount of 10 ton of CHB ha^{-1}, 100% of STV ha^{-1}, and 7.5 ton of CHB + 75% of STV ha^{-1} had decreased soil BD (0.97 to 1.02 g·cm^{-3}). Application of 5 ton of CHB + 75% of STV ha^{-1}, 10 ton of CHB + 75% of STV ha^{-1}, 10 ton of CHB + 50% of STV ha^{-1} and 7.5 ton of CHB + 50% of STV ha^{-1} were statistically similar to one another. Chimdi[19] and Karim et al. [75] found the reduced soil compaction following the application of lime and biochar, respectively. Also, Periyasamy and Temesgen [32] organic liming of soil has an inverse relationship with soil BD that analyses to soil organic matter growth.

Biochar decreased the bulk density of soil, which could directly increases soil aggregation and indirectly porosity of soil [73]. This could be caused by the porosity of the biochar, drainage, aeration, or in a condition of biochar application,

Table 3: Mean squares of the analysis of variance for soil bulk density (BD), porosity (Po), moisture content (MC), potential of hydrogen (pH), soil organic carbon (SOC), soil organic matter (SOM), total nitrogen (TN), carbon-to-nitrogen ratio (C/N), cation exchange capacity (CEC), available phosphorous (available P), exchangeable acidity (EA), exchangeable aluminum (EAl), ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), and total mineral nitrogen (TMN) of acidic soils.

Source of variance	Df	BD	Po	MC	pH	SOC	SOM	TN	C/N	CEC	Available P	EA	EAl	NH_4-N	NO_3-N
Farm-1															
Rep	2	0.00	1.30	6.31	0.00	0.00	0.00	0.00	0.04	0.04	0.00	0.01	0.01	0.39	0.06
Trt	7	0.03	44.58	65.51	0.34	13.26	39.43	0.83	14.68	389.98	2.50	3.33	3.33	3.05	204.80
MSE	23	0.00	2.42	8.10	0.00	0.00	0.01	0.00	0.05	0.18	0.01	0.00	0.01	0.27	0.07
CV	—	3.92	2.58	8.56	0.57	1.40	1.39	3.98	6.06	1.96	4.04	4.47	4.47	9.14	6.03
LSD (0.05)	—	0.07	2.72	4.98	0.05	0.10	0.18	0.08	0.45	0.75	0.22	0.14	0.14	0.91	0.47
P-V	—	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fcal	—	18.3	18.4	8.1	315.6	3516.3	3563.6	345.3	253.1	2083.1	146.8	475.4	475.4	1113.2	2819.1
Farm-2															
Rep	2	0.09	0.43	0.03	0.00	0.00	0.01	0.00	0.14	0.03	0.00	0.01	0.01	0.18	0.16
Trt	7	0.05	79.55	177.3	0.78	12.60	37.47	1.12	18.52	331.90	4.86	4.23	2.94	354.01	218.59
MSE	23	0.00	1.26	0.20	0.00	0.00	0.01	0.01	0.47	0.59	0.02	0.00	0.00	0.21	0.18
CV	—	2.69	1.92	1.36	0.00	1.63	1.63	11.89	11.97	3.67	2.92	2.52	3.51	6.74	8.85
LSD (0.05)	—	0.05	1.96	0.78	0.10	0.13	0.23	0.20	1.20	1.35	0.25	0.12	0.12	0.81	0.74
P-V	—	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fcal	—	63.1	63.1	878.5	236.6	2044.0	2044.1	85.6	39.3	557.2	233.3	839.4	580.4	1646.8	1202.7

ns: non-significant, *: significant ($P < 0.05$), **: highly significant ($P < 0.01$).

the soil's decreased mechanical barrier to root activity. In addition, the applying of lime could increase the soil tilth, which reduced crusting and promoted soil aeration, which in turn increased microbial activity, similar to approved in Gurmessa [76]. By combing, adding biochar and lime rates on the acid soil could reduce compaction [75, 76]. In the current investigation, BD in strongly acidic soils displays an inverse relationship with SOC (−0.83**). The difference in the soils' capacity to act as a buffer is responsible for this association's presence via different farm field [77, 78].

3.3.2. Soil Porosity (Po). The effects of biochar and/or lime rate on porosity (Po) of soil in both Farms-1 and 2 had statistically significant ($P < 0.05$) difference. As demonstrated in Figure 4, all treatments on both farms improved soil porosity, with the exception of the control treatment. The biochar and/or lime treatments resulted in an increase in soil porosity from 3.69 to 21.05% compared to the not amended treatment in Farm-1. The 10 tons of CHB and 75% of STV ha^{-1} (65.78%) and 10 tons of CHB (64.65%) treatments had the highest values for soil Po percent. The application of STV ha^{-1}resulted in the lowest soil Po (56.35%) compared to the control (54.34%). The Farm-2's soils modified with CHB and/or STV treatments had soil Po values (23.13 to 35.22%) higher than the control treatment. The 10 tons of CHB (63.27%), 100% of the STV ha^{-1} (61.76%), and the 7.5 ton of CHB + 75% of the STV ha^{-1}(62.13%) had the highest Po values, while the control (46.79%) had the lowest. In this study, the application of lime and biochar resulted in a negative correlation between the carbon content and bulk density, and therefore, the improvement in soil porosity was investigated. This idea is confirmed by Mosharrof et al. [40].

The higher the total porosity of the soil, the better the soil's physical quality [32]. One of the crucial properties of biochar that can increase the amount of water that is available to plants and enhance the soil's capacity to retain nutrients is its pore size [33]. By enhancing soil macroaggregate content and pore space persistence, biochar and/or lime have boosted overall porosity [40]. Microspores are involved in molecular adsorption and transport, whereas microspores have an impact on aeration and hydrology [29]. As a result, biochar is an ameliorant helps the pore dispersion, alter soil compaction for increased aggregate stability, or lessen the likelihood of soil erosion by enhancing pore space persistence. The pyrolysis temperature and feedstock, however, may affect the Po of biochar [31]. A few key characteristics of biochar, such as its high porosity, quantity of microspores, and surface area, may have the potential to alter the physical characteristics of soil and improve the conditions for plant root development and nutrient uptake. Furthermore, because biochar has pores and a particular surface area, it has the potential to adsorb and fix a wide range of inorganic ions as well as polar or nonpolar organic molecules [30], and then, it boosts the ventilation of the soil and speeds up the creation of stronger aggregates to create large aggregates that are both organically and inorganically mediated. Chen et al. [79] also found that applying limestone increased the porosity of the soil.

3.3.3. Soil Moisture Content (MC). The effect of biochar and/or lime rate addition on soil moisture content taken into account for both Farms-1 and 2 soils was demonstrated to be statistically significant at ($P < 0.05$) as shown in Table 2 compared to the control treatment, all the treatments in both farms improved the MC of the soil (Figure 5).

The soil MC was increased by 7.25 to 50.06% after STV and/or CHB were added, as compared to the control one in Farm-1. The highest soil MC measurements were made with

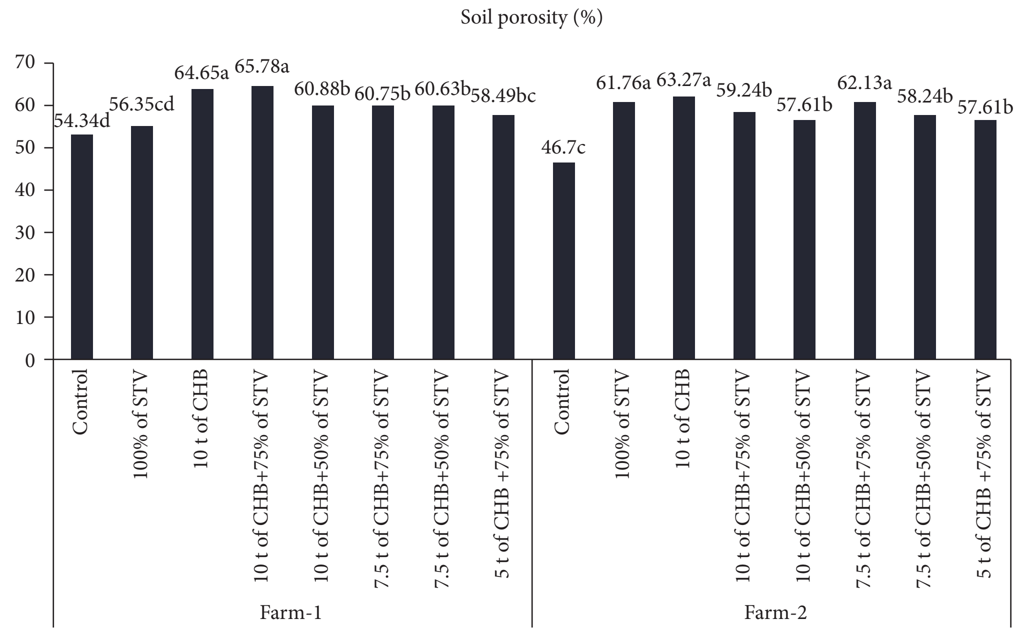

Figure 4: The effect of coffee husk biochar (CHB) and soil test value-based lime (STV) rates on soil porosity (Po) of acidic soils.

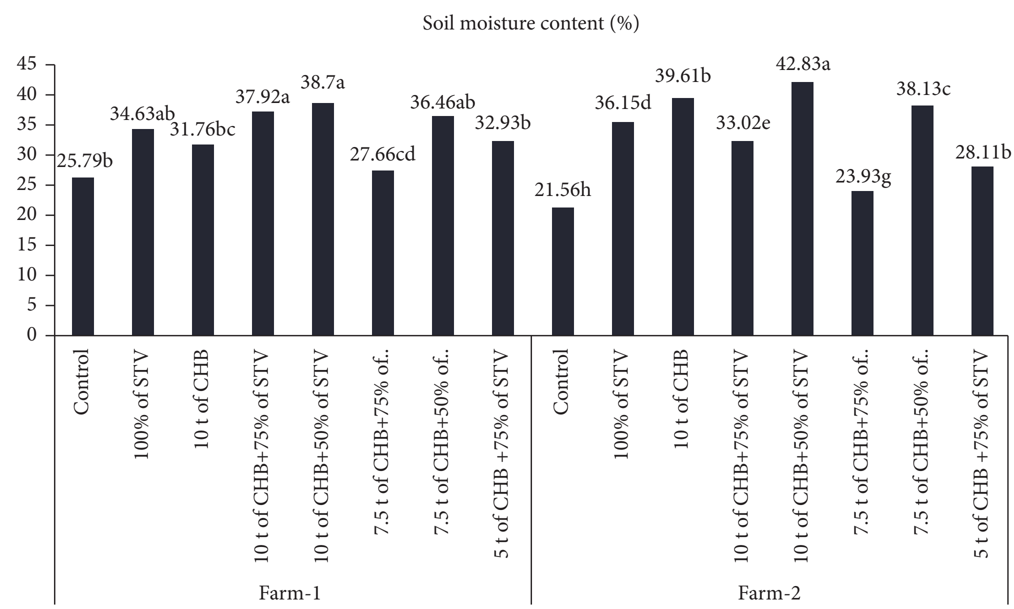

Figure 5: The effect of coffee husk biochar (CHB) and soil test value-based lime (STV) rates on moisture content (MC) of acidic soils.

10 ton of CHB + 75% of STV ha^{-1} (37.92%) and 10 ton of CHB + 50% of STV ha^{-1} (38.70%). The highest MC, 10 ton of CHB + 75% of STV ha^{-1} and 10 ton of CHB + 50% of STV ha^{-1}, and were statistically similar with 100% of STV ha^{-1} and 7.5 ton of CHB + 50% of STV ha^{-1}. Lowest MC was found in the control (25.79%). The 7.5 ton of CHB + 75% of Soil test value-based lime ha^{-1} (27.66%) was statistically comparable to the control at $P < 0.05$. Regarding Farm-2, the soil MC increased by 10.99 to 98.65% compared to control one's MC in the soil modified with biochar and/or lime. The 10 ton of CHB + 50% of STV ha^{-1} had the highest MC (42.83%) compared to the earlier treatments. The control treatment produced the lowest amount of MC (21.56%; $P < 0.01$). Different authors were reported the increase in soil MC when biochar and lime is applied [40, 72, 80]. This return was strongly related to changes in BD and Po that were seen in plots that had been changed with biochar and lime.

3.4. Effect of Combined Biochar and Lime Application Rate on Acidic Soil Chemical Characteristics

3.4.1. Soil pH Level. The mean value of soil pH (1 : 2.5 H_2O) was significantly ($P < 0.01$) changed by the application of biochar and/or lime on acidic soil (Table 3). Mosharrof et al. [40] confirmed this study, as appreciated the change of soil pH level in acid soil properties in condition of biochar and lime amending. Positive relationship was found between ameliorant and soil pH for both Farms-1 and 2 soils. The pH was noticeably ($P < 0.01$) higher for the other treatments compared to the control (Figure 6). Both farms experienced a dramatically different impact of the ameliorants, with responses from both very strongly acidic and the strongly acidic soil.

Compared to the control treatment, the pH level of the soil that was tested for Farm-1 rose by 0.48 to 1.09 units. When applied to severely acid soils, the 10 ton of CHB + 50% of STV ha^{-1} (6.09) and 10 ton of CHB ha^{-1} (6.11) increased the pH of the soils the most in comparison to the other treatments. However, compared to the control, which had the lowest soil pH (5.10), all the treatments raised the pH of the soil. According to Dang et al. [81], the soil pH level of 4.95 in the Vietnamese Mekong Delta showed a decrease in soil acidity after lime and biochar were applied. The pH-H_2O of the adjusted soil rose by 0.38 to 1.58 units when biochar and/or lime were applied to Farm-2's soil (Table 3). The 10 ton of CHB ha^{-1} treatment had the highest soil pH (6.22), followed by 10 ton of CHB + 75% of STV ha^{-1}, 10 ton of CHB + 50% of STV ha^{-1}, and 10 ton of CHB + 100% of STV ha^{-1} with values ranging from 6.02 to 6.08, while the control treatment (4.64) had the lowest pH of all the treatments (Figure 6). According to reports by different scholars, the pH level of acid soil improved when it was modified with organic liming [3, 17, 40, 72].

Although there were similarities in the field experiments conducted, the favorable effects of biochar and/or lime on soil performance have been fairly extensively addressed for strongly and very strongly acid soils. The analysis's findings indicated that Farms-1 and 2's extremely and very strongly acidic soils have improved in terms of their chemical qualities. Although the low soil pH level, fixation, and non-availability of significant nutrients were expected in highly and very strongly acidic soil conditions, liming soil with biochar and/or lime could enhance the soil attributes. Biochar can serve as an additional source of soil nutrients, acting as a K, P, and N fertilizer from ash accumulation [82, 83]. The OH^- and HCO_3^- ions that are released when lime is added to soil react with the moisture in the soil to balance the H^+ in the soil solution. In addition, the lime mostly serves as a cradle for Ca and Mg; it lessens the toxicity of H^+, Al^{3+}, and Mn^{2+} ions and helps to maintain soil pH and CEC levels in acidic soils [79, 84]. Then, the hydroxyl ions produced by the hydrolytic reaction react with the H and Al ions to produce water and insoluble aluminum hydroxide ($Al(OH)_3$), respectively [85]. This mechanism may be brought on by microbial decarboxylation of the calcium-organic matter complex, which releases the calcium ion and causes it to be hydrolyzed later. Not as a lime, biochar may have a low Ca and Mg concentration that is not particularly prominent [25, 33].

3.4.2. Soil Organic Carbon (OC) and Organic Matter (OM). The mean value of soil OC and OM was considerably ($P < 0.01$) impacted by the application of biochar and/or lime on Farms-1 and 2 soils (Table 3). Biochar and lime rate had significantly ($P < 0.01$) impacted on soil organic carbon (SOC) in both extremely acidic and severely acidic soils. When compared to the control treatment, SOC for all the other treatments significantly rose (Figure 7), and SOM improved in a similar manner (Figure 8). Application of biochar and/or lime rate additions displayed greater SOC buildup, ranging from 57.24 to 398.47% over the control in Farm-1. The amount of SOC that accumulated was greatest in the 10 ton of CHB + 75% of STV ha^{-1} (7.44%) followed by the 10 ton of CHB ha^{-1} (6.37%). Ten (10) ton of CHB + 75% of STV ha^{-1} and 10 ton of CHB ha^{-1} surpassed by 5.92% and 5.27% units, respectively, compared to the control treatment, which increased lowest accumulation of SOC (1.52%). Regarding Farm-2, treatments that had biochar and/or lime rates added demonstrated increased SOC buildup, ranging from 194.11 to 652.94% over the control group. The 10 ton of CHB + 75% of STV ha^{-1} therapy had the highest SOC (7.68%), followed by the 10 ton of CHB + 50% of lime ha^{-1} treatment (6.31%), and the 10 ton of CHB ha^{-1} treatment (5.59%), while the control treatment's soil OC was the lowest (1.02%). The high OC concentration and recalcitrance of C-organic in biochar and inert parts of the biochar may be the cause of the soil OC increase. Different researchers discovered an increase in the soil organic carbon and matter value of lime and biochar [40, 86, 87].

3.4.3. Soil Total Nitrogen and Carbon-to-Nitrogen Ratio. A substantial ($P < 0.01$) impact of biochar and/or lime rate on soil TN and C/N in very highly acidic and strongly acidic soil was examined (Table 4). The TN was enhanced independently for all the treatments other than the treatment of 100% STV, which is lower than the control (Figure 9). The TN content of the soil treated with biochar and/or lime increased by 15.87% to 195.24% as compared to control in Farm-1. The highest TN was recorded at 7.5 ton of CHB + 50% of STV ha^{-1} (1.86%) and the lowest at 100% of STV ha^{-1} (0.46%). The application of 10 ton of CHB + 50% of STV ha^{-1} sample had the highest C/N (8.46%), while the control sample (2.23%), the 7.5 ton of CHB + 50% of STV ha^{-1} sample (1.96%), and the 5 ton of CHB + 75% of STV ha^{-1} sample (1.95%) had relatively lower C/N. In Farm-2, the soil's TN content increased from 48.15 to 681.48% when CHB and/or STV were added, making it similar to the control treatment. Following 10 ton of CHB + 75% of STV ha^{-1} (2.11%), 7.5 ton of CHB + 75% of STV ha^{-1} (1.31%), and 5 ton of CHB + 75% of STV ha^{-1} (1.30%) treatments, in order of TN accumulation, were the treatments that produced the largest amounts. The 10 ton of CHB + 50% of STV treatment had the lowest C/N (3.68%) as compared with the control, 7.5 ton of CHB + 75% of STV and 5 ton of CHB + 75% of STV ha^{-1} with C/N ratio of 3.75, 3.84%, and 4.15%,

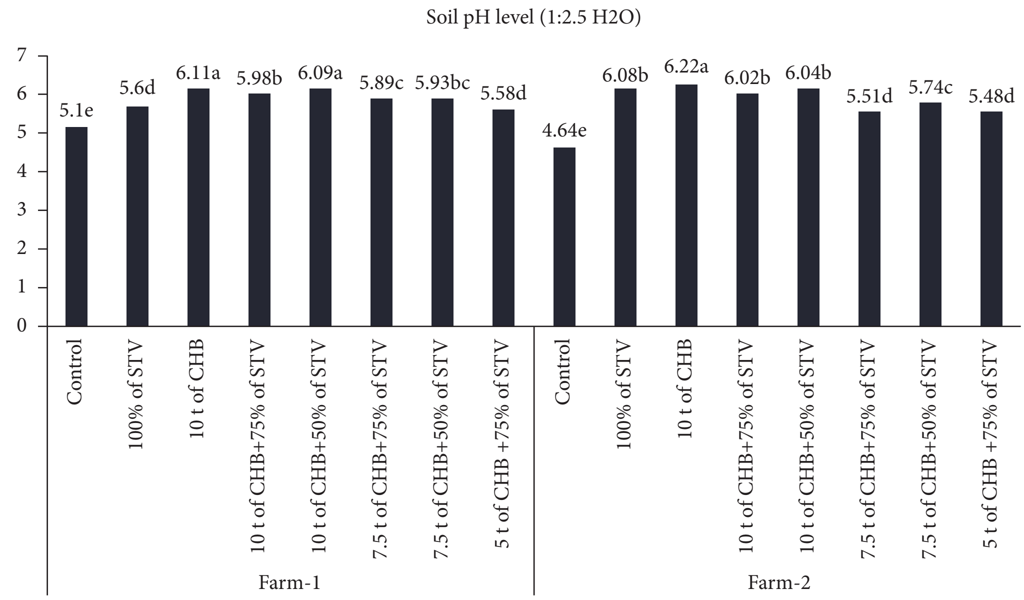

Figure 6: The effect of coffee husk biochar (CHB) and soil test value-based lime (STV) rates on soil pH level of acidic soils.

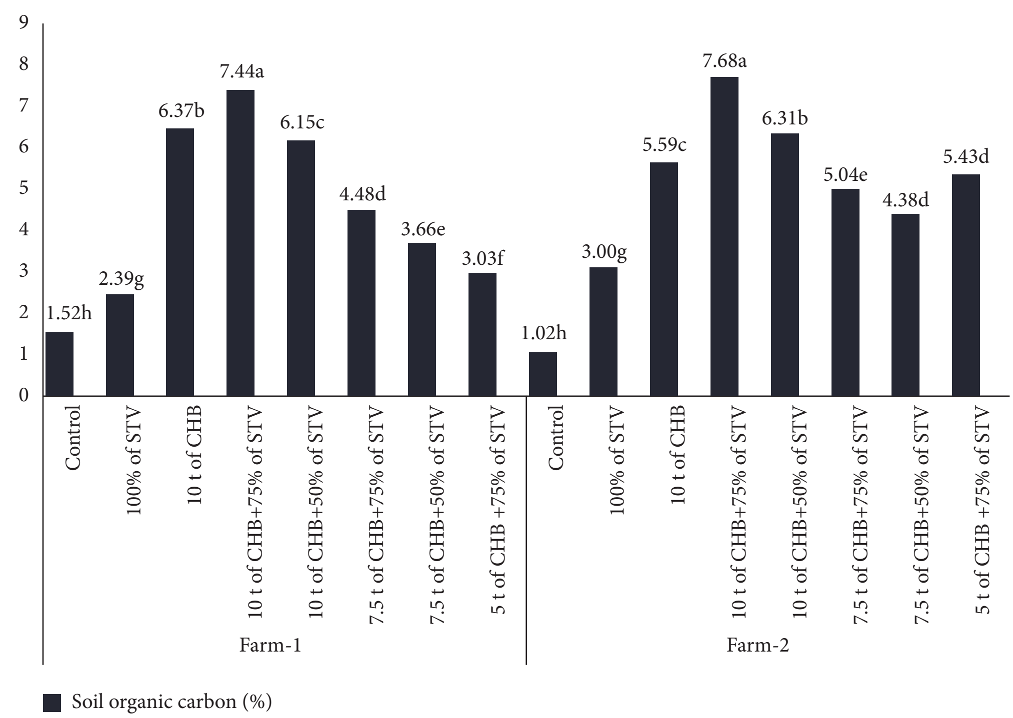

Figure 7: The effect of coffee husk biochar (CHB) and soil test value-based lime (STV) rates on soil organic carbon (SOC) of acidic soils.

respectively (Figure 10). The 7.5 ton CHB with 50% of STV ha^{-1} had the highest C/N (10.78%).

According to Maulana et al. [48], biochar has a high carbon content, which helps to produce humus and boost soil fertility. Contrary to this conclusion, Karim et al. [75] claimed that biochar is not a direct source of readily available nitrogen and can actually decrease the availability of nitrate and ammonium. However, there was a distinct trend in the effects of lime and biochar on soil total N in the current study, with biochar rate (10 $ton{\cdot}ha^{-1}$) and STV need rate at 50 to 75% of STV ha^{-1}, respectively. Lime can directly influence the pH of the soil, creating a more hospitable environment for soil microbiological activity and speeding up the release of plant nutrients, particularly nitrogen and phosphorus. The higher C/N could be related to lower nitrogen levels in the soils, as soil microbial activity releases extra carbon to soils. Similar idea was suggested in study of Liu et al. [88] and Ren et al. [89].

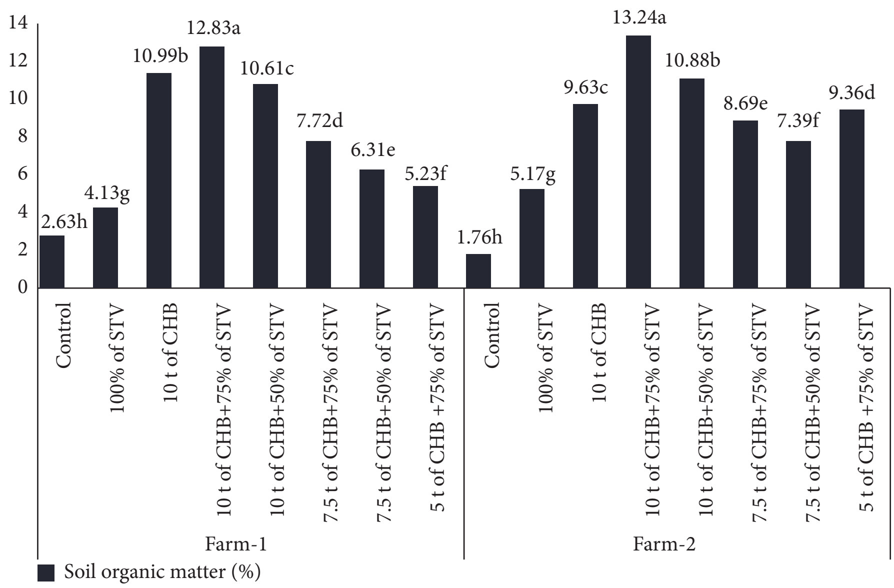

Figure 8: The effect of coffee husk biochar (CHB) and soil test value-based lime (STV) rates on soil organic matter (SOM) of acidic soils.

Table 4: Effect of coffee husk biochar (CHB) and/or soil test value-based lime (STV) rates on pH, SOC, TN, and available P of acid soils.

Factor ha^{-1}	pH (H_2O)	SOC (%)	SOM (%)	TN (%)	C/N (%)	Available P ($mg \cdot kg^{-1}$)
Farm-1						
Control	5.10^{e}	1.52^{h}	2.63^{h}	0.63^{e}	2.23^{e}	2.19^{d}
100% of STV	5.60^{d}	2.39^{g}	4.13^{g}	0.46^{f}	5.17^{b}	2.19^{d}
10 ton of CHB	6.11^{a}	6.37^{b}	10.99^{b}	1.40^{d}	4.55^{c}	2.81^{c}
10 ton of CHB + 75% of STV	5.98^{b}	7.44^{a}	12.83^{a}	1.68^{b}	4.43^{c}	4.86^{a}
10 ton of CHB + 50% of STV	6.09^{a}	6.15^{c}	10.61^{c}	0.73^{e}	8.46^{a}	3.61^{b}
7.5 ton of CHB + 75% of STV	5.89^{c}	4.48^{d}	7.72^{d}	1.50^{c}	2.98^{d}	3.81^{b}
7.5 ton of CHB + 50% of STV	5.93^{bc}	3.66^{e}	6.31^{e}	1.86^{a}	1.96^{e}	3.59^{b}
5 ton of CHB + 75% of STV	5.58^{d}	3.03^{f}	5.23^{f}	1.55^{c}	1.95^{e}	2.75^{c}
CV (%)	0.57	1.40	1.39	3.99	6.07	4.04
LSD (0.05)	0.05^{**}	0.10^{**}	0.18^{**}	0.08^{**}	0.45^{**}	0.22^{**}
Farm-2						
Control	4.64^{e}	1.02^{h}	1.76^{h}	0.27^{d}	3.75^{d}	2.81^{g}
100% of STV	6.08^{b}	3.00^{g}	5.17^{g}	0.46^{d}	6.46^{bc}	6.08^{b}
10 ton of CHB	6.22^{a}	5.59^{c}	9.63^{c}	0.97^{c}	5.72^{c}	4.08^{f}
10 ton of CHB + 75% of STV	6.02^{b}	7.68^{a}	13.24^{a}	2.11^{a}	3.68^{d}	6.96^{a}
10 ton of CHB + 50% of STV	6.04^{b}	6.31^{b}	10.88^{b}	0.84^{c}	7.47^{b}	4.71^{d}
7.5 ton of CHB + 75% of STV	5.51^{d}	5.04^{e}	8.69^{e}	1.31^{b}	3.84^{d}	5.53^{c}
7.5 ton of CHB + 50% of STV	5.74^{c}	4.38^{d}	7.39^{f}	0.40^{d}	10.78^{a}	4.88^{d}
5 ton of CHB + 75% of STV	5.48^{d}	5.43^{d}	9.36^{d}	1.30^{b}	4.15^{d}	4.37^{e}
CV (%)	1.01	1.64	1.64	0.97	11.98	2.92
LSD (0.05)	0.10^{**}	0.13^{**}	0.23^{**}	0.20^{**}	1.20^{**}	0.25^{**}

pH: potential of hydrogen, SOC: soil organic carbon, TN: total nitrogen, C/N: carbon-to-nitrogen ratio, P: phosphorous, ns: non-significant, *: significant ($P < 0.05$), and **: highly significant ($P < 0.01$).

3.4.4. Soil Available Phosphorous. Application of biochar and/or lime affected the amount of accessible P in the strongly and very strongly acidic soils (Table 3). A significant ($P < 0.01$) relationship was found between the ameliorant rate and soil accessible P in both Farm-1 and Farm-2 soils. The available P was increased in comparison to the control under the application of all the biochar and lime treatments (Figure 11). The highest available P ($4.86\ mg \cdot kg^{-1}$) was obtained from application of 10 ton of CHB + 75% of STV in Farm-1. The sedimentation of available P was improved from 25.57 to 121.92% in other treatments altered by CHB and STV rates followed by SOC and SOM, with the exception of the 100% of STV ha^{-1} ($2.19\ mg \cdot kg^{-1}$), which was statistic and figure par with control, and the least available phosphorous. Chali and Wakgari [35] found a direct association between the

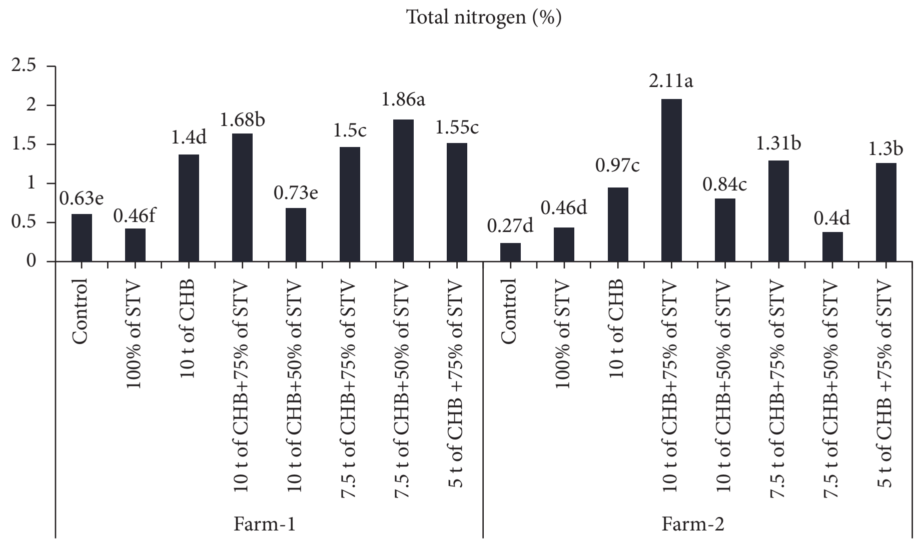

Figure 9: The effect of coffee husk biochar (CHB) and soil test value-based lime (STV) rates on soil total nitrogen (TN) of acidic soils.

pH level of acidic soil and its accessible p content. In addition, the restoration of soil phosphorous after application of organic matter in soil has been reported by Periyasamy and Temesgen [32]. The highest possible p accumulation was found in the treatment group that got 10 ton of CHB + 75% of STV ha^{-1} (6.96 $mg{\cdot}kg^{-1}$), while the lowest was found in the control group (2.81 $mg{\cdot}kg^{-1}$) in Farm-2. The application of CHB and/or STV resulted in a greater buildup of accessible p by 45.19 to 147.68% than the control treatment. The amount of readily available phosphorus increased under the effect of biochar and lime [25, 40].

Availability of phosphorous might be as a result of applying biochar and lime that reducing the activity of toxic ions, e.g., Fe and Al in soil reactions. Biochar can increase soil P sorption and help to increase the supply of mineralized phosphorous [36] and lime influences the soluble Al, H, and Fe to nontoxic levels and indirectly increases microbial activity to promote the use of remaining nutrients by plants [22]. The positive correlation between accessible p and pH (0.62%) showed that soil pH has a significant role in controlling the amount of P that is available to plants. The phosphorus was negatively linked to Al and Fe at low soil pH levels and is only available in less accessible forms in acidic soils [30].

In addition, lime based on the results of a soil test and biochar's pore size enables the adsorption of nutrients and the retention of heavy metals. According to Du et al. [90], biochar has the capacity to retain nutrients for four years, particularly those that are less mobile, like phosphorus, and it also helps the soil bind together and boosts its organic matter (OM) content. According to Table 5's correlation matrix analysis's description, the available P and EA for Farm-1 and Farm-2, respectively, had a moderately negative association (-0.44^{*}) and a strongly negative relationship (-0.50^{**}). In comparison to non-amended soils, biochar-amended soils had higher soil accessible P levels. This improvement was attributed to biochar's propensity to exchange and hold onto phosphate ions because of its positively charged surface sites.

3.4.5. Soil Cation Exchange Capacity (CEC), Exchangeable Acidity (EA), and Aluminum (EAl). The soil's CEC, EA, and EAl, variance analysis is depicted in Table 6. There were a significant level ($P < 0.05$) differences in CEC, EA, and EAl following the application of biochar and lime (Figures 12–14). The CEC of the soil was improved after addition of biochar and lime but the EA and EAl were decreased compared to the control treatment. The application of 10 ton of CHB + 75% of STV ha^{-1} and 7.5 ton of CHB + 50% of STV ha^{-1} rate applications resulted in the greatest CEC (37.76 to 37.78 $cmol_{(+)}kg^{-1}$) values in Farm-1 while the lowest CEC (5.66 $cmol_{(+)}kg^{-1}$) obtained from control. A highly significant ($P < 0.01$) difference was found in EA and EAl related to the application of biochar and lime rate. The highest EA (4.64 $cmol_{(+)}kg^{-1}$) was observed from control. The application of 10 ton of CHB + 75% of STV ha^{-1} resulted in the lowest EA (0.98 $cmol_{(+)}kg^{-1}$). The highest EAl (3.92 $cmol_{(+)}kg^{-1}$) was obtained from control. Thus, the application of 10 ton of CHB + 75% of STV ha^{-1} resulted in the lowest EAl concentration (0.70 $cmol_{(+)}kg^{-1}$) ever reported. The application of 7.5 ton of CHB + 75% of STV ha^{-1} resulted in the maximum CEC (37.44 $cmol_{(+)}kg^{-1}$), whereas the control had the lowest CEC (1.59 $cmol^{(+)}kg^{-1}$) in Farm-2. All treatments that used biochar and/or lime had a greater CEC content than the control.

The application of 10 ton of CHB + 50% of STV ha^{-1} and 7.5 ton of CHB + 50% of STV ha^{-1} exhibited the lowest EA (0.85–0.92 $cmol_{(+)}kg^{-1}$) whereas the control had the highest EAl (3.92 $cmol_{(+)}kg^{-1}$). The inherent qualities of surface area, porosity, variable charge and sorption capacity in biochar, and base saturation in lime could lead to the greatest increase in CEC. Similarly, an increase in CEC and a decrease in EA and EAl in soil with an initial strongly acidic soil after the application of biochar and lime were reported by different authors [40, 72, 83].

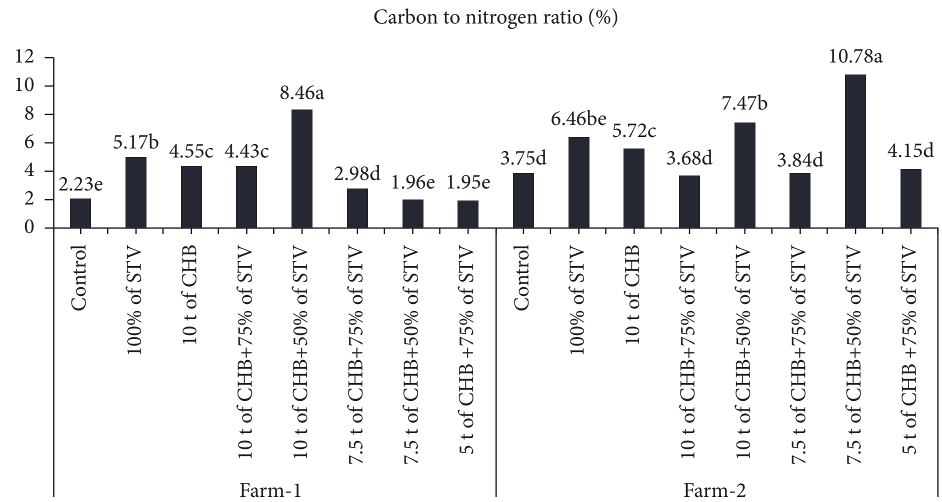

Figure 10: The effect of coffee husk biochar (CHB) and soil test value-based lime (STV) rates on soil carbon-to-nitrogen ratio (C/N) of acidic soils.

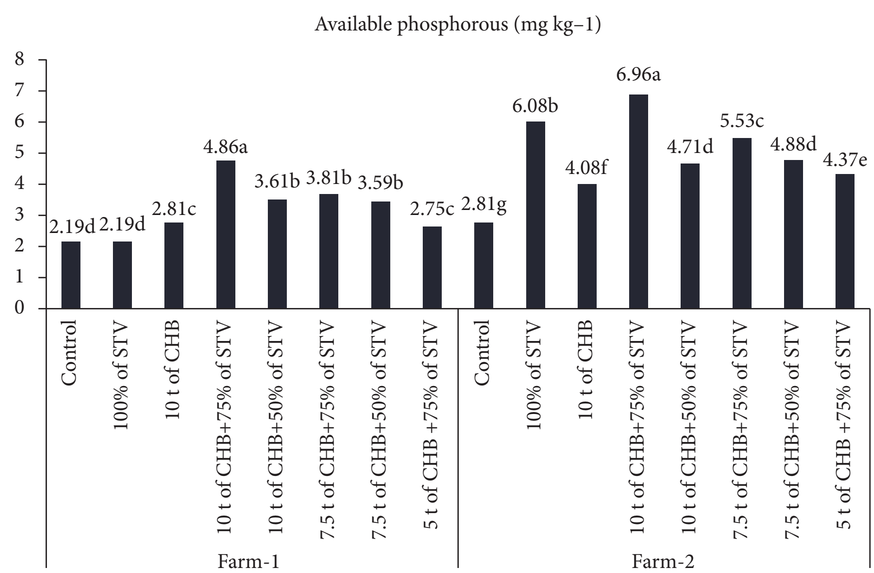

Figure 11: The effect of coffee husk biochar (CHB) and soil test value-based lime (STV) rates on available phosphorus (P) of acidic soils.

According to Manso et al. [91], lime augmentation of the Ca^{2+} and Mg^{2+} dissociated in soils to replace H and Al ions from the soil solution and soil exchange complex. Contrarily, oxidation following weathering leads to the production of carboxylic groups on the margins of the aromatic carbon, which increases CEC [85]. The existence of pH-dependent negative charges, which might rise with rising soil pH due to added lime, may be responsible for the link between CEC and soil pH level. It is possible that the decline in EA and EAl is being caused by an increase in CEC, which has the ability to bind Al and Fe to the soil exchange sites. This, in turn, would provide a higher amount of basic cations to decrease EA ($H^+ + Al^{3+}$) by combined application of biochar and lime. The direct correlation between CEC and soil pH in Farm-1 may be owing to the presence of pH-dependent negative charges, which rise in concentration with soil pH as a result of lime and biochar application. Additionally, the formation of an Al complex by oxidized organic functional groups such as carboxylic and phenolic at the biochar surface may be responsible for the reduction of exchangeable EAl content by biochar and/or lime [40].

3.4.6. Soil Ammonium (NH_4-N) and Nitrate (NO_3-N) and Total Mineral Nitrogen (TMN). The application of combined biochar and lime rate had recorded the significant ($P < 0.05$) difference in the content of soil's ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), and total mineral nitrogen (TMN) (Figures 15–17, and Table 6). The NH_4-N in Farm-1 was increased by applying single CHB at a rate of 10 ton·ha^{-1}, whereas the control had the lowest amount (15.55 mg·kg^{-1}). Contrarily, the control and 100% of

Table 5: Pearson correlation among acidic soil properties' parameters.

Variable	BD	pH	SOC	CEC	Available P	EA	NH_4-N	NO_3-N	TMN
Farm-1									
BD	1								
pH	-0.80^{**}	1							
SOC	-0.83^{**}	0.83^{**}	1						
CEC	-0.41^{*}	0.29^{ns}	0.46^{*}	1					
Available P	-0.61^{**}	0.62^{**}	0.63^{**}	0.66^{**}	1				
EA	0.13^{ns}	-0.35^{ns}	-0.23^{ns}	-0.07^{ns}	-0.44^{*}	1			
NH_4-N	-0.54^{**}	0.66^{**}	0.64^{**}	-0.26^{ns}	0.12^{ns}	-0.06^{ns}	1		
NO_3-N	0.71^{**}	-0.77^{**}	-0.87^{**}	-0.10^{ns}	-0.23^{ns}	-0.00^{ns}	-0.83^{**}	1	
TMN	0.56^{**}	-0.51^{**}	-0.71^{**}	-0.55^{**}	-0.26^{ns}	-0.10^{ns}	-0.17^{ns}	0.68^{**}	1
Farm-2									
BD	1								
pH	-0.64^{**}	1							
SOC	-0.19^{ns}	0.24^{ns}	1						
CEC	-0.31^{ns}	-0.24^{ns}	0.62^{**}	1					
Available P	-0.45^{*}	0.37^{ns}	0.08^{ns}	0.24^{ns}	1				
EA	0.32^{ns}	-0.28^{ns}	-0.35^{ns}	-0.33^{ns}	-0.50^{**}	1			
NH_4-N	-0.56^{**}	0.25^{ns}	0.34^{ns}	0.57^{**}	0.26^{ns}	-0.56^{**}	1		
NO_3-N	0.52^{**}	-0.21^{ns}	-0.49^{**}	-0.53^{**}	0.03^{ns}	0.50^{**}	-0.79^{**}	1	
TMN	-0.43^{*}	0.21^{ns}	-0.13^{ns}	0.44^{*}	0.42^{*}	-0.45^{*}	-0.88^{**}	-0.40^{*}	1

Bulk density (BD), potential of hydrogen (pH), soil organic carbon (SOC), cation exchange capacity (CEC), available phosphorous (available P), exchangeable acidity (EA), ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), total mineral nitrogen (TMN) as influenced by effect of biochar (CHB), and soil test value-based lime (STV) rates. ns: non-significant, *: significant ($P < 0.05$), **: highly significant ($P < 0.01$).

Table 6: The effects of coffee husk biochar (CHB) and soil test value-based lime (STV) rates on cation exchange capacity (CEC), exchangeable acidity (EA), exchangeable aluminum (EAl), ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), and total mineral nitrogen (TMN) of acidic soils.

Factor ha^{-1}	CEC ($cmol_{(+)}kg^{-1}$)	EA ($cmol_{(+)}kg^{-1}$)	EAl ($cmol_{(+)}kg^{-1}$)	NH_4-N ($mg{\cdot}kg^{-1}$)	NO_3-N ($mg{\cdot}kg^{-1}$)	TMN ($mg{\cdot}kg^{-1}$)
Farm 1						
Control	5.66^{g}	4.64^{a}	3.92^{a}	15.55^{e}	21.26^{a}	36.81^{a}
100% of STV	11.82^{f}	1.76^{e}	1.07^{f}	17.64^{d}	19.03^{b}	36.67^{a}
10 ton of CHB	20.01^{d}	3.19^{b}	2.66^{b}	25.69^{a}	6.14^{g}	31.83^{b}
10 ton of CHB + 75% of STV	37.76^{a}	0.98^{f}	0.70^{g}	21.01^{c}	12.57^{e}	33.58^{b}
10 ton of CHB + 50% of STV	21.60^{c}	2.00^{d}	1.28^{e}	24.18^{b}	9.23^{f}	33.41^{b}
7.5 ton of CHB + 75% of STV	37.78^{a}	2.54^{c}	1.47^{d}	15.88^{e}	16.87^{d}	32.75^{b}
7.5 ton of CHB + 50% of STV	16.60^{e}	2.12^{d}	1.45^{d}	21.01^{c}	17.13^{cd}	38.14^{a}
5 ton of CHB + 75% of STV	24.95^{b}	3.05^{b}	2.40^{c}	18.52^{d}	18.08^{bc}	36.60^{a}
CV (%)	4.05	3.72	4.48	3.91	3.90	3.14
LSD (0.05)	0.75^{**}	0.14^{**}	0.14^{**}	1.36^{**}	1.02^{**}	1.92^{**}
Farm 2						
Control	1.59^{h}	5.00^{a}	3.95^{a}	13.51^{f}	13.76^{a}	27.28^{e}
100% of STV	11.48^{g}	3.21^{c}	2.10^{c}	15.78^{e}	12.69^{a}	28.47^{de}
10 ton of CHB	19.67^{e}	2.79^{e}	2.23^{b}	22.78^{b}	6.59^{e}	29.37^{cd}
10 ton of CHB + 75% of STV	31.50^{b}	1.10^{h}	0.85^{e}	21.21^{c}	8.96^{cd}	30.17^{bc}
10 ton of CHB + 50% of STV	21.27^{d}	3.08^{d}	2.33^{b}	19.62^{d}	11.22^{b}	30.85^{b}
7.5 ton of CHB + 75% of STV	37.44^{a}	2.27^{f}	1.44^{d}	24.68^{a}	8.17^{d}	32.85^{a}
7.5 ton of CHB + 50% of STV	16.93^{f}	1.66^{g}	0.92^{e}	18.70^{d}	9.93^{bc}	28.63^{de}
5 ton of CHB + 75% of STV	24.95^{c}	3.38^{b}	2.33^{b}	14.15^{f}	11.07^{bc}	25.22^{f}
CV (%)	3.68	2.52	3.52	2.91	7.85	2.80
LSD (0.05)	1.35^{**}	0.12^{**}	0.12^{**}	0.95^{**}	1.41^{**}	1.42^{**}

ns: non-significant, *: significant ($P < 0.05$), **: highly significant ($P < 0.01$).

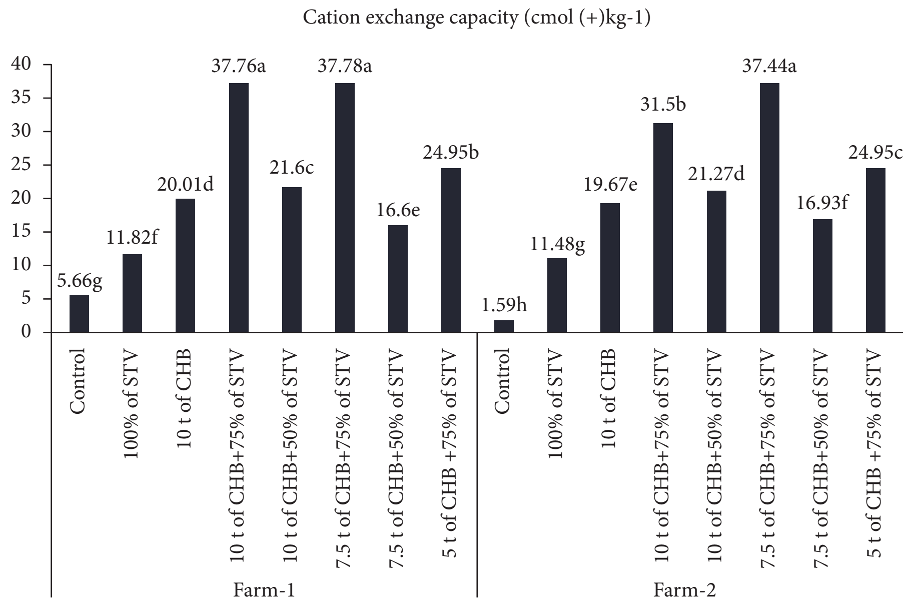

Figure 12: The effect of coffee husk biochar (CHB) and soil test value-based lime (STV) rates on cation exchange capacity (CEC) of acidic soils.

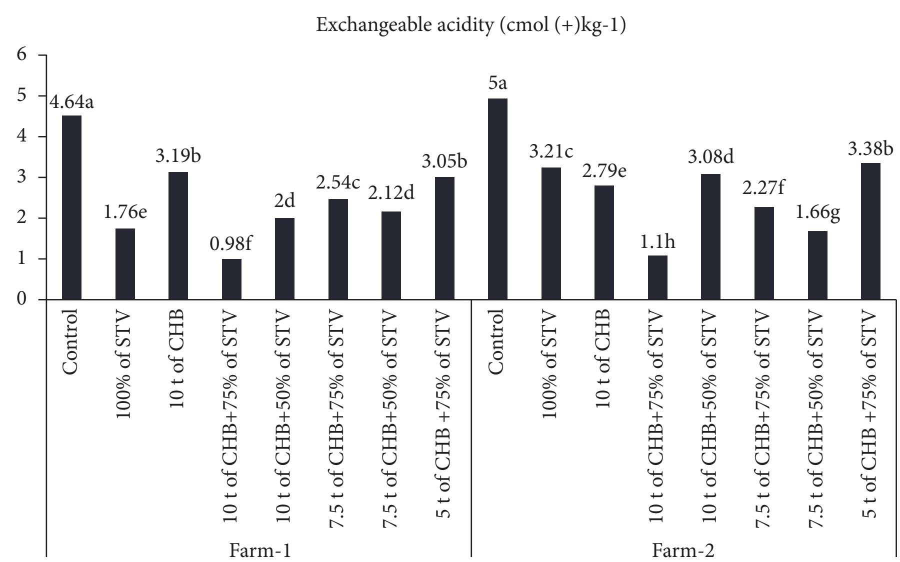

Figure 13: The effect of coffee husk biochar (CHB) and soil test value-based lime (STV) rates on exchangeable acidity (EA) of acidic soils.

STV ha^{-1} produced the greatest and lowest NO_3-N contents, respectively (control: 25.26 mg·kg^{-1} and 100% of STV ha^{-1}: 19.03 mg·kg^{-1}, respectively), and the direction of 10 ton of CHB: 6.14 mg·kg^{-1}. 7.5 ton of CHB + 50% of STV ha^{-1} (38.14 mg·kg^{-1}), control (36.81 mg·kg^{-1}), 100% STV (36.67 mg·kg^{-1}) and 5ton of CHB + 75% of STV ha^{-1} (36.60 mg·kg^{-1}) had the highest total mineral nitrogen values. Regarding Farm-2, the highest NH_4-N (24.68 mg·kg^{-1}) was obtained from the 7.5 ton of CHB + 75% of STV proceeding the treatment of 10 ton·ha^{-1} (22.78 mg·kg^{-1}) and 10 ton of CHB + 75% of STV ha^{-1} (21.21 mg·kg^{-1}), while the lowest NH_4-N (13.51 mg·kg^{-1}) was obtained from 5 ton of CHB + 75% of STV ha^{-1} next to control treatment (14.15 mg·kg^{-1}). Full doze (100%) of STV ha^{-1} treatment yielded the highest NO_3-N concentration (13.76 mg·kg^{-1}), whereas 10 ton of CHB yielded the lowest (6.59 mg·kg^{-1}). The amount of TMN (mg·kg^{-1}) that was recorded was 32.85 mg·kg^{-1} in 7.5 ton of CHB + 75% of STV ha^{-1}, and 25.22 mg·kg^{-1} in 5 ton of CHB + 75% of STV ha^{-1}. According to Aubertin's study [92], mixtures containing labile fraction or inhibitory compounds have a negative impact on the mineralization of nutrients. Similarly, different researchers were reported the impact of biochar and lime application on mineral nitrogen [93–95].

The highest residual NH_4-N levels may be related to the organic matter in biochar and plant residues from the previous year when nitrification is the only process allowed. The decrease in NO_3-N level following application biochar

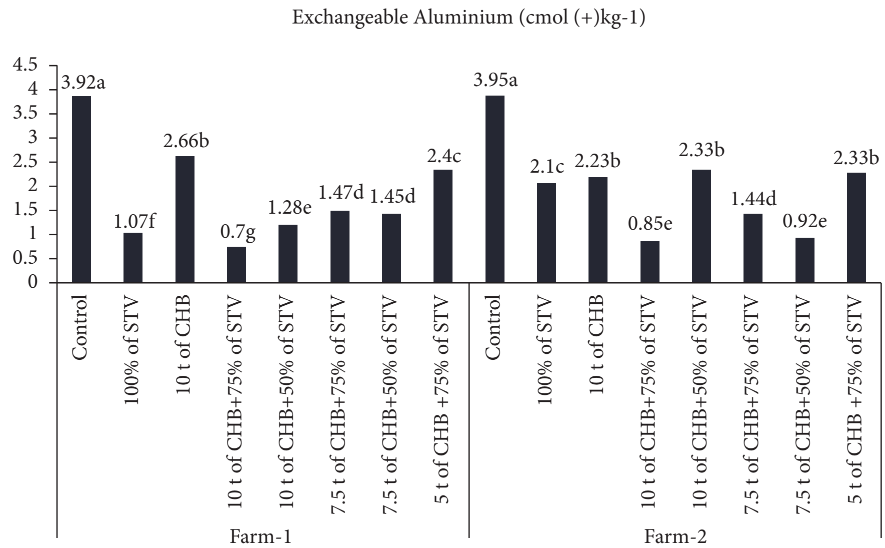

Figure 14: The effect of coffee husk biochar (CHB) and soil test value-based lime (STV) rates on aluminum (EAl) of acidic soils.

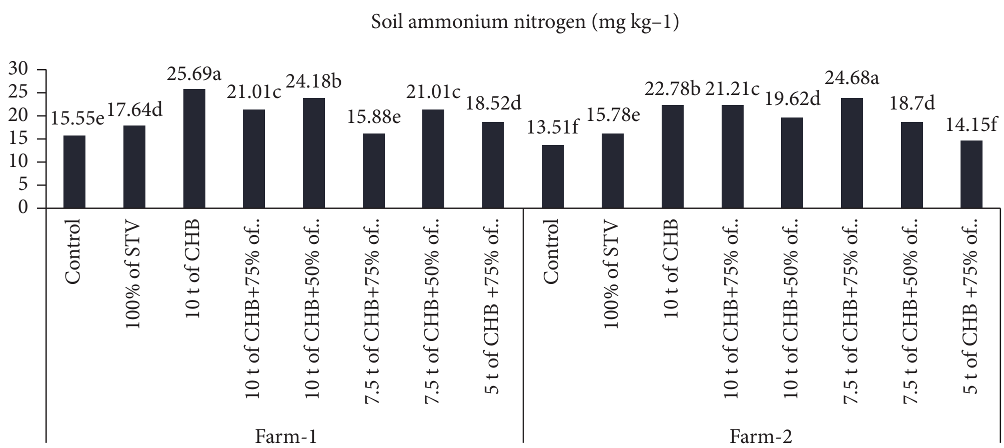

Figure 15: The effect of coffee husk biochar (CHB) and soil test value-based lime (STV) rates on soil ammonium nitrogen (NH_4-N) content of acidic soils.

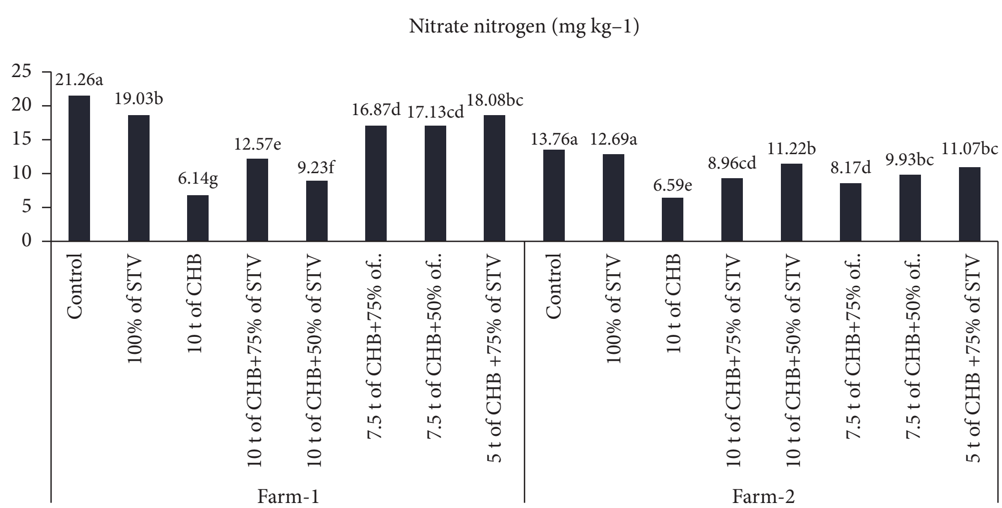

Figure 16: The effect of coffee husk biochar (CHB) and soil test value-based lime (STV) rates on soil nitrate nitrogen (NO_3-N) content of acidic soils.

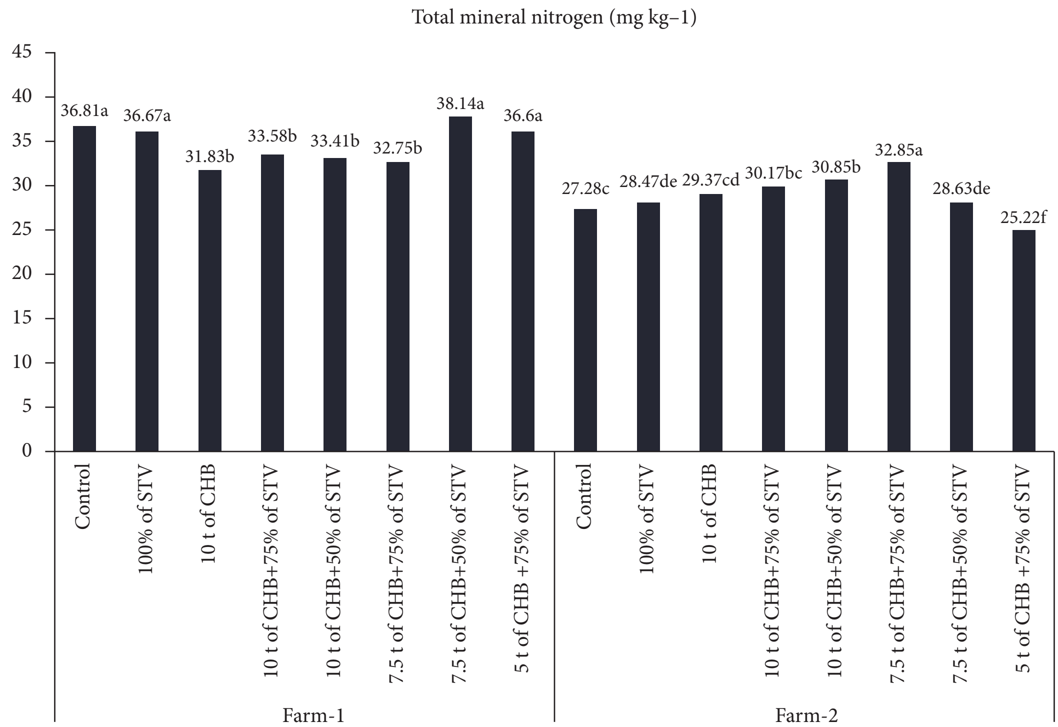

Figure 17: The effect of coffee husk biochar (CHB) and soil test value-based lime (STV) rates on soil total mineral nitrogen (TMN) content of acidic soils.

may perhaps be related to biochar's capacity for adsorption, which inhibits nitrification. Therefore, the application of biochar and/or lime to the soils reduced the likelihood of nutrient losses in the soils and could boost beneficial effects on crop growth and yields over time through gradual release of nutrients to the soils. In support of the current study, several investigations have demonstrated that the addition of lime and biochar keeps mineral nitrogen in the soil longer by preventing it from leaching [29, 31, 32]. By contradicting this present study's findings, Radziemska et al. [41] observed higher rates of nitrification on severely acidic soil when liming is administered.

The highest soil TMN concentration of Farm-1's control treatment may be because of the soil's relatively inherent N content and higher rate of nitrogen mineralization in soils with low C/N rates. Comparatively, TMN was better in amended soils than in no-amended treatments; this improvement may have been due to the increased CEC in biochar. Cation exchange capacity discharges the negative charges and could create high reaction within soils systems [79].

3.5. Relationships between the Physical and Chemical Parameters of the Acidic Soils as Affected by Biochar and Lime Rates. There was a significant correlation in each parameter tested at a $P < 0.05$) level (Table 5). In Farm-1, the soil pH exhibited a strong and negative correlation with BD (−0.80), but a strong and positive relationship with SOC (0.83). Available P has a statistically significant and favorable link with the pH (0.62), SOC (0.63), and CEC (0.66), respectively. The available P was negatively and significant correlation with BD (−0.61) and EA (−0.44). Moreover, negative correlations between NH_4-N and BD (−0.54) and NO_3-N (−0.83) were grasped. In Farm-2, soil pH had a strongly and negative relationship with BD (−0.64). Available P was strongly and negatively associated with EA (−0.50) and moderately and negatively associated with BD (−0.45) and strongly and negatively correlated with BD (−0.56), EA (−0.56), and NO_3-N (−0.79), NH_4-N exhibited a substantial positive and significant relationship with CEC (0.57). Total mineral nitrogen had negative and significant association with NH_4-N (−0.88), BD (−0.43), and negative correlation with EA (−0.45), and positive correlation with CEC (0.44) and available P (0.42).

Interestingly, in the soils of the two study sites (Farms-1 and 2), the rise in soil pH and SOC almost entirely explained the gradual rise in the ability of acidic soils to retain nutrients, particularly the available P and NH_4-N, while, the direction of TMN could depend on the outcomes of both the NH_4-N (denitrification) and NO_3-N (nitrification) processes. This finding of nutrient retention is confirmed by studies of Li et al. [94] and Munera-Echeverri et al. [95]. The NO_3-N was negatively linked with soil pH level, CEC, and NH_4-N. When nitrification rose in the instance of Farm-1, the relationship between TMN and NO_3-N also grew. However, the Farm-2 soil had recorded the opposite process. It is probable that in this situation, denitrification is taking place more slowly than nitrification [41, 96].

4. Conclusion and Recommendation

The results show that the physicochemical characteristics of the soil under investigation were enhanced by applying lime and biochar together. The application of biochar and lime, when compared to the control, showed enhanced soil physicochemical characteristics. This improvement was mostly observed after two rates of biochar (7.5 and 10 ton·ha^{-1}) were combined together with two rates of lime (50 and 75% ha^{-1}). Soil porosity and moisture content increased with decreasing bulk density. The soil also showed increases in pH, organic carbon content, carbon-to-nitrogen ratio, total nitrogen, available phosphorus, and cation exchange capacity, but decreased aluminum toxicity. Moreover, there was a negative correlation observed for NO_3-N, whereas NH_4-N increased as soil pH level and organic carbon content increased. The combination of lime and biochar rate had improved the soil's moisture content and porosity, enabling the preservation of the soil's improved physical characteristics. The ash accumulation in biochar and the exchangeable basic cations in lime may have played a role in chemical alterations in the soil that reduced the toxicity of ions.

According to the results of the current study, applying biochar at a rate of 7.5 to 10 ton·ha^{-1} combined with lime at a rate of 50 to 75% of lime ha^{-1} is capable of enhancing the properties of strongly and very strongly acidic soils. In order to provide an explicit recommendation, more research is required to examine the effects of combined biochar and lime rates on soil after harvest, crop yield, and financial gains.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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