Effect of Biochar Application Rate, Production (Pyrolysis) Temperature and Feedstock Type (Rice Husk/Maize Straw) on Amendment of Clay-Acidic Soil

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Abstract. Biochar is a porous solid material produced by pyrolysis (oxygen-free burning) of biomass for the sake of improving soil quality. The aim of this study was to examine the effect of biochar application rate, pyrolysis temperature and feedstock type on the fertility of leached, acidic, clay soil. The biochars used in the study were produced from rice husk (RH) and maize straw (MS) at pyrolysis temperatures of 350, 450 and 550 °C, so in total six biochars were used. To examine the effects of biochar on soil amendment, the six biochars were mixed with the acidic, clay soil at four different levels of applications (0.5, 2.0, 5.0 and 10.0% w/w) then they were chemically characterized. pH, electrical conductivity, CEC, exchangeable basic cations, WHC, organic carbon and total nitrogen content were determined. The increment in the application rate of biochar resulted in a significant increment in soil pH, CEC, exchangeable basic cations, WHC, Organic carbon content. Increasing the biochar production temperature from 350 to 550 °C brought slight increment in pH, Electrical conductivity and Organic carbon content of the soil. Incorporating RH biochar in the soil resulted in higher soil pH but higher organic carbon content of the soil was acquired by incorporating MS biochar.

Keywords: Biochar · Pyrolysis temperature · Soil amendment · Rice husk · Maize straw

1 Introduction

Ethiopia is among the developing countries with majority (about 85%) of the people earn their living mainly by agriculture. Agriculture in Ethiopia has a significant role in securing economic development since the sector generates over 46% of GDP and 80% of export earnings [1]. Nonetheless, many challenges are facing the sector which makes it difficult to attain the pre-planned targets. Among these challenges, the soil fertility issue is the main one. Some of the reasons that bring a poor soil quality in the country include poor agronomic practices, limited awareness of communities, absence of proper

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land policies and inappropriate agricultural techniques. The low nutrient concentration and high acidity are becoming the major challenges of the country's soil.

Agricultural residue management is recommended in several researches as one method for enhancement of soil fertility [2, 3]. However, a problem of agricultural residue management is widely available in Ethiopia although residues are found in surplus. Few amounts of the country's agricultural residues are utilized as a fodder but huge amount is un-utilized as transformation of the residues to an asset is lacking. As a result of this, the surplus residues are typically burnt on-farm [4]. The burning of these residues leads to a release of GHGs to the atmosphere and contributed to bring the agricultural sector as a leader in GHGs emission compared to other sectors [5]. Ethiopia's GHGs emission has shown an increment from time to time despite it has insignificant contribution at global scale. If current practices prevail, GHG emissions in Ethiopia will more than double from 150 Mt CO_2e to 400 Mt CO_2e in 2030 [5].

Therefore, it is very important for developing inexpensive and efficient solution that enhances soil fertility and reduces the emission of GHGs before they bring a devastating problem on human life and the ecosystem of Ethiopia. Many studies have proposed biochar technology as a viable option to offer an integrated approach to contribute to the challenges [6]. In the last decade an interest in biochar and its impact on soil properties has boomed worldwide. The use of biochar amendments to replenish soil organic carbon (SOC) pools, restore soil fertility and sequester carbon has been recommended by the United Nations Convention to Combat Desertification (UNCCD) during Climate Change Conference held in Copenhagen in 2009 [7].

Biochar is solid material produced by pyrolysis (oxygen-free burning) of biomass. Although biochar and charcoal are used interchangeably in many literatures, there is a major distinction between the two. Unlike charcoal, biochar is produced at specific temperature with the intent to be added to a soil as a means of enhancing soil quality and sequestering carbon. Biochar has different properties depending on the type of biomass feedstock and the pyrolytic conditions used in its production [8].

The outputs of several researches have shown the potential of biochar to improve soil quality by retaining nutrients and water, reducing the acidity, enhancing the cation exchange capacity (CEC) of the soil and attracting more beneficial fungi and microbes to the soil [9–12]. On the other hand, biochar's environmental benefit is a straight forward mechanism. The organic matter used for biochar production forms a stable structure while it is pyrolyzed. The stable form of the biochar is highly resistant to chemical and biological degradation and makes it stable in the soil for a long term; even for centuries and millennia. Consequently, it sequesters carbon derived from the organic matter for a long period which leads to withdrawal of CO_2 from the atmosphere [8].

Upon the author review, no scientific study has been carried out regarding the simultaneous impact of biochar production temperature, application rate and feedstock type despite many researches are conducted around the area. Hence, the motivation behind this research is assessing the simultaneous impact of the above three parameters on the amendment of clay, acidic soil which is the common problematic type among wide variety of soils available in Ethiopia.

2 Materials and Methods

2.1 Raw Material Collection

The major raw materials used in this study are soil and agricultural residues (rice husk and maize straw). The soil for the study was collected from farmer's field in Entoto area, North of Addis Ababa. The area was selected based on the recommendation of soil experts of the Agricultural research center. The study outcome of the center has shown the agriculture around the area is currently facing a severe problem of intensive run-off and erosion due to reduction in organic matter, water filtration, and water and nutrient retention capacity of the soil. The rice husk was acquired from Fogera district of South Gondor zone in the Amhara regional state, one of high rice producing place in Ethiopia. The maize straw was collected from government farm in Ziway town.

2.2 Soil Sampling and Preparation

Soil was sampled with a soil auger at a depth of 20 cm after clearing the top 10 cm of the soil surface. Thereafter soil samples were subjected to air-drying, and further crushed to reduce heterogeneity and provide maximum surface area for physical and chemical reactions. After crushing, soil samples sieved through a mechanically vibrating 2-mm mesh for 10 min so as to sort out coarse fragments and also bigger organic materials, whose nutrients might influence the results of the upcoming analyses. Because the soil samples were not allowed to stay moist for extended periods of time, the sieved soil was spread on plastic covers and left to dry in the sun for one day. Finally, soil used for laboratory analyses was put into polythene bags.

2.3 Biochar Production

Biochar was produced using a lab-scale slow pyrolysis process after preparing a new pyrolysis set up in the School of Chemical and Bio-Engineering laboratory of Addis Ababa University. All runs in the experimentation of this research were conducted in a batch process of pyrolysis. First pretreated feedstocks of approximately 100 grams were added into the reactor tube. The reactor was then flushed with N_2 gas at a pressure of 5 bar to maintain anoxic environment. Whenever there was N_2 flushing the other hole that was closed with a lid becomes uncovered to allow the release of the unwanted oxygen. The flushed reactor was then placed in the furnace at room temperature for the start of the charring process and the temperature was raised at an average rate of 10 °C min^{-1} until the specific desired temperature was reached and held constant. The series of experiments were conducted to pyrolyze the rice husk and maize straw at 350 °C, 450 °C and 550 °C to obtain six samples (RH350, RH450, RH550, MS350, MS450 and MS550). After one hour of heating and charring the power supply was turned off and the system was cooled over night to reach room temperature. Then, the biochar were grounded and sieved through a mechanically vibrating 2-mm mesh for 10 min so as to have the same particle size as that of the soil.

2.4 Preparation of Soil-Biochar Mixtures

The six biochars produced from RH and MS at 350, 450 and 550 °C pyrolysis temperatures were applied to the soil at 0.5%, 2%, 5% and 10% application rates and mixed thoroughly. Therefore, a total of 24 soil-biochar mixtures were prepared.

2.5 Laboratory Analysis

The raw soil's and soil-biochar mixtures' pH and Electrical conductivity (EC) were measured in water at a soil-water ratio of 1:2.5 using pH and conductivity meter respectively. The water holding capacity (WHC) was determined by putting the soil or soil-biochar mixtures into a glass funnel fitted with filter paper then saturating it with water and determines the quantity of water it retained after one day. The organic carbon and total nitrogen (N) content of the soil and soil-biochar mixtures were determined by Walkley-Black and Kjeldahl methods respectively [13, 14]. Total exchangeable K and Na amounts were analyzed using flame photometer whereas total exchangeable Ca and Mg were analyzed by atomic absorption spectrophotometer from the soil leached by 1 N ammonium acetate at pH 7 [15]. In similar fashion, CEC was determined after leaching the soil using 1 N ammonium acetate at pH 7 then titrimetrical estimation by distillation of ammonium that was displaced by sodium [16].

2.6 Statistical Analysis

One-way analysis of variance (ANOVA) was performed to assess the significance differences in soil parameters and plant growth between different soil-biochar treatments, using the general factorial procedure of Design-expert@7.1.

3 Result and Discussion

3.1 Effect of Biochar Application Rate, Biochar Production (Pyrolysis) Temperature and Biochar Production Feedstock on Soil PH and EC Content

The effect of biochar application rate, biochar production (pyrolysis) temperature and biochar production feedstock on clay acidic soil pH and EC are given in Figs. 1 and 2 respectively. The statistical analysis revealed that the soil pH and EC values were significantly ($p < 0.05$) affected by biochar application rate and biochar production (pyrolysis) temperature. However, the biochar feedstock (being RH or MS) does not have significant ($p > 0.05$) effect on soil pH and EC.

The highest values of pH and EC were observed in soil treated with 10% biochar application rate, while the lowest values were recorded at the untreated soil. In consistence with these results, Agusalim et al. also reported increment of soil pH from 3.75 to 4.90 after applying 10 tones/ha of rice husk biochar [17]. The existence of alkaline carbonates, oxides, and hydroxide in the ash fraction of the biochar is the main potential reason for the observed increment of soil pH in the biochar treated soil compared to the control is likely due to [6].

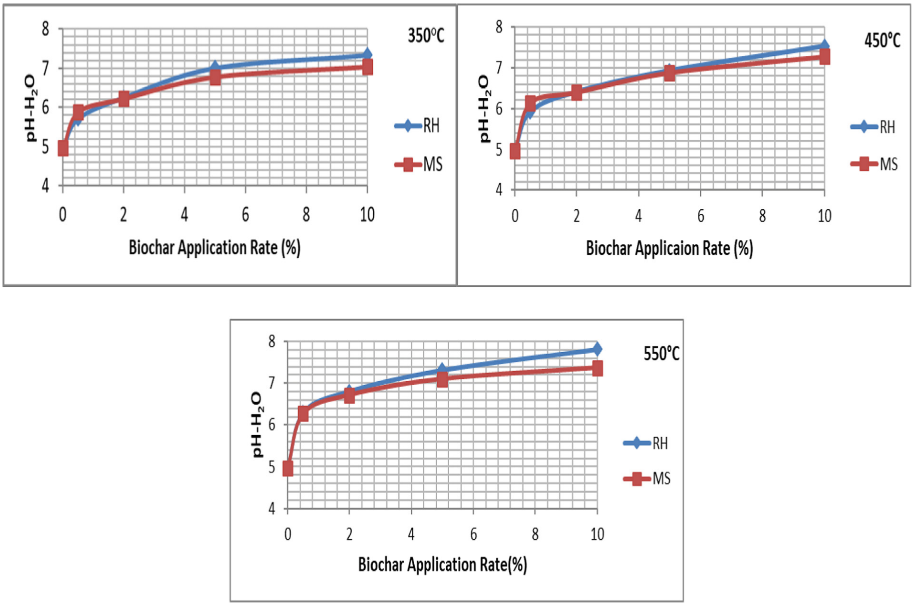

Fig. 1. Effect of application rate and feedstock type of biochars produced at pyrloysis temperature of 350 °C (top left), 450 °C (top right) and 550 °C (bottom) on soil pH

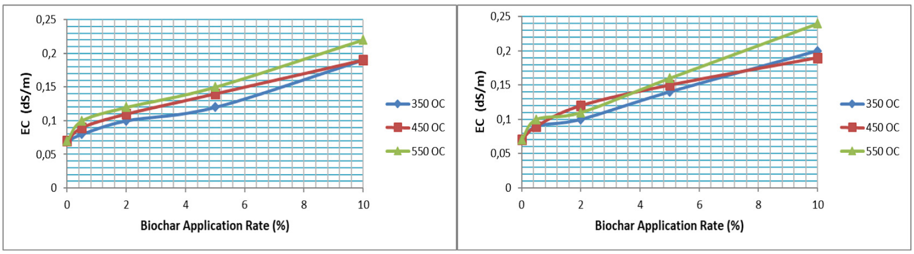

Fig. 2. Effect of application rate and production (pyrolysis) temperature of biochars derived from rice husk (left) and maize straw (right) on soil EC

According to the results of this study, the soil pH and EC increases with the biochar production (pyrolysis) temperature. The highest pH and EC values were observed in soil treated with biochar produced at 550 °C pyrolysis temperature. The potential reason for increment of the soil pH with pyrolysis temperature of the biochar might be the destruction of acidic functional groups on the biochar surface and the reduction of oxygen that resulted in the removal of various acidic functional oxides at high temperature. In agreement to this result, the pH increment also observed with increasing the pyrolysis temperature between 300 and 500 °C during rice husk and sugar cane bagasse pyrolysis from the research output of Shinogi and Kanri [18]. On the other hand, the ash content of biochar obtained at higher pyrolysis temperatures is a possible reason to bring an increment in the soil EC with pyrolysis temperature.

3.2 Effect of Biochar Application Rate, Biochar Production (Pyrolysis) Temperature and Biochar Production Feedstock on Soil WHC

The effect of biochar application rate, biochar production (pyrolysis) temperature and biochar production feedstock on WHC of clay acidic soil is given in Fig. 3. The WHC of the soil was significantly ($p < 0.05$) affected by biochar application rate only. However, the pyrolysis temperature to produce the biochars and the type of feedstocks (being either RH or MS) for biochar production don't have a significant ($p > 0.05$) effect on the WHC of the soil.

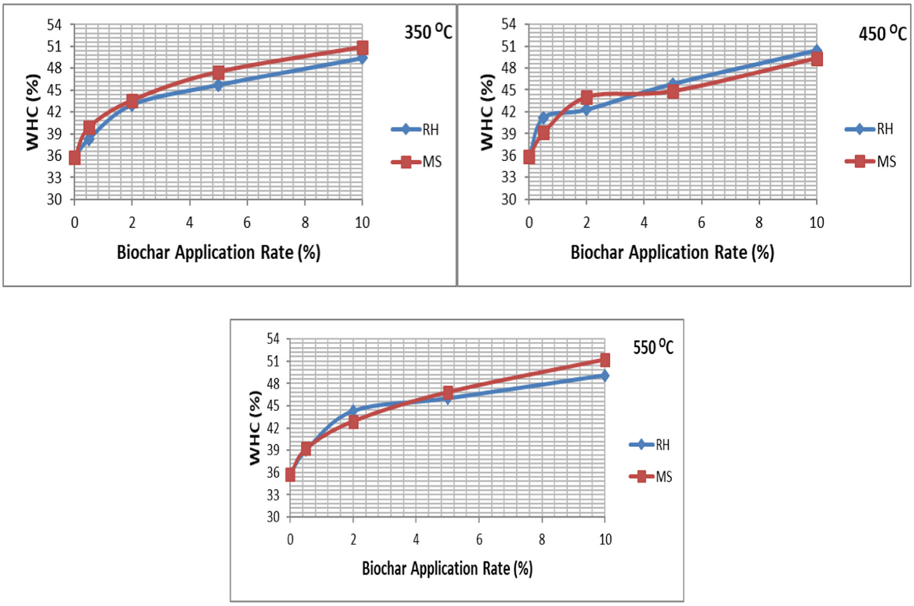

Fig. 3. Effect of application rate and feedstock type of biochars produced at pyrloysis temperature of 350 °C (top left), 450 °C (top right) and 550 °C (bottom) on soil WHC

The highest values of WHC were observed in soil treated with 10% biochar application rate, while the lowest values were recorded at the control (0%) or untreated soil.

The potential increment of WHC with the application rate of biochar is due to the ability of the porous structure of the biochar to retain water. The other hypothesized reason is the improved aggregation or structure of the soil after biochar incorporation. Therefore, it is quite logical that soil applied with biochar had the highest WHC. The results of this study is similar to those reported by Agusalim et al., Sokchea et al. and Sisomphone et al. where WHC was increased from 11.3 to 15.5%, 43 to 53% and 40 to 50% respectively due to the application of biochar [17, 19, 20].

3.3 Effect of Biochar Application Rate, Biochar Production (Pyrolysis) Temperature and Biochar Production Feedstock on Soil Organic C and Total N

The mean values of Soil Organic Carbon (SOC) and Total Nitrogen (TN) across different biochar application rates, pyrolysis feedstocks and temperatures are given in Figs. 4 and 5 respectively. The SOC was significantly (P < 0.05) affected by the biochar application rate and pyrolysis temperature. Nevertheless, it was not significantly (P > 0.05) affected by the biochar production feedstock either being RH or MS. On the other hand, the TN content of the soil was not significantly (P > 0.05) affected by all the three parameters.

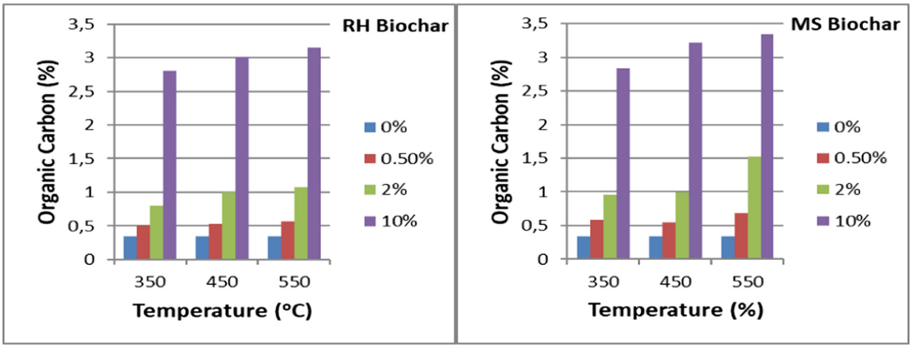

Fig. 4. Effect of application rate and production (pyrolysis) temperature of biochars derived from rice husk (left) and maize straw (right) and on SOC

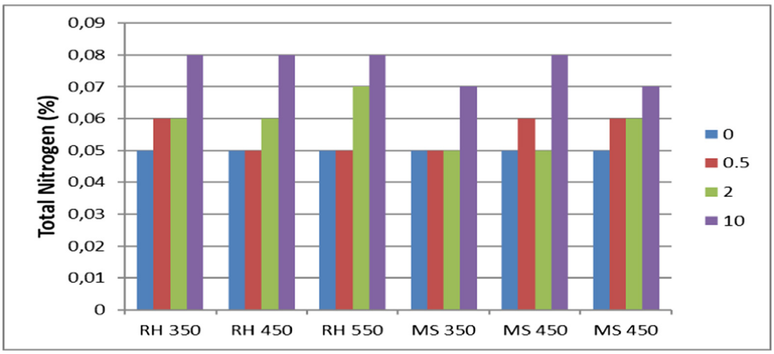

Fig. 5. Effect of application rate, production (pyrolysis) temperature and feedstock type of on soil TN

The soil treated with 10% biochar application rate gives the highest value of SOC. There was a general trend of increasing SOC with increasing biochar application rates. The increase in organic carbon could be resulted from the presence of high amount of carbon in the biochars. In consistent to this study Liang et al. also reported that high organic carbon is available in soils treated with higher biochar rate than lower application rate [21]. Similarly, the SOC increased as the temperature of biochar production increased. Clearly, the reason is due to the fixed carbon content of the biochar increases as the pyrolysis temperature increases. However, the TN increases only by 0.03% compared to the control soil even at the highest biochar application rate (10%). A possible reason could be the insignificant amount of nitrogen in the biochars.

3.4 Effect of Biochar Application Rate, Biochar Production (Pyrolysis) Temperature and Biochar Production Feedstock on Soil CEC and Exchangeable Bases

The statistical analysis showed that application rate of biochar was significantly ($p < 0.05$) affect the cation exchange capacity and exchangeable bases of the soil. However, biochar production (pyrolysis) temperature and biochar production feedstock do not have significant ($p > 0.05$) effect on Soil CEC and Exchangeable Bases: The effect of biochar application rate on CEC and content of exchangeable bases of the soil is presented in Table 1.

Table 1. Effect of biochar application rate on soil CEC and exchangeable bases

Biochar application Rate (%)	Exch. Na (meq/100 g)	Exch. K (meq/100 g)	Exch. Ca (meq/100 g)	Exch. Mg (meq/100 g)	CEC (meq/100 g)
0	0.33	0.42	10.27	6.85	28.84
0.5	0.4	0.73	12.18	8.01	33.94
2	0.43	1.27	13.82	8.64	38.03
10	0.83	1.44	15.55	10.37	40.38

The least values for the all four exchangeable bases and CEC were acquired when the soil is untreated whereas the highest values achieved when the soil is treated with biochar at the highest application rate (10%). The observed highest values of CEC and exchangeable bases at biochar treated soils might be attributed to the inherent characteristics of biochar including high surface area, high porosity and existence negatively charged sites on the biochar surfaces. In agreement to this result, Chan et al. also reported increment of soil CEC and exchangeable bases through application of biochar [22].

4 Conclusion

This study is conducted to investigate the effect of biochar application rate, production temperature and feedstock type on leached acidic soil properties. Rice husk and maize straw biochars were produced at a pyrolytic temperature of 350, 450 and 550 °C and mixed thoroughly at application rates of 0.5, 2, 5 and 10.0% w/w with the leached acidic soil. The chemical laboratory analysis has indicated that the increment biochar application rate led to a significant increment in the soil pH, electrical conductivity, water holding capacity, cation exchange capacity, exchangeable bases and organic carbon content and the highest value of all these soil properties was acquired at 10% biochar application rate. Nonetheless, no significant change has been shown in the total nitrogen content of the soil after biochar application. The presence of ash in the biochar, high surface area and porous nature of the biochar were identified as the main reasons for the increase in the above soil properties. The pH, electrical conductivity and organic carbon content of the soil showed slight increment as the biochar producing temperature increased and this is due to the increment of the ash and carbon content of the biochar with pyrolysis temperature. Incorporating rice husk biochar in the soil results in higher soil pH and electrical conductivity compared to maize straw biochar but higher organic carbon content of the soil was obtained by incorporating maize straw biochar in the soil. In general, the results of this study showed application of biochar derived from rice husk and maize straw on acidic, clay soil increases soil fertility by improving some soil physico-chemical properties. As evident from the present study, it is recommended that the effect of various pyrolysis conditions must be investigated on a variety of feedstocks aimed at producing biochar for different type of soil application.

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