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Biochar and Biochar-Compost Effects on Soil Quality and Maize (*Zea mays L.)* Performance in Mubi, Northern Guinea Savannah of Nigeria

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Abstract

An experiment was conducted at the research farm of the Federal Polytechnic, Mubi, in 2025 cropping season to analyzed the effect of biochar, and biochar-compost on maize performance and soil quality in Mubi. Mubi lies between latitude $10^0\ 8^I$ N and $10^0\ 30^I$ N of the equator and longitude $13^0 10^1$ E and $13^0 25^1$ E at an altitude of 696 m above sea level located in the Northern Guinea Savanna zone of Nigeria with mean annual rainfall of 1000 mm with peak from July to September. There have been many studies on soil quality and crop yield using different biochar application amounts, but few studies have focused on the combination of different amounts of biochar applicationmixed with compost in moderately degraded soils. In this study, the methods of mixing biochar alone evenly with the soil (B) and mixing compost (BC)) were used to reveal how biochar, biochar-compost application methods influenced soil quality, crop yield and agronomic characteristics in moderately degraded soil (soil organic matter (SOM), 30.33 g kg^{-1}). The biochar and compost application amounts were 0 (control), 10 (level 1), 15 (level 2), and 20 (level 3) t ha^{-1} in both the B and BC treatments. The results showed that, compared with control, BC3, B2 and B3 increased maize yield but not significantly. BC1 and B1 had the lowest maize yield. BC2 tended to delay maize leaf senescence. There was a positive linear relationship between soil quality index (SQI) and biochar application amount in BCO. Compared with other treatments, the pH, EC, SOM, available phosphorus, sucrase and catalase activities were highest in BC3. However, the effects of B on soil quality and crop productivity were limited at first but gradually increased with time. Overall, BC3 was beneficial for improving the soil quality and crop productivity in Mubi soils for short-term cultivation.

Keywords: Biochar, Compost, Maize, Soil, Quality and Yield

Introduction

Soil fertility depletion, declining agricultural productivity because of reduction of Soil Organic Matter (SOM), nutrient imbalance, and climate change due to increase greenhouse gasses emission are major constraints in most tropical agricultural soils (Lal, 2015; Pender, 2009; Sandez, 2002). Globally, acidic soil occupies 30% ice free land (Van uexkull and Mutert, 1995), and 20% of irrigated global land has been seriously affected by high salinity level (Pitman and Lauchli, 2002). More than half of all African people are affected by land degradation, making this an urgent development issue for the continent. For example, an estimated US$ 42 billion in income and 6 million ha of productive land are lost every year due to land degradation and declining agricultural productivity (Bationo *et al*., 2006). Moreover, Africa is saddled with a US$ 93 billion annual cost associated with desertification. Research has shown that nutrient losses are only partially compensated by natural and synthetic inputs, thus, the nutrient balance across the whole sub-saharan Africa appears to be negative, by 26 kg N, 2 kg P, and 19 kg K ha^{1} yr^{1} (Drechsel *et al*., 2001). Many tropical soils are lacking in inorganic nutrients and rely on the recycling of nutrients from SOM to maintain fertility. In the 21st century, agriculture faces various challenges i.e., it has to meet food and industrial needs of the growing population, while concurrently protecting the environment. In 2015, the world population was 7.35 billion, while projection show that population would reach 9.72 billion by 2050 (UN, 2015). Thus, world food production must increase by 70% from its current level to satisfy food needs by 2050 (FAO, 2009), the majority of agricultural production depends on synthetic fertilizers, and one of the major problems is over-application of fertilizers, especially N-fertilizer, such as urea. For instance, intensification of agricultural and human activities, such as the increased use of synthetic fertilizer (103 million tons of N worldwide in 2010), and inefficient use of N fertilizer are blamed for the increased N_20 emission of 17.7 T/g of N per year to the atmosphere (IFA, 2011; Zaman *et al*., 2012). The total global demand for N P K fertilizer was 180 million tons in 2012, of which nitrogen fertilizer constituted 109.9 million tons (61%). The world nitrogen fertilizer demand is expected to be around 116.0 million tons in 2016 at an annual growth rate of 1.3%. Of the overall increase in demand for 6 million tons of nitrogen, between 2012 and 2016, 60% would be in Asia, 19% in America, 13% in Europe, 7% in Africa, and 1% in Oceania (FAO, 2012). In monetary value, the annual loss in N fertilizer has been estimated to be $ 18.8 billion with the 33% N recovery efficiency (Raun *et al*., 2002) and USD 225 per ton (World Bank, 2015).

The benefits of inorganic fertilizers, which have played a significant role in increasing agricultural production and productivity over the last half century, have been widely demonstrated since the green revolution. However, the productivity boost provided by fertilizer technology may be reaching a point of diminishing returns (Gruhn *et al*., 2000; Rosset *et al*., 2000), with industrial fertilizer use becoming increasingly unsustainable, environmentally damaging, and unlikely to keep up with demand (Barrow, 2012). The increase in human population pressure has decreased the availability of arable land and it is no longer feasible to use extended fallow periods to restore soil fertility in the tropics (Nandwa, 2001). Shrinking land area per capita and declining soil quality have led to a sustained increase in the rate of inorganic fertilizer application from year to year, to enhance or maintain agricultural productivity where this is an option. However, the application of fertilizer alone is not a sustainable solution to improve soil fertility and maintain yield increase (Gruhn *et al*., 2000), rather, it has been widely realized that application of excessive inorganic fertilizer, especially N, may cause soil

deterioration and other environmental problems due to more rapid organic matter mineralization (Liu *et al.,* 2010; Palm *et al*., 2001).Soil degradation is the most serious biophysical constraint limiting agricultural productivity in many parts of the world, particularly in the tropics (Lal, 2015; Pender, 2009). The long-term benefit of assigning more land to agriculture will not offset the negative environmental impacts of land degradation in the future (Tilman *et al*., 2002). Instead, a more promising approach to ensuring food security is to increase yield from currently cultivated land where productivity is low (Foley *et al.,* 2011). Sustainable agricultural intensification i.e., increasing productivity per unit land area, is thus necessary to secure the food supply for the increasing world population (Godfray *et al*., 2010; Tilman *et al*., 2011). In most tropical environments, sustainable agriculture faces significant constraints due to low nutrient status and rapid mineralization of SOM (Zech *et al.,* 1997). Decline in SOM content leads to decreased cation exchange capacity (CEC), and under such circumstances, the efficiency of applied mineral fertilizer is low. In addition, most small-scale farmers cannot afford to apply fertilizer regularly due to high cost. Thus, nutrient deficiencies are prevalent in many crop production systems in the tropics and this constrain productivity (Glaser *et al*., 2002). Biochar is a solid material obtained from thermo chemical conversion of biomass in an oxygen limited environment (IBI, 2014).

Biochar as a solid amendment has potential benefits in improving the quality of soils, including the physiochemical properties of degraded or nutrient depleted soils, thereby making more agricultural land available, while increasing crop yields, so that the need for expansion of agricultural land area decreases (Barrow, 2012; Luo *et al*., 2016). The application of biochar to infertile soils decreases soil bulk density, and increases total pore volume and water holding capacity (Omondi *et al*., 2016). Soil with a high CEC has the ability to retain cations on the surface of biochar particles, humus, and clay, so nutrients are retained and more available for uptake by plants rather than leached below the root zone (Ding *et al*., 2016). Other studies indicate significant changes in soil quality, including increases in pH, organic carbon, exchangeable cations, and N fertilizer use efficiency as well as a reduction in aluminum toxicity (Hewage, 2016). Recent studies have also indicated that the simultaneous application of biochar and compost resulted in enhanced soil fertility and water holding capacity, crop yield, and C sequestration potential (Luo *et al*., 2016; Plaza *et al*., 2016). Biochar is a solid material obtained from thermo chemical conversion of biomass in an oxygen limited environment (IBI, 2014). Biochar as a solid amendment has potential benefits in improving the quality of soils, including the physiochemical properties of degraded or nutrient depleted soils, thereby making more agricultural land available, while increasing crop yields, so that the need for expansion of agricultural land area decreases (Barrow, 2012; Luo *et al*., 2016). The application of biochar to infertile soils decreases soil bulk density, and increases total pore volume and water holding capacity (Omondi *et al*., 2016). Soil with a high CEC has the ability to retain cations on the surface of biochar particles, humus, and clay, so nutrients are retained and more available for uptake by plants rather than leached below the root zone (Ding *et al*., 2016) . Other studies indicate significant changes in soil quality, including increases in pH, organic carbon, exchangeable cations, and N fertilizer use efficiency as well as a reduction in aluminum toxicity (Hewage, 2016). Recent studies have also indicated that the simultaneous application of biochar and compost resulted in enhanced soil fertility and water holding capacity, crop yield, and C sequestration potential (Luo *et al*., 2016; Plaza *et al*., 2016).

The objectives was to; investigate the soil fertility treatments in relation to biochar and biocha-compost mixture on soil physiochemical properties and improvement in soil fertility, to determine the response of maize to biochar and bioch-compost mixture on soil in Mubi and to evaluate the effect of soil fertility

treatments in relation to organic amendments on nutrient uptake, nitrogen recovery, and use efficiency of maize.

Description of the site and experimental materials

A field experiment was conducted under rainfed condition at the research farm of the Federal Polytechnic, Mubi, and the pot experiment was conducted in a screen house at the Food and Agricultural Organization/Tree Crops Plantation (FAO/TCP) farm of the department of crop science, Adamawa State University, Mubi during 2025 cropping reason. Mubi lies within latitude 10'8' N and N10'30`N and longitude 13'10'E and 13'25`E at 696m above sea level located in the Northern Guinea Savannah Zone of Nigeria with annual rainfall ranges from 700mm – 1000mm with peaks in July to September, (Whiteman, 1981).

The biochar raw material was made up of neem heated at 750 °C in anaerobic conditions, and the retention time of the pyrolysis process was 18 h. The biochar was prepared locally, and has a particle size of 2.5–5 mm, total pore volume of 0.0054 ml g^{-1}, microporous pore volume of 0.0006 ml g^{-1}, pH of 7.25, total nitrogen (TN) of 15.12 g kg^{-1}, total phosphorus (TP) of 9.93 g kg^{-1}, and total potassium (TK) of 14.54 g kg^{-1}.

Experimental design

The experiment was laid out in a randomized complete block design (RCBD) for both the field and the pot experiments, there were six (6) treatments replicated three times. Nitrogen source for the experiment was urea (46% nitrogen). The experimental area measured 11m x 20.5m (225.5m^2). Each plot measured (9m^2) with 0.5m between plots and 1m between replication. Exta-early maize seeds (SAMAZ- 15) obtained from tropical/agro centre, Yola, was used for the experiment, after land preparation, seeds were sown at 75 x 35cm, two to three seeds were sown per hole by dibbling method, and later thinned to one plant per stand two weeks after sowing (WAS). Seeds were sown after the experimental sites was ploughed harrowed and then levelled. Biochar and compost were applied one week before planting at 0, 10 ,15 and 20 tons per ha, (Debele *et al*., 2002; Negassa *et al*., 2002). Nitrogen fertilizer was applied to all plots at the rate of 180kg N/ ha (Alemu *et al*., 2014) at 2 and 5 WAS.

Plant growth and development parameters

The agronomic characteristics of maize plants were determined at different growth periods. Three uniform plants were selected from each plot, and the leaf chlorophyll relative content (SPAD) and leaf nitrogen content (leaf N-content) were monitored using a chlorophyll meter (TYS-4 N,). Simultaneously, the plant height was measured with a measuring tape from the ground to the top of the newly emerged and flattened leaves. In addition, the aboveground biomass and yield of the plants were measured. All plants were harvested in each plot, and the field weighing method was used to obtain the above-ground biomass. All maize in each plot was exposed to the sun and threshed to measure the yield, which was converted into a hectare yield. The 100-grain weight was measured after the seeds were air-dried into constant weight.

Soil properties and overall soil quality assessment

Soil samples were collected from the experimental site at the depth of 0-20 and 20-40 cm and was analyzed for chemical and physical properties. The soil samples collected were analyzed before and after the experiment.

Soil samples were collected using a ring belt with 100 cm^3 cylinders for the determination of BD and soil moisture (SM), (Bao 2000). A five-point sampling method was adopted to collect soil samples in the 0–20 and 20-40 cm soil layer with soil drills in each plot after the corn harvest. The residues and rocks in the soil samples were removed, and the soil was air-dried and then passed through a 2-mm sieve for testing. Parts of the soil samples were used for pH, electrical conductivity (EC), SOM, available nitrogen (AN), TP and available phosphorus (AP) analysis, and the others were used for catalase, phosphatase, urease and sucrase activity analysis.

The soil's natural moisture content was determined by the drying method. Soil pH and EC (1:5 soil to water ratio) were analyzed using a pH meter (PHS-25) and an EC meter (DDSJ-308F), respectively. SOM was measured by the dichromate oxidation and titration method (Kalembasa and Jenkinson 1973). AN was measured by the alkaline solution diffusion method (Dorich and Nelson 1984). TP was measured by the $HClO_4$-H_2SO_4 digestion-molybdenum antimony colorimetric method. AP was measured by the 0.5 mol L^{-1} $NaHCO_3$ extraction-molybdenum antimony colorimetric method (Bao 2000).

Soil catalase, phosphatase, urease and sucrase were determined by the potassium permanganate titration method (substrate: hydrogen peroxide), disodium phenyl phosphate colorimetric method (substrate: phenyl phosphate), indophenol blue photometry (substrate: urea), and 3, 5-dinitrosalicin acid colorimetric determination (substrate: sucrose), respectively (*Guan et al.* 1991).

To evaluate the overall quality of the soil, a soil quality index (SQI) was calculated by integrating key soil quality indicators (KSQIs) using the method described by Zhang *et al*. (2020). Briefly, soil quality-related parameters (i.e. pH, EC, nutrients and enzymes) were selected to establish a minimum dataset (MDS) of soil quality based on Pearson correlation analysis (Pearson) and principal component analysis (PCA) (Gong *et al*. 2015).

Statistical analysis

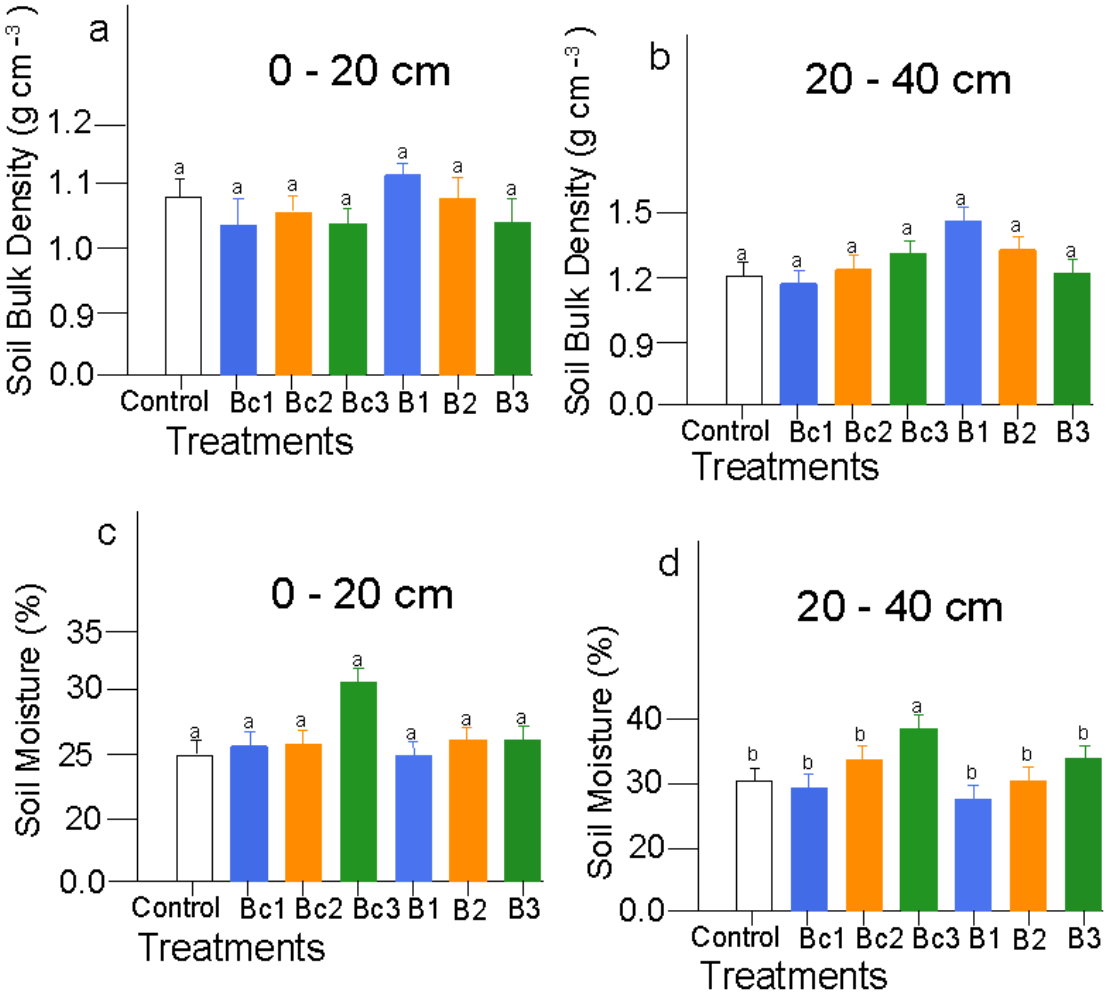
Statistical analysis and graphs were plotted with SPSS 21.0 (SPSS Inc., Chicago, USA) and Origin 2019. Each data point was summarized by calculating the average value and standard deviation (S.D.). Quantitative data of the soil properties and plant parameters were screened for normal distribution using the Shapiro–Wilk test, and homogeneity of variance was determined by using Levene's test. One-way analysis of variance (ANOVA) was used to test the differences between the control and biochar and biochar compost treatments. When the ANOVA indicated a significant F value ($P \leq 0.05$) for treatments, multiple comparisons using Duncan's test were performed. The single linear and nonlinear regression analyses were tested via ANOVA at $P < 0.05$. Multiway ANOVA was used to reveal the effects of biochar and biochar compost application methods (A), application amount (B) and the interaction of A × B on soil physicochemical properties and enzyme activities.

Soil properties and overall soil quality assessment

BC3 had the lowest BD but it was not significant in the 0–20 cm soil layer (Fig. 1a); however, the BD significantly decreased in the 20–40 cm soil layers and SM increased in the 0–20 cm and 20–40 cm soil layers (Fig. 1b–d). The linear models can be used to depict SM and BD changes with different biochar and compost application amounts (Fig. 2). BD gradually decreased in the 20–40 cm soil layers in BC and B (Fig. 2a), and SM gradually increased with biochar and compost application ($P < 0.05$) in the 0–20 cm and 20–40 cm soil layers in BC (Fig. 2b and c). It is worth mentioning that the influence of BC on BD was stronger than that of B in the 20–40 cm soil layer ($R^2 = 0.47$ vs. $R^2 = 0.36$) (Fig. 2a), and the influence of BC on SM was stronger in the 20–40 cm soil layer than in the 0–20 cm soil layer ($R^2 = 0.76$

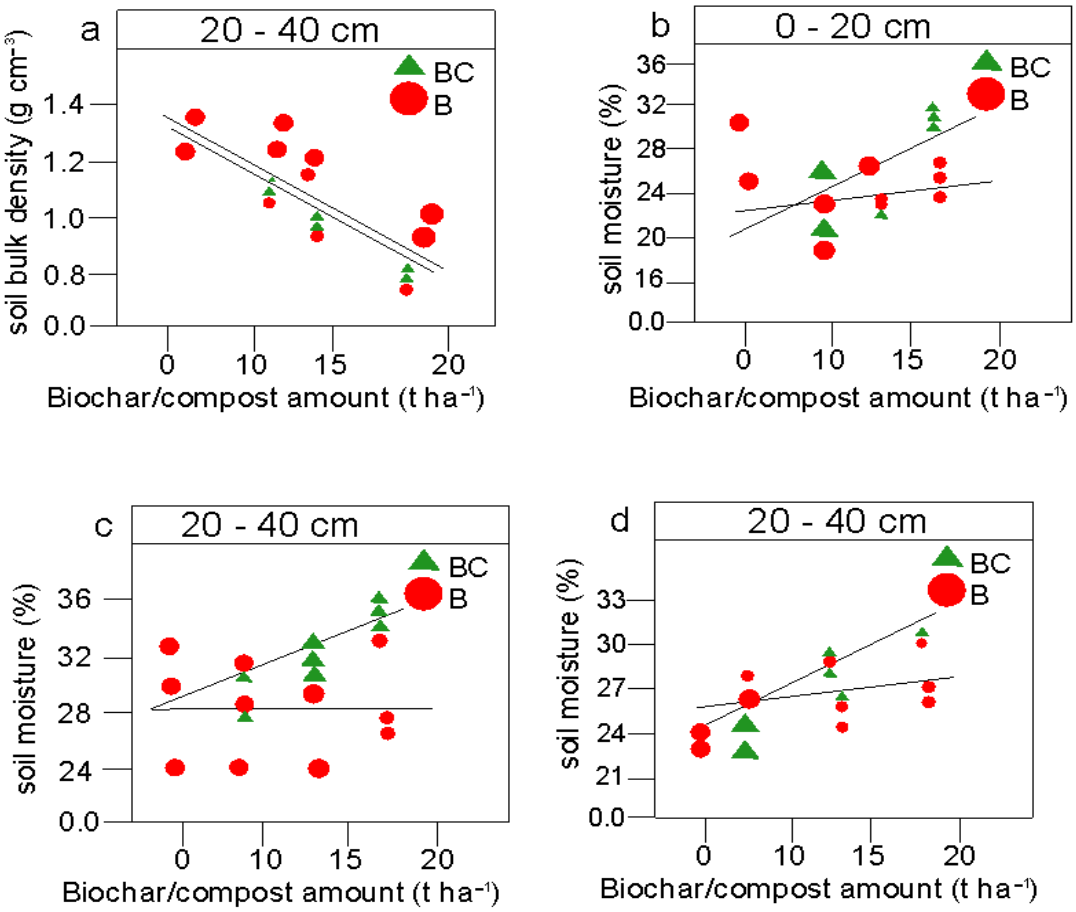
vs. $R^2 = 0.34$) (Fig. 2b and c). Additionally, a high biochar-compost content (BC3) significantly increased the average SM in the 20–40 cm soil layers (Fig. 1d), and the average SM at BC increased with biochar application (Fig. 2d) ($P < 0.05$). Two-way multivariate analysis of variance (MANOVA) for SD and SM was significantly affected by biochar and compost application methods (A) in the 20–40 cm soil laye BD and SM were significantly affected by biochar and compost application amount (B) in the 20–40 cm soil. The average SM was significantly affected by biochar and compost in the 20–40 cm soil layer ($P < 0.05$)

Fig. 1.



Soil bulk density and soil moisture in 0–20 cm and 20–40 cm soil layers as affected by biochar and compost application methods and amount. **a-b** Soil bulk density in 0–20 cm and 20–40 cm soil layers as affect by biochar and compost application methods and amount in. **c-d** Soil moisture in 0–20 cm and 20–40 cm soil layers as affect by biochar and compost application methods and amount. BC, biochar-compost application; B, biohar application; 1, 2 and 3, biochar and compost application was 10, 15 and 20 t ha^{-1}, respectively, Control, biochar and compost application was 0. The same lowcase letter over each bar in the same cropping stage represents no significant difference ($P > 0.05$) between treatments

Fig. 2



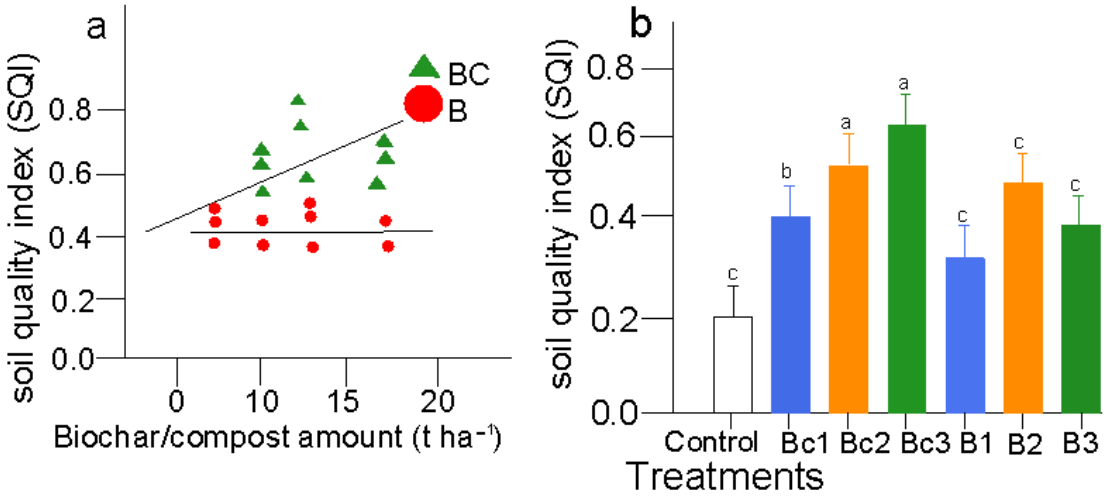
The relationship between soil bulk, soil moisture and biochar and compost application amount. **a** The relationship between bulk density in 20–40 cm soil layers and biochar and compost application amount. **b** The relationship between moisture in 0–20 cm soil layers and biochar and compost application amount. **c** The relationship between soil moisture in 20–40 cm soil layers and biochar and compost application amount. **d** The relationship between average soil moisture in 20–40 cm soil layers and biochar and compost application amount. BC, biochar-compost application; B, biochar application

In general, biochar and compost application improved most soil physicochemical properties and soil enzymatic activities compared to the control. pH, SOM, urease, sucrase, and activities were significantly affected by the B, C and B × C interactions ($P < 0.05$). BC3 had the highest soil pH and EC ($P < 0.05$), providing the most suitable environment for crop growth and preventing soil acidification. In addition, compared to control, BC3 had the highest SOM, AP, sucrase and catalase activities ($P < 0.05$), and BC1 and B1 significantly decreased AP ($P < 0.05$). This indicated that high biochar-compost content had more advantages.

Soil properties differed between different biochar and biochar-compost application treatments

To further evaluate the response of overall soil quality to biochar and biochar-compost, the SQI was assessed by comprehensively selecting appropriate soil quality indicators. Ten soil quality parameters were used for PCA and then the correlation between indicators was analyzed. After comparing the

correlation coefficients between two indicators in the same group, the minimum dataset (MDS) of soil quality evaluation indicators of sucrase, EC and TN were finally determined in this study. The soil quality and biochar application amount can be depicted as a linear model in BC-related treatments (Fig. 3a) ($P < 0.001$). Each treatment significantly increased the SQI compared with the control ($P < 0.001$), and the BC3 treatment had the highest (Fig. 3b). It is worth noting that although B-related treatments improved the SQI, they did not reach a significant difference ($P > 0.05$) (Fig. 3b). These results indicated that biochar and compost application can improve soil quality, and BC was better than B.
Fig.3.

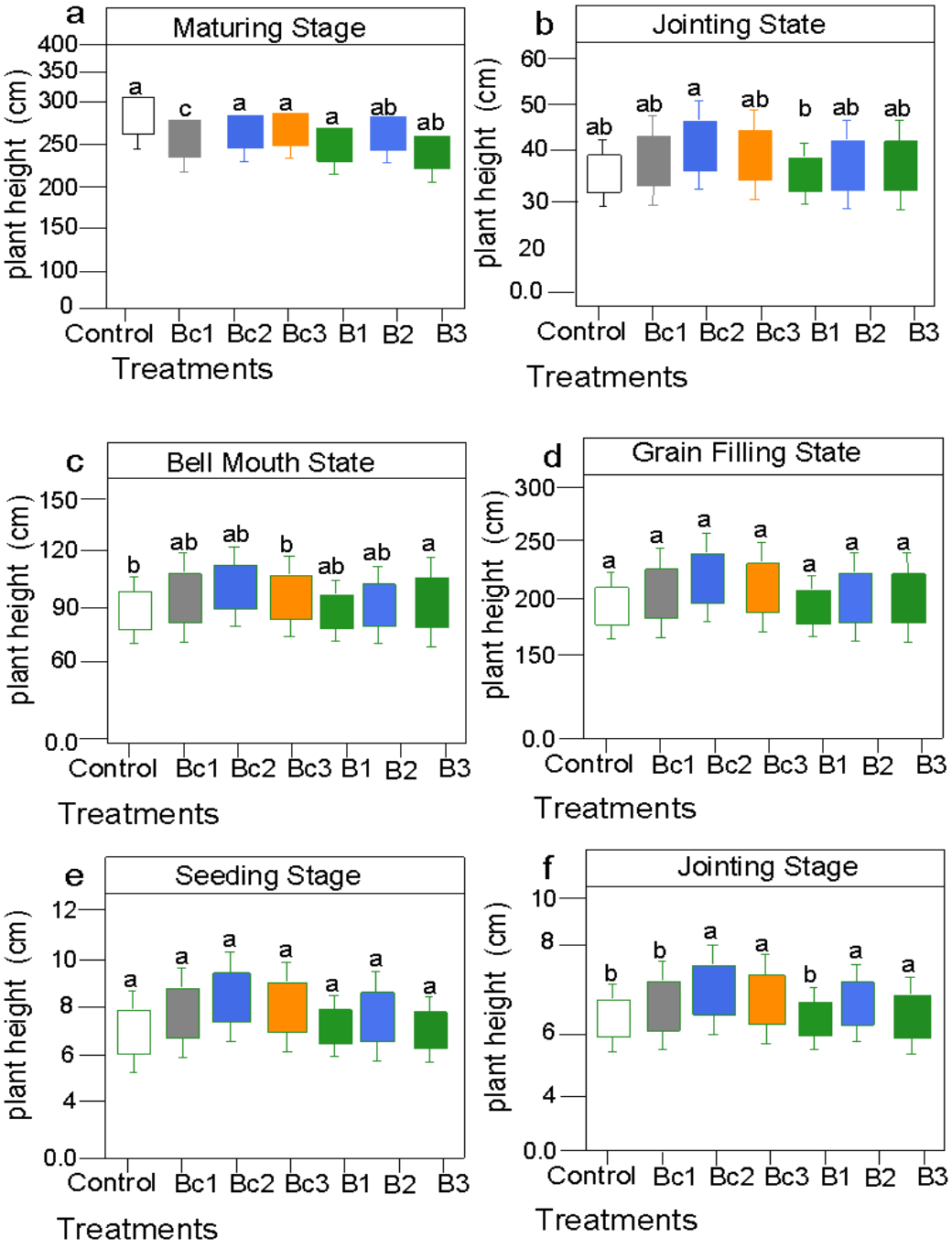


Soil quality index (SQI) as affected by biochar and compost application methods and amount. **a** SQI under different treatments. **b** The relationship between SQI and biochar and compost application amount. BC, biochar and compost application; B, biochar application; 1, 2 and 3, application rate was 10, 15 and 20 t ha^{-1}, respectively, in both BC and B treatments, Control, biochar biochar and compost application was 0. The same lowercase letter represents no significant difference ($P > 0.05$) between treatments.

Plant height

Biochar and compost application influenced maize plant height differently during growth stages (Fig. 4). Compared with the control, BC1 significantly decreased the plant height at the maturing stage ($P < 0.05$) (Fig. 4a). B3 significantly increased the plant height at the bell mouth stage ($P < 0.05$) (Fig. 4c). BC2 had the highest constant plant height during most growth stages (Fig. 4b and d). Each treatment had no significant effect on plant height at seeding(Fig. 4e). BC3 had the highest plant height at the jointing stage ($P < 0.001$) (Fig. 4f). It was interesting that the plant height decreased with application amount in B treatments at the maturity stage (Fig. 4a) and can be depicted as linear models (Fig. 5a) ($P < 0.05$), while the plant height increased with biochar-compost application amount at the bell mouth stage (Fig. 5b) and jointing stage (Fig. 5c) ($P < 0.05$). Generally, both the BC and B methods were helpful to accelerate the maize growth, especially BC2 and BC3, which had better performance than all treatments, and B gradually showed a positive effect over time.

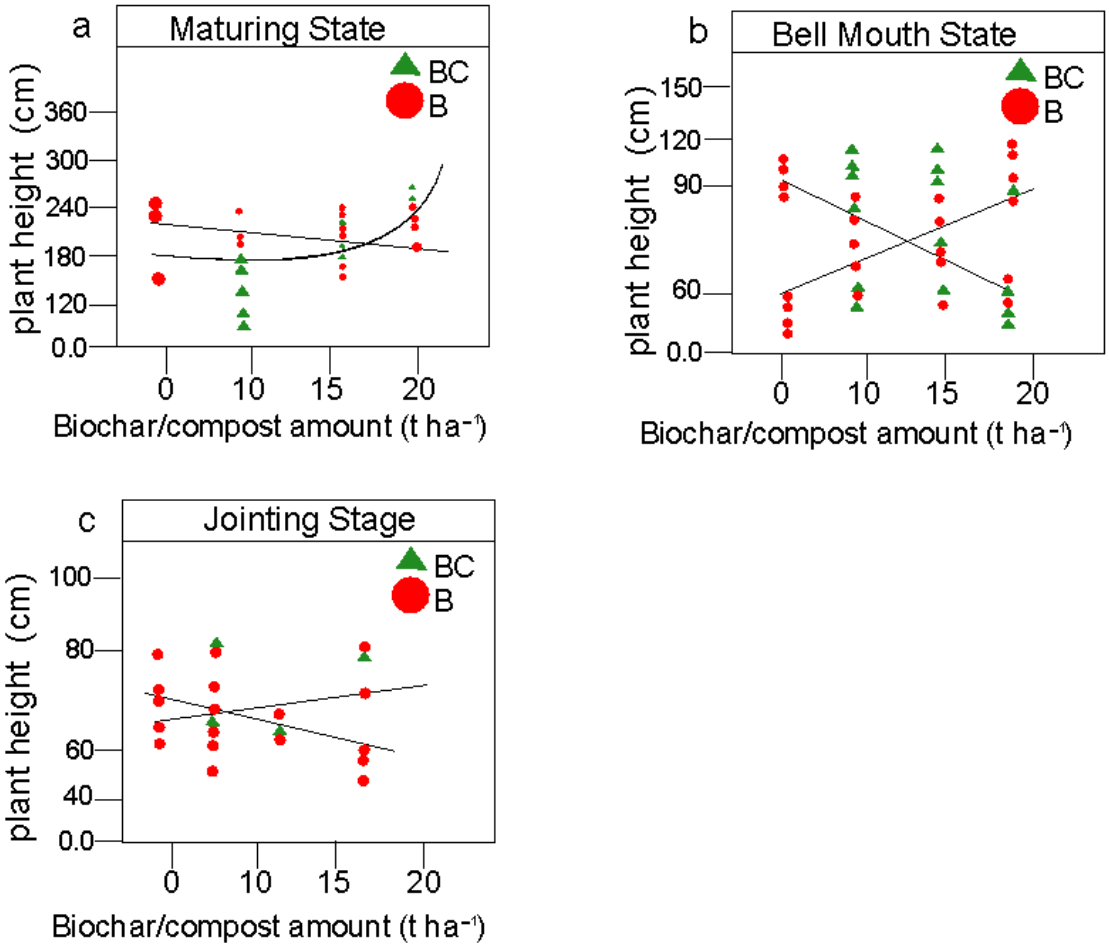
Fig.4.



Plant height as affected by biochar and compost application methods and amount. **a** Plant height at maturing stage. **b**–**d** Plant height at jointing, bell mouth and grain filling stage. **e** and **f** Plant height at seeding and jointing stage. The upper and lower box edges of boxes show the 75th and 25th percentiles, respectively; the '●' shows outliers; '○' shows the average value; the interior horizontal bar marks the median line. BC, biochar-compost application; B,biochar application: 1, 2 and 3, biochar and compost application was 10, 15 and 20 t ha^{-1}, respectively, in all treatments, Control, biochar and biochar-

compost application was 0. The same lowercase letter over each box in the same cropping stage represents no significant difference ($P > 0.05$) between treatments

Fig. 5



The relationship between plant height and biochar and biocahr-compost application amount. **a** The relationship between plant height and biochar and biochar-compost application amount at maturing stage. **b** The relationship between plant height and biochar and biochar-compost application amount at bell mouth stage. **c** The relationship between plant height and biochar and biochar-compost application amount at jointing stage. BC, biochar-compost application; B, biochar application.

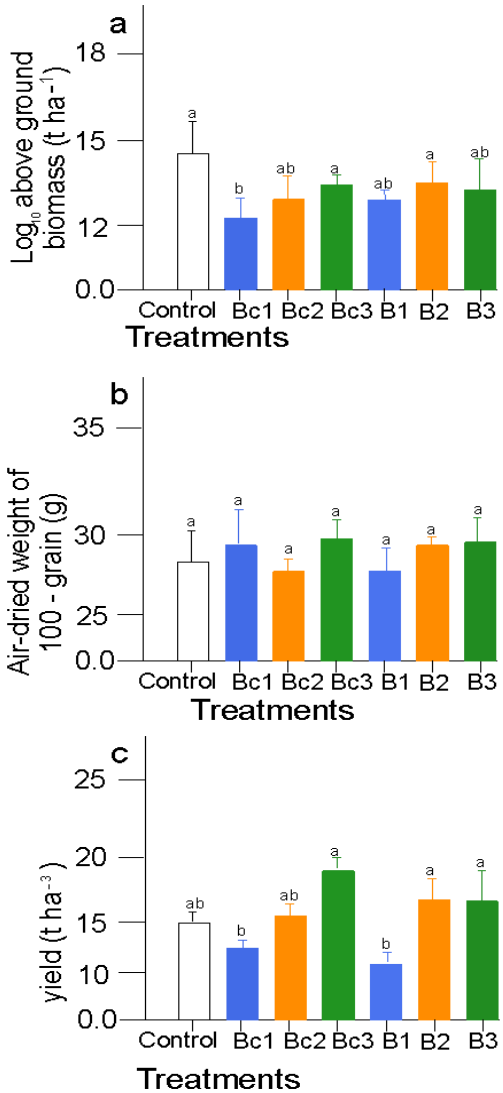
SPAD and leaf-N content

Except for the control, SPAD and leaf-N content showed an upward trend with the biochar and biochar-compost application during the grain filling stage (Fig. 4a and c). This indicated that biochar and compost application could delay leaf senescence in the late growth stage of maize and contribute to the accumulation of photosynthetic products, and BC3 and B3 were the most obvious in delaying leaf senescence. Additionally, except for the control, it could be clearly seen that BC2 and B2 were more conducive to the growth of plants during the vegetative growth period at the seedling and jointing stages (Fig. 4e and f). Generally, the biochar and biochar-compost application amount might greatly influence the leaf photosynthetic index, and the application method had less effect on it.

Crop productivity

Biochar and compost application contributed to the increase in crop productivity. Compared with the control, the aboveground biomass, air-dried weight of 100 grains and yield of the BC3 treatment were the highest (1.67 t ha^{-1}, 38.31 g and 11.81 t ha^{-1}), and those of the BC1 treatment were the lowest (1.65 t ha^{-1}, 31.54 g, 8.16 t ha^{-1}) (Fig. 6a–c). BC3 significantly increased the yield ($P < 0.05$) (Fig. 6c). B3 had the highest yield, but the difference was not significant (Fig. 6c). Additionally, the relationship between the yield of BC-related and B-related treatments and biochar and compost application can be described as a quadratic function, respectively ($P < 0.05$) (Fig. 7a and b). This indicated that regardless of the method of biochar or compostapplication, higher amounts of biochar or compost application can increase crop productivity, while less biochar or compost application tends to reduce crop productivity.

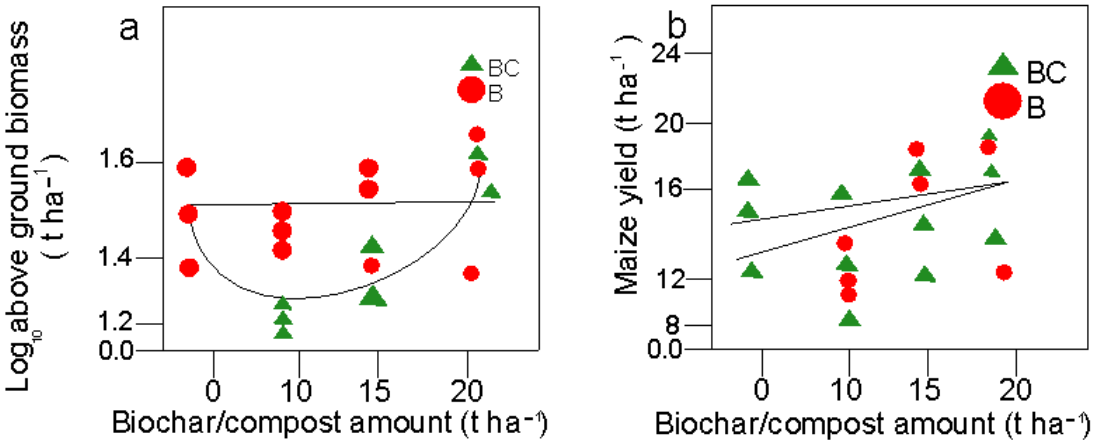
Fig.6.



Crop productivity index as affected by biochar and biochar-compost application methods and amount. **a** aboveground biomass. **b** air-dried weight of 100 grain . **c** The total yield. BC, biochar-compost

application; B, biochar application; 1, 2 and 3, biochar application was 10, 15 and 20 t ha^{-1}, respectively, in all the treatments, Control, biochar and biochar-compost application was 0. The same lowercase letter over each bar in the same cropping stage represents no significant difference ($P > 0.05$) between treatments

Fig. 7



The relationship between crop productivity index and biochar and biochar-compost application amount. **a** The relationship between yield and biochar and biochar-compost application amount. **b** The relationship between average aboveground biomass and biochar and biochar-compost application amount. **c** The relationship between total maize yield and biochar and biochar-compost application amount. BC biochar-compost application, B biochar application

In addition, BC1 significantly decreased the average aboveground biomass compared with the control ($P < 0.05$) (Fig. 6a). Each treatment had no significant effect on the average air-dried weight of 100 grains (Fig. 6b). The total yields of the BC3 and B3 treatments increased by 16.50% and 12.31% compared with the control, respectively, and were significantly higher than those of BC1 and B1 ($P < 0.05$) (Fig. 6f). The relationship between the average aboveground biomass of the BC treatments, the total yield of the B treatments and biochar and compost application amounts can be described by a quadratic function and a linear model (Fig. 7a and b).

This indicated that the average aboveground biomass was more sensitive to the increased amount of biochar-compost application BC treatment, and the total yield was more sensitive to the increased amount of biochar application under the B treatment.

Discussion

Because of the low inputs, high outputs, and unbalanced fertilization in the farming process, constraining soil degradation and maintaining soil quality have become a research focus worldwide (Guo *et al.* 2010). The methods to solve soil degradation include straw amendment, application of organic fertilizer and planting green manure; however, biochar and compost as a soil carbon-rich amendment to improve degraded soil is still debated (Hardy *et al.* 2017). Soil quality is severely degraded, threatening crop production in Mubi due to long-term high-intensity cultivation, and the amount of chemical fertilizer application sharply increases without organic fertilizer (Zhou *et al.* 2016). This study clearly showed that biochar and compost application methods had different performances, and influenced maize growth, yield and soil physicochemical properties.

Response of soil properties to biochar application

Biochar and compost interactions within soils can have a direct or an indirect impact on the plant -soil interface (Lehmann *et al.* 2015). BD is one of the important indicators to characterize soil physical properties, and it affects the diffusion of nutrients in the soil and the absorption of nutrients by crops (Costa *et al.* 2013). Similar to a previous report (Zhao *et al.* 2019), in this study, more biochar and compost application (HO3) tended to decrease the BD while increasing the SM (Fig. 1). This can be attributed to the fact that, compared with soils, both biochar and compost has a lower density and looser structure due to their higher cellulose, pure carbon and carbon compounds (Bird et al. 2008; Spokas et al. 2009; Downie *et al.* 2012). However, this study also found that the influence of BC treatment on BD was stronger than that of B treatment in the 20–40 cm soil layer (Fig. 2a), and the influence of BC treatment on SM was stronger in the 20–40 cm soil layer than in the 0–20 cm soil layer (Fig. 2b–d). Therefore, compared with B, BC was more effective at reversing soil compaction. In addition, the small effect of biochar-compost on the upper SM content could be attributed to the fact that surface soil is susceptible to experiencing evaporation by wind flow, and biochar-compost does not play a dominant role. (Zhao *et al.* 2021). Thus, in the moderately degraded soils, BC had a better performance than B in the early stage of maize growth by mediating both BD and SM.

Previous studies indicated that 1 t ha^{-1} of biochar-compost application significantly increased soil pH but did not obviously increase the EC in both nutrient-poor and nutrient-rich soils (Kang *et al.* 2016b). In this study, more biochar-compost application significantly increased soil pH and EC, which provided the most suitable environment for crop growth. This could be due to higher amounts of biochar-compost application containing greater amount of ash and mineral elements such as Na, K, Mg, Ca, etc., which are alkaline after being dissolved in the solutions of soils (Kimetu and Lehmann 2010). Additionally, Mubi soil had a relatively higher content of SOM (3.07%) and clay particles (sizes of 2.03–21.03 μm, 60.8%), which could moderate the alkalinity caused by biochar-compost. Thus, the addition of Na, K, Mg, and Ca to ash accelerates the activity of iron in soils. Therefore, in the moderate degradation of soil, biochar and compost application was slightly different from the previous results. The higher amount of biochar-compost application not only significantly increased soil pH, but also significantly increased soil EC, which could balance soil acidity, especially alkalinity.

In this study, BC3 significantly increased SOM, AP, sucrase and catalase activities. This can be explained by the fact that (1) biochar-compost is an additional source of SOM and AP, which can directly increase soil nutrient levels (Antal and Grønli, 2003), and (2) biochar-compost has a high capacity for soil cation exchange and surface area, which can adsorb more substances, especially P with the mode of "deposition cycling" in soils, and increase the soil nutrient levels (Dahlawi *et al.* 2018; Zhang *et al.* 2020). In addition, the AP increase is partially explained by the increase in enzyme activities (such as phosphatase, sucrase, and catalase), which increases the transformation of non-available P, especially soil phosphatase, sucrase and catalase, which are specific and crucial to the P and C cycles (Frankenberger and Bingham 1982). Thus, more BC had more obvious effects on improving SOC, available nutrients, and enzyme activities.

Most previous studies on biochar-compost application mainly focused on improving the soil quality of problematic soils. This study emphasized the importance of the overall soil in the Mubi area. Clearly, the SQI is a valuable index that can reflect the overall quality of the soil covering a wide range of physicochemical and microbial properties (Yan *et al.* 2021). In this study, the SQI gradually increased with biochar-compost application, and was significantly higher in both BC2 and BC3 than in the other treatments (Fig. 3a and b). This indicated that BC had a greater impact on soil quality than B. However, when the amount of biochar-compost application reached a certain level, the soil quality no longer

significantly improved. The trends of SQI slowly increasing with biochar-compost application were obvious in this study, but the results were not all significantly different. This may be due to that the amount of biochar-compost application is not enough at present. However, the effects of B should be focused on in the future because B has relatively weak negative effects on soil animal diversity and soil ecosystem health compared to BC (Wu *et al.* 2021; Maurer *et al.* 2017). Therefore, based on the purpose of production practices, appropriate methods and amounts of biochar-compost application should be considered in farming practices. Interestingly, AN, EC and sucrase were most closely related to soil quality in this study, which indicated that these indicators could be used to coarsely estimate the soil quality after biochar-compost application in Mubi.

Response of crop yield and growth to biochar application

Previous studies indicated that biochar and compost application can change the nutrient availability and status in soils, and further influence crop growth (Sohi *et al.* 2010; Yuan *et al.* 2016). Plant height is typically considered an indicator reflecting the photosynthesis and respiration capacity of the plant (Guenni *et al.* 2018). Plants have higher heights, and more therefore branches and leaves can capture more solar radiation and carbon dioxide, further increasing crop yields (Chen *et al.* 2021). In this study, medium and high amounts of BC and B promoted maize growth and delayed leaf senescence, and the effects were slightly different. This indicated that in the early stage of biochar and compost application, the influence of BC on maize height was more significant compared with that of B, while B can show an effect over time. This can be a possibility due to the fact that the biochar and compost condensing at 0-20 cm and at 20-40 cm can effectively filter the nutrients and hold water and is further beneficial to crop growth in all stages (Reddy *et al.* 2014). As well, with increasing time, plant roots tend to grow deeper into the biochar-compost layer with high nutrient filtration during the leaching process in 0-20 cm. This results in the root system absorbing more nutrients from the biochar andcompost layer and promotes crop growth (Li *et al.* 2014).

Furthermore, both BC3 and B3 increased the leaf SPAD value and leaf-N content, delayed leaf senescence during the later stage of maize growth, and thereby extended the grain-filling duration of maize. Additionally, BC2 promoted an increase in the leaf SPAD value and leaf-N content in the seedling stage, which was beneficial to increasing photosynthate accumulation in the early stages of crop growth. This may be due to the higher content of biochar-compost application promoting the soil nutrient cycling, such as nitrification, through the holding, adsorption and desorption of nutrients in the porous structure of biochar-compost (Joseph *et al.* 2010). This process increased the soil available nitrogen and promoted plant nitrogen absorption. Thus, both higher amounts of BC and B tend to promote vegetative growth in the early stage and delay leaf senescence in the later stage of crops to a certain extent. In contrast, lower biochar-compost application reduced the plant height (Fig. 4a) and SPAD (Fig. 4a, c). It may be due to the fact that lower amounts of biochar- and compost application just filled the space of the soil pores, and resulted in acceleration of anoxic conditions which weakened nitrification in the soil. Therefore, low application of biochar-compost (BC1) reduced the uptake of soil AN by crops and further constrained the growth and development of crops (Kammann *et al.* 2011). In general, both BC and B had little influence on plant height, SPAD and leaf-N content, and the influence of biochar and compost on maize performance had the dose effects.

Previous studies indicated that different types of biochar mostly increased the production of crops in various climates and soils (Major *et al.* 2010; Uzoma *et al.* 2011). This can be attributed to (1) biochar application increasing the abundance of beneficial bacteria in the soils, which improves the function of the soil ecosystem and provides a more friendly environment for crop root growth (Beesley *et al.* 2010;

Steiner *et al.* 2008a); or (2) biochar improving the physicochemical properties of the soils, especially the high adsorption ability of biochar reducing nutrient loss, while increasing the available nutrient content and promoting crop growth (Wang *et al.* 2010; Chen *et al.* 2013); or (3) the adsorption of biochar slowing the release of toxic substances when they are confined to biochar and thus reducing the toxic effects of toxic ions and organic pollutants on plants (Uchimiya *et al.* 2011). Hussain *et al.* (2017) found that biochar-compost application enhanced the crop yield in highly degraded or infertile soils based on a summary of previous publications, but it was not significant in fertile and healthy soils. This means that biochar does not always enhance crop yield in cultivated soils. In this study, we found that BC3 significantly increased maize yield (Fig. 6c). This was due to biochar-compost application improving soil physicochemical properties such as pH, EC, SOM and AP. Meanwhile, EC and AP were significantly positively correlated with yield ($P < 0.05$). In addition, this may be due to biochar and compost application influencing maize yield, which could be severely affected by weather conditions, such as precipitation and temperature, especially in extreme weather condition, As well, the ability of biochar and compost to improve soil quality and microecosystems could be weakened with increasing time, although biochar is relatively stable in the soil environment (Spokas *et al.* 2014; Ippolito *et al.* 2012). We also found that B3 had the highest yield (Fig. 6c); this can also be attributed to the maize trapping more nutrients at 0-20 cm layer (Hossain *et al.* 2020). Thus, the effects of the amount and the method of biochar and compost application on maize yield should be continuously studied in the moderately degraded Mubi soils in further studies. Generally, the effect of biochar and compost on soil quality and crop yield cannot be negated in the moderately degraded soils, and both the higher BC and B can effectively promote crop growth and the accumulation of maize yield to a certain extent, although the effect is determined by various environmental conditions.

Conclusion

The results of the study suggested that the application of biochar and compost can improve the overall quality of moderately degraded soils to varying degrees. The improvement of overall soil quality was conducive to the growth and development of crops (e.g. delayed leaf senescence), which can increase crop productivity (e.g. crop yield and aboveground biomass of crops). Higher and lower amounts of biochar and compost application could promote vegetative growth in the early stage, delay leaf senescence in the later stage of crops to a certain extent and improve crop productivity. In general, BC3 was the best soil carbon-rich amendment for improving overall soil quality and crop productivity for short-term cultivation, while B3 showed an effect over time.

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