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Research Application Summary

Biochar and Inorganic NPK Fertilizer or Compost Application Improves Soil Quality and Cabbage Yield

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Abstract

Soil fertility decline and loss of organic matter are widespread challenges to crop production in sub-Saharan Africa (SSA). Combined biochar and compost application has potential to increase crop yield due to direct nutrient addition and liming effect, particularly in acidic soils, which enhances nutrient use efficiency. The study examined the effect of biochar (B) and / or compost (C) application on soil physicochemical properties characteristics, cabbage yield, and N and P uptake and use efficiencies, compared to sole application of either input or inorganic NPK fertilizer in a highly weathered Haplic Acrisol under humid tropical climatic conditions. Biochar or compost (10 ha^{-1}) were incorporated solely or in combination (BC) in a 12-week field experiment. The results showed that addition of biochar and/ or compost increased soil pH, Total Organic Carbon (TOC) and available P and lowered soil exchangeable acidity. Furthermore, combined application of biochar and/ compost significantly increased cabbage head N and P uptake, resulting in greater biomass and cabbage head dry weights of 9 to 18% and 10-29%, respectively. Agronomic efficiency of N was significantly higher in C and NPK than B and CB, physiological efficiency of N was higher in B and CB than NPK and C. The inorganic NPK treatment showed greater apparent N recoveries of 48%, followed by the sole compost treatment which showed ARE of 39.6% for N. The sole biochar and the combined biochar and compost treatments showed less than 25% Apparent Nutrient Recovery Efficiency (ARE) for N, suggesting that N could have been retained in the soils amended with biochar solely or together with compost. We conclude that combined biochar and compost application is a sustainable soil fertility management approach for cabbage production in low nutrient and highly weathered soils in SSA.

Keywords: Biochar, cabbage head dry weight, compost, nutrient use efficiency, soil fertility

Résumé

La baisse de la fertilité des sols et la perte de la matière organique constituent des défis répandus à la production agricole en Afrique subsaharienne (ASS). L'application combinée de biochar et de compost a le potentiel d'augmenter le rendement des cultures en raison de l'ajout direct des éléments nutritifs et de l'effet de chaulage, en particulier dans les sols acides, ce qui améliore l'efficacité de l'utilisation des nutriments. Cette étude a examiné l'effet de l'application de biochar (B) et/ou de compost (C) sur les caractéristiques des propriétés physicochimiques du sol, le rendement du chou et l'efficacité de l'absorption et de l'utilisation de N et P, par rapport à la seule application d'intrants ou d'engrais NPK inorganique dans un environnement hautement HAPLIC ACRISOL altéré dans des conditions climatiques tropicales humides. Le biochar ou le compost (10 ha-1) étaient incorporés seuls ou en combinaison (BC) dans une expérimentation au champ de 12 semaines. Les résultats ont montré que l'ajout de biochar et/ou de compost avait augmenté le pH du sol, le carbone organique total (COT) et le P disponible et réduisait l'acidité échangeable du sol. De plus, l'application combinée de biochar et de compost a considérablement augmenté l'absorption de N et de P de chou, ce qui a entraîné une plus grande biomasse et un poids sec de la tête de chou passant de 9 à 18 % et 10-29 %, respectivement. L'efficacité agronomique de N était significativement plus élevée dans C et NPK que dans B et CB. L'efficacité physiologique du traitement N était plus élevée dans B et CB que dans NPK et C, qui a démontré une efficacité de récupération des nutriments (ARE) de 39,6% pour N. Le biochar et les traitements combinés au biochar et au compost ont démontré moins de 25% d'efficacité apparente de récupération des nutriments (ARE) pour le traitement N, ce qui suggère que N aurait pu être retenu dans les sols amendés avec du biochar seul ou en association avec le compost. Nous concluons que l'application combinée de biochar et de compost est une approche de gestion durable de la fertilité des sols pour la production de choux dans les sols à faible teneur en éléments nutritifs et très altérés en Afrique au sud du Sahara.

Mots clés : Biochar, poids sec de la tête de chou, compost, efficacité de l'utilisation des nutriments, fertilité du sol

Introduction

Soil fertility decline remains the major biophysical constraint to increasing crop productivity in sub Saharan Africa (SSA). Inorganic fertilizer application can significantly increase crop yields. Exclusive use of inorganic fertilizers in smallholder farming systems in SSA is not sustainable as the resource poor farmers have limited capital and poor knowledge in the proper use of synthetic fertilizers (Vanlauwe *et al*., 2001). Moreover, inorganic fertilizer application does not increase soil organic C, which is needed to stimulate microbial activity and provide ecosystem services. Compost application can improve soil fertility, but its rapid mineralization causes nutrient loss. Biochar has recently gained global attention as a useful soil amendment due to its capacity to enhance crop yield, sequester carbon and mitigate greenhouse gas emissions (Lehmann and Joseph, 2015). However, most biochars have low nutrient contents due to the feedstock that is used to produce them.

Combined application of compost and biochar offer the potential to improve soil quality better than sole addition of either input as biochar can adsorb nutrients provided from mineralization of compost and release them slowly to ensure synchrony between nutrient release and uptake by crops (Sohi *et al*., 2010). This study examined the effect of combined addition of compost and biochar on soil physiochemical properties such as pH, total N, available P, total O.C, bulk density, field capacity, hydraulic conductivity as well as the yields of cabbage, cowpea and cassava in a two year crop rotation system. However, this paper focuses only on the effect of biochar and/ or compost application on soil fertility and cabbage yield. The study was underpinned by the hypothesis that i) application of nutrient-rich compost with a carbon-rich biochar, will improve soil quality indices such as soil pH and organic matter content better than sole application of biochar or compost, and ii) combined application of compost and biochar will provide greater liming effects and higher N and P uptake for improved cabbage yield compared to sole application of biochar or compost

Materials and methods

The study was conducted at the University of Cape Coast Teaching and Research farm in the coastal savanna agro-ecological zone of Ghana (5°07'N, 1°17'W). The field had been previously cropped with maize without any previous fertilizer nor biochar application. The soil in the area (Haplic Acrisol) was developed on sandstone, shale and conglomerate-based parent materials (IUSS Working Group WRB, 2015). The soil was well-drained and had a sandy loam texture (approximately 8.0, 12 and 80 % clay, silt, and sand, respectively); and pH 6.1, bulk density of 1.56 gcm-3, total organic carbon 0.5 %, and total nitrogen 0.09%, respectively.

The maize cob biochar was produced by slow pyrolysis at approximately 450 °C in a locally produced kiln under low oxygen conditions at the Soil Research Institute, Kumasi, Ghana. The compost was produced using the pit method at the University of Cape Coast Research and Teaching farm, Cape Coast, Ghana. The basic feedstock mixture of the compost was poultry manure (55 mass %) and maize straw (35 mass %) and *Leucaena leucocephala* leaves (10 mass %). The compost and maize cob biochar used in the study has pH values of 8.2 and 8.0; total organic N contents of 9 and 11 g kg^{-1}; and total organic carbon contents of 798 and 319 g kg^{-1}, respectively.

Field experiment. The field experiment was done using a two-factorial randomised block design. Each treatment was replicated three times. Compost or biochar was incorporated singly at 10 tons ha^{-1} (dry weight basis), respectively. Where compost and biochar were applied together, each amendment was added at 10 t ha^{-1}. Two control treatments of no amendment and inorganic NPK fertilizer (added at rates of 90 N, 60 P_2O_5 and 60 K_2O per hectare), respectively were also included. In the NPK fertilizer treatments, a compound NPK 15:15:15 fertilizer was applied five days after transplanting to supply 60 each of kg N, P_2O_5 and K_2O, per hectare equivalent, respectively by band placement. Urea was added as supplementary fertilizer to supply the 30 kg N per hectare equivalent three weeks after transplanting, also by band placement. The Fortune variety of cabbage was transplanted at four weeks old in nursery at a spacing of 60 cm x 60 cm. In the study, each plot measured 7.2 m^2 with a spacing of two meters each between plots and blocks, respectively.

Yield data collection and laboratory analyses. The dry weight of the economic yield, i.e., head of cabbage was determined at physiological maturity (12 weeks after transplanting). Soil samples collected after harvest were analysed for physico-chemical properties using standard laboratory procedures (Rowell, 1994) at the Soil Research Institute, Kumasi, Ghana. The soil samples were analysed using standard laboratory methodology (Rowell, 1994) .

Nutrient Use Efficiency indicators (Physiological Efficiency (PE), Agronomic Efficiency (AE) and Apparent Nutrient Recovery Efficiency (ARE). In the study, different NUE indicators i.e., Physiological Efficiency (PE), Agronomic Efficiency (AE) and Apparent Nutrient Recovery Efficiency (ARE) were calculated according to the formulae described by Dobberman (2007) as follows:

(i) Physiological efficiency (PE) was calculated as:

$$PE = \frac{Yf - Yo}{Uf - Uo}$$

Where Y_f is cabbage head dry weight (kg) in fertilized soils, Y_o is cabbage head dry weight (kg) in control soil; U_f is N uptake (kg) in cabbage head from fertilized soils and U_o is N uptake (kg) in cabbage head from control

(ii) Agronomic efficiency (AE):

$$AE = \frac{Yf - Yo}{Nf}$$

Where Y_f is cabbage head dry weight (kg) in fertilized soil and Y_o is cabbage head dry weight (kg) in control soil and N_f is N content in compost and / or biochar applied (kg).

(iii) Apparent Nutrient Recovery efficiency (ARE)

$$ARE = \frac{Uf - Uo}{Nf}$$

Where U_f is the N uptake (kg) in cabbage from fertilized, U_o is N uptake (kg) in cabbage from control soil and N_f is N content in compost and / or biochar applied (kg)

Statistical analyses. The data collected in the study were analyzed using GenSTAT version 12.1 and the 2-way ANOVA procedure. Mean separation was done using least significance difference at a significance level of $P < 0.05$.

Results and discussion

Effect of biochar and/ or compost on the soil pH, exchangeable acidity, total organic carbon, available P and effective cation exchange capacity. Application of biochar and / or compost increased soil pH compared to the unamended control. This finding is in agreement with Mensah and Frimpong (2018) who reported an increase in soil pH 14 days after sole biochar, sole compost or biochar (2 % w/w) and compost (2% w/w) additions. They explained that increase in soil pH in biochar amended soils was due to ash accretion. Oguntunde *et al*. (2004) posited that the ash content of incorporated biochar released basic metallic ions, which exerted a liming effect, creating a growth-stimulating effect, especially in soils with low fertility. The study showed that application of inorganic NPK, biochar and compost or a mixture of compost and biochar reduced exchange acidity in the soil.

Decreased soil acidity reflected in significant increases in ECEC of the amended soils relative to the control. This was consistent with reports of Mensah and Frimpong (2018) who found lower exchangeable acidity and greater ECEC in biochar amended soils than in the control. Biochar and / or compost additions increased TOC in the increasing order BC > B > C relative to the control. This indicates that additions of biochar solely or in combination with compost has potential to increase C sequestration and accumulation. The sole biochar and combined biochar and compost treatments significantly increased soil available P content compared to the control. Increased available P in the B and BC treatments could be attributed to the relatively high pH increase in those treatments. Application of compost singly or in combination with biochar significantly increased total soil N compared to the control.

The highest increase in total soil N was found in NPK treatment. The higher initial N contents of the inorganic NPK and compost, and subsequent N mineralization from sole compost additions may account for the comparatively higher total soil N content in soils incorporated with those amendments. Thus, it is not unexpected that the low N biochar applied did not significantly increase soil total N compared to the N-rich compost alone and the combined compost and biochar or inorganic NPK fertilizer treatments. Hence, in agreement with Major *et al*. (2009) who reported a significantly higher N retention in charcoal-amended soil, we speculate that biochar additions increased soil N retention in the porous surface of biochar, which could have reduced leaching of applied nutrients in the biochar amended soils, particularly, in the field. This would ensure synchrony between nutrient release and plant uptake. Increased CEC following biochar application could have further increased nutrient retention in the sole biochar treated soil

Effect of biochar and / or compost on cabbage N and P contents and uptake. Nutrient (N or P) uptake was calculated as the product of the nutrient content and the biomass dry weight of the crop. We focused mainly on N and P uptake because soil N and P, in addition to soil organic C, are critical in providing energy to support agricultural resiliency, food security and ecosystems efficiency. The results showed that cabbage head N and P uptakes were generally greater in all the amended soils than in the control, with C and inorganic NPK treatments recording greater head P uptake than CB and B treatments. Application of inorganic NPK fertilizer and compost and / or biochar all promoted growth and productivity of cabbage in that cabbage head yield and total biomass increased from 10–29% and 9–18%, respectively relative to the control. These improvements in crop performance may be attributed to improved availability of nutrients. Biochar is widely reported to boost crop growth and yield especially in acidic soils, through modification of soil thermal dynamics due its dark colour, facilitating rapid germination, and allowing more time for growth and biomass gain (Kammann *et al.*, 2011). However, the yield-enhancing effects of biochar are not universal.

Table 1. Effect of biochar and / compost on biochar root and head dry weights (12 weeks after transplanting)

Soil Amendment	Root dry weight (kg ha^{-1})	Cabbage head dry weight (kg ha^{-1})
Biochar	12.69^{a}	1272^{ab}
Compost	10.88^{a}	2054^{c}
NPK	12.92^{a}	1905^{c}
B+C	12.55^{a}	1724^{bc}
Control	8.62^{a}	826^{a}
l.s.d	12.74^{a}	510.8
F.prop	0.289	< 0.001

The results showed that biochar additions alone had only small increases on cabbage head yield compared to the unamended control, which is indicative that low nutrient biochar application alone cannot significantly increase crop yield.

Effect of compost and/ or biochar application on N use efficiencies in cabbage. Nitrogen use efficiency in cabbage expressed as Agronomic Efficiency (AE), Physiological Efficiency (PE) and Apparent Recovery Efficiency (ARE) in relation to N applied in biochar and/ or compost are presented in Figure 1. The AE of N (yield increase per unit of N applied) were significantly higher ($P < 0.05$) in C and NPK than B and CB. On the other hand, PE (yield increase per unit of N uptake) of N was higher in B and CB than NPK and C. Indeed PE (yield increase per unit of N uptake) of N in CB was also greater than NPK. Regarding cabbage N recovery, the sole compost treatment showed greater apparent N recoveries of 40%, followed by the NPK treatment which showed ARE of 48% for N. The sole biochar, and the combined biochar-compost treatments showed less than 25% ARE for N, suggesting that N could have been retained in the soils amended with biochar solely or together with compost.

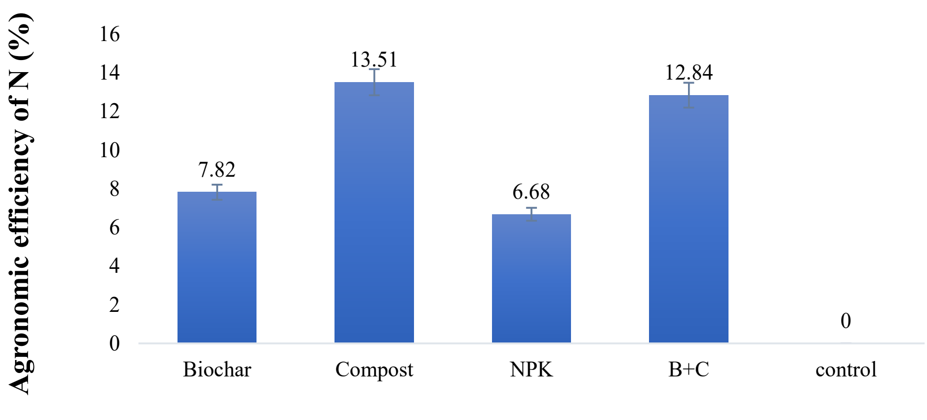

Figure 1 Effect of inorganic NPK fertilizer or compost and / or biochar on agronomic efficiency of N in cabbage

The results showed that biochar applied solely or in combination with compost in this study did not increase nitrogen use efficiency from the applied nutrients. Hence, we suggest that biochar application could have increased N sorption. This has implications for lower leaching losses and increased synchrony between nutrient release and crop uptake. Regression analyses carried out with the pooled data showed that both cabbage N uptake and Agronomic Efficiency of N correlated positively with cabbage head dry matter ($R^2 = 0.59$ and 0.50, $P < 0.05$, respectively).

Similarly, Physiological Efficiency of N and Apparently N recovery efficiency also positively correlated with cabbage head dry weight but these were not statistically significant (R^2 = 0,32 and 0.35, P > 0.05). The NUE indicators calculated for P did not show any obvious relationships with cabbage head yield.

Agronomic N-use efficiency (i.e., nutrients recovered within the soil-crop system) is the basis for economic and environmental efficiency, and an effective agro-ecosystem management practice. Results from this study showed that N use efficiency in terms of recovery and uptake both significantly influenced cabbage yield by improving the agronomic and physiological efficiencies of the crop. Therefore, soil management practices that increase agronomic efficiency are likely to results in optimization of economic (farm income is maximized from proper use of nutrient inputs) and environmental efficiency (reduced risk of nutrient losses) (Robert, 2008).

Conclusion

The study showed that biochar application increased cabbage growth and yield, but the effect was higher when biochar was applied together with compost. However, increased yield in combined biochar and compost application was lower than yield recorded in inorganic NPK fertilizer amended soils. Furthermore, Agronomic efficiency of N applied in sole biochar and combined biochar and compost treatments were lower than in sole NPK treatment but physiological efficiency, which reflected cabbage yield per nutrient taking up was relatively higher in the biochar amended treatments. We conclude that if agronomic efficiency (i.e., optimized nutrients recovery within the soil-crop system) can be achieved by maximisation of nutrient use from combined compost and biochar application, the risk of nutrient loss is likely to reduce resulting in optimized yields and farm incomes. Therefore, there is a critical need for further studies to gain a clearer understanding of how compost and / biochar application affects NUE and sustainable cabbage production in different soils and cropping systems in sub-Saharan Africa agricultural systems.

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