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Post–Pyrolysis Nutrient Enhancement of Wood Biochar with Compost and Uncharred Wastes– Influence on Soil Chemical Properties and Crop Productivity

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Highly carbonised biochar with desirable characteristics such as high porosity, surface area, mechanical strength, and others is attainable at higher highest treatment temperatures (HTTs). Conversely, however, at these higher temperatures, the availability of most plant nutrients reduces. It is therefore vital to nutritionally enrich such biochar for the betterment of crop growth and development. In this study, we employed two different biochar nutrient enhancement strategies. In one approach, oak biochar pyrolysed at higher HTTs of 600°C was combined with livestock compost in a ratio of 1: 4 (biochar: compost). The second strategy involved pelletizing a mixture containing 30% of the biochar mentioned above, 50% of nitrogen–rich castor meal, 10% spent coffee grounds and 10% rice bran (binding material). These two improved biochar fertilisers were then evaluated for their efficiencies in improving soil chemical properties and supporting the growth and development of eggplants through a pot experiment that lasted for a single growing season. Also tested were the effects of combined applications of the nutrient–enhanced biochar fertilisers (EBF) and NPK. The results indicate that both enhancement strategies positively influence biochar's ability to improve soil chemical properties, although the influence on agronomic performance was mostly negative. Such enhanced biochar fertilisers should, therefore, be applied to the soil in combination with mineral fertilisers if excellent benefits accruing from their usage are to be realised.

Key words: Agronomic potential, Biochar nutrient enhancement, Desirable properties of biochar, Wood biochar

INTRODUCTION

The discovery of anthropogenic immensely fertile soils in the Amazon dating as far as more than 1000 years ago elated the entire world (Glaser, 1999) – for they presented a unique opportunity of sustaining the productivity of organic farming systems while sequestering atmospheric carbon (Hagemann, 2012). It's with the view of simulating the characteristics and potential fertility of these soils that the concept of using charred biomass for amending agricultural lands erupted. Biochar, sometimes referred to as agrichar is a carbonaceous material produced by thermal decomposition of biomass in the absence of oxygen (Lehmann and Joseph, 2009; Joseph *et al*., 2015). Biochar differs from charcoal because the former is charred with the intent of using it to improve soil properties and crop productivity (Clough and Condron, 2010). Biochar is considered the best soil organic amendment owing to it's stability and ability to hold nutrients against leaching (Lehmann and Joseph, 2009). Biochar has also been credited for abating particulate matter PM2.5 emissions from the soil through ammonia absorptions (Mandal, 2016).

To adequately perform each of the roles mentioned above, biochar must possess specific properties. For instance, mechanical strength is a highly desirable attribute of biochar because it determines its life span in the soil and resistance to cleaving during handling and storage. The higher the mechanical strength, the higher the resistance to cleavage during storage and handling hence longevity in the soil (Downie *et al*., 2009). Microporosity is another crucial aspect which influences biochar's adsorptive power (Rouquerol *et al*., 1999 and Downie *et al*., 2009). Biochar's macroporosity on the other hand impacts vital soil functions including aeration, hydrology (Troeh and Thompson, 2005) – as well as the movement of roots through the soil and provision of habitats to soil microbes (Downie *et al*., 2009). A higher biochar surface area stimulates an increase in the total soil–specific surface culminating into improved water and nutrient storage in sandy soils and better aeration in clayey soils (Troeh and Thompson, 2005; Downie *et al*., 2009). Lastly, the high nutrient value of biochar as measured by the availability of nutrients to crops rather than their total elemental content, is probably the most crucial aspect to farmers (Chan and Xu, 2009).

It's important to note that although most of the desirable attributes of biochar develop at higher HTTs, the availability of nutrients in biochar dwindles at such temperatures (Chan and Xu, 2009) – because large quantities of nutrients are lost through vaporisation

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while the remaining ones convert to less available forms (Bagreev *et al.*, 2001; Bridle and Pritchard, 2004; Shinogi, 2004). Thus post–pyrolysis nutrient enhancement of such biochar through mixing with other nutrient-rich organic substances in the pursuit of producing nutritionally rich biochar product with desirable properties is inevitable. This study, therefore, strived to assess the influence of two different post–pyrolysis nutrient enhancement strategies on biochar's ability to improve soil chemical properties and supporting growth and productivity of eggplants (*solanum melongena*).

MATERIALS AND METHODS

Biochar Fertiliser Production and Nutrient Composition

The two nutrient enriched biochar fertilisers employed in this study were; biochar pellets (BP) and biochar–blended compost (BBC). The pelletized mixture (BP) contained 50% of N–rich castor meal, 10% spent coffee grounds, 30% oak biochar and 10% rice bran (binding agent). BBC was formulated by mixing 20% oak biochar with 80% livestock manure compost. The biochar pellets were manufactured with a locally fabricated biochar pellet machine sps 200 model (made by Gumgang engineering, Korea). The chemical properties and nutrient concentrations of each of the EBF fertilisers are indicated in table 1 below.

Experimental Design and Fertilisation

A pot experiment was conducted using 2000/1a Wagner pots placed inside a greenhouse at Chungnam National University research farm, Korea. The study was conducted through six treatments set in a randomised block design. Each treatment had three replicates. The soil (chemical properties indicated in table 2 below) obtained from 4EN, a Korean fertiliser research company (Seoul, Korea) was sieved through a 5–mm strainer. 14 kg of the sieved soil was weighed into each of the Wagner pots, amended with EBF and or their combinations with NPK after which Eggplants (Solanum melongena) seedlings were planted. The soil amendments constituted five treatments which included; NPK, BBC, BBC + NPK, BP, BP + NPK and of course the control experiment (un–amended soil). Each of the EBF was added to the soil at a rate of 2%, i.e. 20 grams for every 1 kg of soil used which translates to 15 tonnes of biochar per hectare (considering the depth of incorporation of 5 cm in soil with a bulk density of 1000 kg m^{-3}).

Analysis of Biochar and Soil Samples

All samples were prepared and analysed with strict adherence to the analytical methods for soil, water quality and liquid fertilisers (NAAS, 2013). The parameters examined included; 1) pH and electrical conductivity (EC) determined using a pH and EC meter (ORION Versa Star Pro; Thermo Scientific, Inc., USA) electrochemical analysis, 2) Soil and biochar exchangeable cations including K^+, Ca^{2+}, Mg^{2+} and Na^+ measured with an inductively coupled plasma optical emission spectrometry (ICP–OES; GBC Scientific, Australia) after leaching with 1N NH4OAC solution at a neutral pH (7.0). 3) Total organic carbon (C), nitrogen (N) and organic matter content (OM) analysed with a CN analyser (Eager 300; Thermo Scientific, Inc.), 4) Available phosphorus (P) determined following the Lancaster method using a UV–VIS spectrophotometer (Evolution 300; Thermo Scientific, Inc.). The soil chemical properties were analysed both before and after the growing season.

Agronomic Parameters of the Eggplants

The eggplant variety grown was called Pps heukmiin the seedlings of which were bought from Nongwoobio, a local seed company. Watering, weed control, pests and disease control, and other agronomic practices deemed necessary for proper crop growth and development were done. At the end of the growing season, the plants were carefully harvested and various agronomic parameters assessed. Plant height was determined with the help of a straight metre rule, stem diameter with vernier calliper, weights of shoots and roots with laboratory scale balance while the chlorophyll content of leaves was

Table 1. Chemical properties of EBF (BBC and BP)

Treatment	pH	EC	Avail. P	Elemental content C	Elemental content N	C/N	Ex. cation K	Ca	Mg	Na
	(1: 5)	(ds m^{-1})	(mg kg^{-1})	(%)		ratio	($cmol_c$ kg^{-1})			
BBC	7.2±0.0	32.1±2.4	190.0±7.0	39.2±5.0	2.7±0.1	14.5	0.16±0.00	0.35±0.05	0.11±0.00	0.01±0.00
BP	7.4±0.0	11.4±0.4	90.0±5.0	50.4±0.9	5.2±0.3	9.6	0.28±0.04	0.65±0.22	0.29±0.01	0.06±0.04

EC: Electrical conductivity, Avail. P: Available Phosphorus, C: Carbon, N: Nitrogen, Ex. Cation: Exchangeable cation

Table 2. Initial chemical properties of the soil

Treatment	pH	EC	Avail. P	Elemental content C	Elemental content N	C/N	Ex. cation K	Ca	Mg	Na
	(1: 5)	(ds m^{-1})	mg kg^{-1}	(%)		ratio	($cmol_c$ kg^{-1})			
Soil	6.4±0.0	0.16±0.01	12.3±1.04	0.07±0.01	0.06±0.00	1.15	0.18±0.02	6.6±0.3	11.0±0.5	0.21±0.05

Table 3. Chemical properties of soil after the experiment

Treatment	pH (1: 5)	EC (ds m^{-1})	Avail. P_2O_5 (mg kg^{-1})	Elemental content C (%)	Elemental content N (%)	C/N ratio	Ex. cation K^+ ($cmol_c$ kg^{-1})	Ex. cation Ca^{2+} ($cmol_c$ kg^{-1})	Ex. cation Mg^{2+} ($cmol_c$ kg^{-1})	Ex. cation Na^+ ($cmol_c$ kg^{-1})
Control	6.4±0.3	0.22±0.14	32.3±1.2	0.05±0.01	0.04±0.01	1.21	0.07±0.01	5.9±0.1	2.2±0.2	0.08±0.02
NPK	6.0±0.2	0.23±0.03	33.6±1.6	0.05±0.01	0.05±0.00	1.11	0.09±0.03	6.3±0.4	2.2±0.1	0.16±0.16
BBC	7.8±0.1	0.78±0.09	273.8±7.3	0.40±0.13	0.05±0.02	7.80	0.08±0.03	8.7±1.2	2.9±0.1	0.50±0.20
BBC+NPK	7.6±0.0	0.83±0.03	298.0±23.7	0.39±0.05	0.07±0.02	5.52	0.08±0.03	8.8±0.2	3.0±0.2	0.62±0.34
BP	7.1±0.1	0.90±0.05	89.8±59.1	0.65±0.07	0.09±0.00	7.57	0.11±0.05	8.6±0.6	2.7±0.0	0.26±0.17
BP+NPK	6.8±0.2	1.08±0.15	128.4±1.6	0.60±0.07	0.09±0.00	6.53	0.14±0.04	8.9±1.5	2.7±0.2	0.25±0.12

assessed using SPAD–502 Plus chlorophyll metre. Other agronomic parameters determined included; number of fruits per plant, total fruit weight, fruit length and diameter and fruit sweetness (Brix).

Statistical Analysis

The resultant data were subjected to a one–way analysis of variance (ANOVA) Post Hoc Tests by Duncan in SPSS version 24.0 to assess the effect of each of the treatments on the growth and development of the Eggplant.

RESULTS

Changes in Soil pH, EC, Carbon and Nitrogen

Both EBF increased soil pH and EC. BBC addition to the soil caused higher increases in soil pH than BP while BP–stimulated soil EC increments were higher than those observed where BBC was used (see table 3 below). Combined application of EBF with NPK had a positive effect on the resultant soil EC but not on the soil pH. This is evidenced by the higher EC values obtained where the combinations were used as opposed to where EBF or NPK were each added alone. Furthermore, applying NPK alone caused slight decreases in soil pH whereas pH in the control experiment remained mostly unchanged. It's important to note however that all treatments including the control culminated into increases in soil EC.

Both EBF stimulated increases in soil organic carbon (SOC) and nitrogen while the control and NPK amended soils experienced gradual reductions in the concentrations of both of them. The soil organic matter concentrations and C/N ratios ratcheted up in EBF amended soils while the increases in the control were modest. On the other hand, SOM and C/N ratios of the NPK treated soils slumped (see table 3). For all these parameters, BP amended soils registered the highest increases.

Changes in Available Phosphorus and Exchangeable Cations

Available phosphorus increased in all in the treatments. The increases were higher in BBC than BP amended soils and there were no noticeable differences in the concentrations of available phosphorus between the control and NPK amended soils (see table 3). Combined application of EBF and NPK culminated into P concentrations higher than those observed in EBF only treatments. Available P increased by over 20 fold and between 8–10 fold in BBC and BP amended soils respectively.

The concentrations of exchangeable potassium slumped in all soils. EBF amended soils had their exchangeable Ca level enhanced while the concentrations of non–amended soils plummeted. There was a slump in the concentration of exchangeable magnesium (Mg^{2+}) in all the treatments with severe losses registered in soils without EBF. Apart from BBC amended soils which generally had enhanced exchangeable sodium (Na^+) concentrations, the rest of other amendments resulted reductions in Na^+ levels.

Growth and Yield Parameters

The analysis of vegetative and root growth parameters indicated variations across all the six treatments. Concerning plant height, NPK containing amendments resulted in the tallest eggplants while the shortest ones came from the control (see table 4 below). The thickest stem diameters came from BP + NPK amended soils followed by those on BBC + NPK and BBC amended soils while stem diameters from the rest of the treatments didn't exhibit any significant differences in comparison with the control. Like plant height, soils amended with NPK or a combination of NPK and EBF fertilisers produced plants with the heaviest shoot biomass followed by the EBF without NPK amendments while the control produced the lightest shoot biomass. The root biomass was densest for plants produced with NPK fertiliser followed by those grown on the BBC + NPK amended soils. Interestingly, the control performed better than BP as far as root weight is concerned (see table 4). In terms of chlorophyll content, eggplants grown on BBC + NPK amended soils had the highest content followed by those from BP, BP + NPK and NPK fertiliser amended soils while the ones harvested from the control had the lowest chlorophyll content.

About yields, NPK only amendments produced the best results across all the fruiting parameters closely followed by BBC + NPK amendment (see table 5 below).

In summary, therefore, the application of EBF and or NPK into the soil boosted the agronomic performance (vegetative, root and fruiting parameters) in comparison

Table 4. Vegetative and root growth parameters of eggplants

Treatment	Height	Stem diameter	Biomass Weight Shoot	Biomass Weight Root	Chlorophyll
	(cm)		(g)		(SPAD)
Control	33.1±1.1[a]	0.71±0.08[a]	27.3±2.7[a]	15.8±3.6[ab]	37.9±4.5[a]
NPK	56.6±3.6[c]	0.76±0.11[a]	103.2±9.4[cd]	37.1±6.1[d]	48.1±6.6[ab]
BBC	42.3±4.0[ab]	0.79±0.09[a]	44.1±9.6[a]	23.7±5.8[bc]	43.0±4.6[a]
BBC+NPK	54.0±5.2[c]	0.87±0.09[ab]	109.5±10.5[cd]	27.7±5.6[cd]	63.6±4.5[c]
BP	50.0±17.3[bc]	0.84±0.25[ab]	77.3±42.7[bc]	10.2±9.5[a]	39.5±0.2[ab]
BP+NPK	58.3±2.0[c]	1.02±0.09[b]	117.2±22.9[d]	12.8±2.9[a]	53.6±8.1[ab]

Table 5. Fruiting parameters of eggplants measured

Treatment	Number of fruits (per plant)	Total fruit weight (g)	Length	Diameter	Sweetness (Brix)
			(cm)		
Control	1.0±0.0[ab]	48.3±11.3[a]	13.4±2.6[abc]	2.9±0.5[bc]	2.2±0.9[a]
NPK	1.2±0.5[c]	82.5±33.9[b]	17.0±4.0[c]	3.6±0.3[cd]	3.2±0.2[b]
BBC	1.0±0.0[ab]	44.9±30.0[a]	14.0±2.6[abc]	3.6±0.2[cd]	2.8±0.3[ab]
BBC+NPK	2.0±0.0[d]	102.7±26.2[b]	15.4±3.3[bc]	4.2±0.9[d]	2.4±0.8[ab]
BP	0.3±0.4[a]	26.69±0.0[a]	10.10±0.0[a]	1.9±0.0[a]	3.2±0.0[ab]
BP+NPK	0.3±0.4[a]	13.89±0.0[a]	11.80±0.0[ab]	2.6±0.0[b]	5.1±0.0[c]

to the control except where BP was used. However, EBF fertilisers trailed NPK amendment for most of the parameters studied. Between the EBF fertilisers, BBC stimulated better plant growth and yield than BP but better agronomic results were obtained when EBF fertilisers were used in combination with NPK.

DISCUSSION

Changes in soil pH and EC

The observed increases in soil pH and EC upon EBF application to the soil was in line with the various formerly concluded studies for example by Nigussie *et al.* (2012), Chintala *et al.* (2013), Luyima *et al.* (2019), Lee *et al.* (2019) and others. These increments can be generally ascribed to the build–up of ash residues during pyrolysis (Nigussie *et al.*, 2012). The ash residues are typically dominated by carbonates of alkali and alkaline earth metals, variable amounts of silica, heavy metals and sesquioxides Raison (1979). Indeed, the capacity of ashes to decrease soil acidity was highlighted by Arocena and Opio (2003); Khanna *et al.* (1994) with Chintala *et al.* (2013) stressing the role of CaCO3 content of biochar in raising soil pH and EC. Another reason for the increase in soil pH could be the high surface area and porosity of biochar which in turn increases the cation exchange capacity (CEC) of the soil with the increased likelihood of Al and Fe binding (Nigussie *et al.*, 2012). Agusalim *et al.* (2010) attributed decreases in exchangeable Al, and soluble Fe in biochar amended soils to increase in CEC while Luyima *et al.* (2019) attributed the raises in soil EC on the increased electron exchanges induced by biochar. Chintala *et al.* (2013) also stressed the role of proton consumption ability of biochar in its capacity to reduce soil acidity and raise soil EC. However, the results from the current study indicate that the strength biochar to reduce soil acidity and raise soil EC remains stronger even when minimal quantities of biochar are admixed with other uncharred materials.

Changes in Total Soil Carbon and Nitrogen

Formerly concluded studies have indicated both increasing and decreasing soil carbon upon the addition of biochar. Lehmann (2007) reported increases in organic carbon in biochar treated soils while Steiner *et al.* (2007) noted decreases in organic carbon in both biochar amended and non–amended soils although the decrements were slimmer in amended soils. The increase in organic carbon due to the addition of biochar observed in this study can be attributed to higher concentrations of recalcitrant carbon contained in the applied biochar as indicated by Nigussie *et al.* (2012). A study by Naeem *et al.* (2018) pointed out that unlike other organic amendments that are easily oxidised, biochar's recalcitrant nature renders it indecomposable with resultant cumulative organic carbon in the soil. That proposition is evident from the studies by Solomon *et al.* (2007) and Liang *et al.* (2006) who found higher organic C and total N at the ancient terra preta in comparison with the adjacent soils. The current study indicates a possible direct correction between biochar's carbon content and soil carbon increments because B. P with the highest carbon content stimulated the highest increases in soil organic carbon. Additionally, biochar induced increments in soil organic carbon consequently raise soil organic matter content of the soil.

The lower concentrations of N in BBC amended soils relative to BP amended ones can be explained by the differences in their C/N ratios since the ability of organic amendments to mineralise and release N when applied to soils decreases with increasing C/N ratios (Chan and Xu, 2009). It is therefore apparent that N immobilisation was higher with BBC than BP.

Changes in Available Phosphorus and Exchangeable Cations

The observed increases in available phosphorus can be attributed to the direct release of phosphorus from the EBF fertilisers into the soil and or the indirect soil liming services rendered by EBF thereby raising soil pH (Deluca *et al*., 2009; Nigussie *et al*., 2012). Raised soil pH palliates Fe and Al toxicity resulting in increased availability of phosphorus in the soil. BBC caused higher increases relative to BP because its phosphorus concentration was higher, something that can be attributed to phosphorus rich livestock compost. Another indirect effect of biochar accounting for the increased availability of phosphorus is the stimulation of the growth of microorganisms that either solubilise phosphorus or improve plant's direct access to P through mycorrhizal associations (Deluca *et al*., 2009).

Although most of the exchangeable cation concentrations except calcium slumped, the decrements in soils treated with EBF were slimmer. The decreases were possibly due to the uptake of these ions by plants, but the slight declines in EBF treated soils mean that the release of the occluded cations such as Ca^{2+}, K^{+}, Mg^{2+} and others (Scheuner *et al*., 2004; Niemeyer *et al*., 2005) contained in the ash fraction of biochar ameliorates soil against severe losses. The results of this study also concur with Lehmann *et al*. (2003), Rondon *et al*. (2007) and Chan *et al*. (2008) who reported higher exchangeable bases in biochar treated soils. The increase in soil Ca^{2+} concentrations can be explained by the release of calcium ions into the soil aided by biochar induced increments in soil pH as stipulated by Lehmann *et al*. (2003) and of course, the release of Ca^{2+} occluded in the biochar ash component (Lehmann *et al*., 2003; Steiner *et al*., 2007).

Growth and Yield Parameters

The improved growth and yield observed with BBC application were consonant with many formerly conducted studies including research by Song *et al*. (2018) and Oh *et al*. (2018). One possible explanation for this improved agronomic performance is the increased availability of nutrients elements released into the soil by these EBF fertilisers as denoted by Lehmann *et al*. (2003). However, some studies for example by Kishimoto and Suguira, (1985) have downplayed biochar's role as a direct source of plant nutrients which can explain the negative yield responses observed where EBF fertilisers were applied alone. Many studies for example by Rondon *et al*. (2007), Lee *et al*. (2018) and others preferred to consider biochar a secondary nutrient source. The latter terminology means that biochar provides little or no nutrients to the growing crops but creates an enabling soil environment that optimises plant uptake of nutrients. The better agronomic parameters observed where EBF fertilisers were applied in combination with NPK can be substantiated by Steiner *et al*. [22] who found little yield improvements where biochar was used alone but several folds of yield increments when biochar was applied in combination with the mineral fertiliser. The reduced root development of eggplants observed in BP amended soils is probably due to the inhibition effect caused by uncharred biomass (castor meal and spent coffee grounds) used in making BP which would have limited plant's ability to absorb nutrients, and hence the resultant low yield obtained.

CONCLUSIONS

The current study indicates that although nutrient–enhanced biochar fertilisers can improve soil chemical properties, their agronomic effects are primarily adverse or at least not sufficient. However, because the application of NPK alone negatively impacts soil chemical properties, a combination of the two fertilisers is proposed as a better option moving forward. In economic terms, EBF fertilisers are more economical because less biochar is needed to make them yet they confer more or less the same benefits as the pure biochar. Lastly, attention should be paid to the nutrient availability of the organic materials used for enhancing biochar as it was witnessed that BBC made with livestock manure compost (that contained higher available nutrients) had both higher soil chemical property amelioration and agronomic potentials.

AUTHOR CONTRIBUTIONS

D. Luyima and J. H. LEE wrote the paper and designed the study. J. H. Yoo and S. H. KIM analyzed the data. Y. SHINOGI commented on the manuscript. T. K. OH and J. K. Sung supervised the work. All authors assisted in editing the manuscript and approved the final version.

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