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Effects of Two Biochar–based Organic Amendments on Soil Chemical Properties and Productivity of Selected Vegetables

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Blending biochar with non–pyrolysed low–cost wastes and or compost has been mooted as a feasible replacement to pure biochars, that are either costly or don't give the desired yield increases when used alone. We, therefore, evaluated the effects of two organic amendments containing small quantities of biochar on the soil chemical properties, and productivity of lettuce and Chinese cabbage. These amendments included; (I) Pellets (made from 30% biochar and 70% non–pyrolysed wastes) and the B–C organic amendment/B–C (made by adding 20% biochar to 80% of livestock compost). The study was conducted through a pot experiment with five soil amendments including; pellets, B–C, NPK+ pellets, NPK+ B–C, NPK and the control. Chinese cabbage and lettuce were each grown separately on the amended soils. Soil chemical properties were determined both before and at the end of the growing season whereas growth and agronomic attributes of the vegetables were taken at the end of the experiment. Both B–C and pellets ameliorated soil chemical properties whilst NPK and the control either had detrimental or no effect in the soil. Regarding vegetable productivity, however, NPK and B–C treatments produced better results than the pellets. From the observations, biochar blended organic amendments are capable of replacing pure biochars in agriculture but more studies are required to clearly discern the extent of their effects on a long–term basis and under field conditions.

Key words: biochar, biochar blend, biochar pellets, soil chemical properties, productivity

INTRODUCTION

Since the discovery of Terra Preta in the Amazon i.e. fertile soils endowed with charred biomass (Sombroek 1966; Glaser *et al.*, 2001; Singh *et al.*, 2010), biochar has been the centre of discussions in the corridors of agricultural and environmental sciences. The major driving factors for its popularity include the ability to sequester carbon in the soil (Lehman *et al.*, 2006; Malghani *et al.*, 2014; Criscuoli *et al.*, 2014) and attenuation of nitrous oxide N_2O emissions (Singh *et al.*, 2010; Harter *et al.*, 2013; Martin *et al.*, 2015; Oo *et al.*, 2018). Owing to its association with increasing greenhouse gas levels in the atmosphere, global climate change has highlighted the importance of organic carbon storage, particularly in soil (Han *et al.*, 2016a). Hence, biochar application in the soil is regarded as a sustainable means of curbing the rising temperatures of the earth's surface (Han *et al.*, 2016b; Ravi *et al.*, 2016).

Biochar, a solid carbonaceous material that is produced by pyrolyzing biomass under limited oxygen conditions (Oh and Shinogi, 2013; Sohi, 2012), has emerged as a promising carbon isolation measure (Lehmann and Joseph, 2015). And, it semi–permanently sequester carbon in the soil, biochar is considered to be an effective soil amendment (Oh *et al.*, 2014; Oh *et al.*, 2017). Agriculturally, biochar exhibits a lot of potentials to ameliorate degraded soils (Jien and Wang 2013; Abbasi *et al.*, 2015; Ding *et al.*, 2016; Ye *et al.*, 2016). Some of the potentials include; (I) Enhancing or maintaining soil fertility through the supply of nutrients (Atkinson *et al.*, 2010; Ding *et al.*, 2016) consequently ratcheting up/ maintaining agricultural productivity (korai, *et al.*, 2018). (II) Adsorbing and immobilising toxic elements in the soil (Cao *et al.*, 2009; Beesley *et al.*, 2010; Inyang *et al.*, 2012; Bogusz *et al.*, 2017). (III) Improving chemical and physical properties of the soil (Laird *et al.*, 2008; Novak *et al.*, 2009; Jien and Wang 2013; Lin *et al.*, 2016). (IV) Improving water and nutrient use efficiencies (Hussain *et al.*, 2016; Ding *et al.*, 2016; Liu *et al.*, 2017). (V) Promoting aggregation stability of the soil (Ouyang *et al.*, 2013; Sun *et al.*, 2013; Ma *et al.*, 2016) which increases its resilience to erosion (Jien and Wang 2013). (V) Ameliorating soil biological properties and ecological functions (Paz–Ferreiro *et al.*, 2016).

It's against this background that biochar has been fronted as a viable solution to rehabilitate unsustainable agricultural systems (Chan *et al.*, 2007; Steiner *et al.*, 2007; Waters *et al.*, 2011; Barrow *et al.*, 2012) that have ensued from poor management and changing climatic conditions. Over–dependence on mineral fertilisers since the green revolution has negatively impacted the biological, physical, chemical and ecological functionalities of the soil. This has led to the depletion of soil

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organic matter socks, excessive nutrient mining (Jones *et al.*, 2013) and imbalances of nutrient elements consequently shrinking crop productivity (Han *et al.*, 2016). Vital micronutrient elements such as selenium, calcium and magnesium (Lungu *et al.*, 2008), zinc (Jones *et al.*, 2013) have also been depleted.

However, it should be noted that although biochar presents immense benefits, high application rates may be required for the realisation of any significant yield increases (Joseph *et al.*, 2013). At such high application rates, the return on investment may be poor for farmers but also manufacturing large quantities of biochar takes a lot of time (Joseph, 2009). Sometimes, application of pure biochar into the soil has had limited beneficial effects especially in the temperate ecosystems (Bonanomi *et al.*, 2017).

Adding a small quantity of biochar (5–20%) to composting organic wastes has been reported to hasten the composting process and enhancing the quality of the resultant product (Hua, 2009 and Dias *et al.*, 2010). This has been suggested as one of the ways of producing low–dose cost effective and high potency biochar–based organic amendments (Joseph *et al.*, 2013). Another feasible approach of producing low–dose biochar–based organic amendments is pelletizing a small amount of biochar with non–pyrolysed low–cost and easily accessible organic wastes (Bonanomi *et al.*, 2017). However, studies about the agronomic values of these blended biochars are still very scarce.

This study, therefore, aimed at unearthing the efficacies of blended biochar pellets (produced by mixing 30% biochar with 70% non–pyrolysed wastes) and the biochar–blended livestock compost in short–term amelioration of soil chemical properties and productivity of lettuce and Chinese cabbage.

MATERIALS AND METHODS

Biochar composition and production methods

The two types of biochar used in this experiment included biochar pellets (Pellet) and finely crushed biochar mixed with compost (B–C). The biochar pellets were produced by the use of a locally made biochar pellet machine sps 200 model (manufactured by Gumgang engineering). The pellets were made by mixing oak biochar pyrolysed at 600 c for 3 hours (30%), used coffee grounds collected from coffee shops (10%), castor bean expeller cake (50%) and rice bran (10%). B–C was produced by mixing 20% of oak biochar with 80% of livestock manure compost.

Study site and experimental design

The study was conducted through a pot experiment using 1/2000 a Wagner pots inside a greenhouse at Chungnam National University research farm, Korea. The experiment was set with six treatments in a randomised block design. Each treatment was replicated five times. Soil used was obtained from Charm Grow, a Korean fertiliser research company and was sifted through a 5–mm sieve. About 14 kg of the sifted soil were weighed and put in each of the Wagner pots. Lettuce and Chinese cabbage seedlings were grown on each of the amended soils including the control. The treatments included; soil + NPK, soil + B–C, soil + B–C + NPK, soil + pellet, soil + pellet + NPK and the control with nothing added in the soil. Both types of biochar were added to the soil at a rate of 2% i.e. 20 grams for every 1 kg of soil used. NPK was added at rates recommended by the Rural Development Administration (RDA) of the ministry of Agriculture, Food and rural affairs of South Korea for each of the crops grown.

Biochar and soil analysis

Biochar and soil samples were prepared and analysed following the analytical methods for soil, water quality and liquid fertilisers (NAAS, 2013). The analysed soil chemical properties included; pH, electrical conductivity (EC) measured with a pH and EC meter (ORION Versa Star Pro; Thermo Scientific, Inc., USA) through electrochemical analysis, Soil exchangeable cati-

Table 1. Chemical properties of pellets and biochar–compost combination (B–C)

Treatment	pH (1:5)	EC (ds m^{-1})	Avail. P (mg kg^{-1})	Elemental content (%)		OM (%)	C/N ratio	K^+	Ca^{2+}	Mg^{2+}	Na^+
				C	N			(cmol$_c$ kg^{-1})			
B–C	7.2±0.0	32.1±2.4	190.0±7.0	39.2±5.0	2.7±0.1	67.5	14.5	0.16±0.00	0.35±0.05	0.11±0.00	0.01±0.00
Pellet	7.4±0.0	11.4±0.4	90±5.0	50.4±0.9	5.2±0.3	86.8	9.6	0.28±0.04	0.65±0.22	0.29±0.01	0.06±0.04

Abbreviations: EC, Electrical conductivity; Avail. P, Available phosphorus; OM, Organic matter; C, Carbon; N, Nitrogen; Ex. cations, Exchangeable cation

Table 2. Chemical properties of soil before the experiment

Treatment	pH (1:5)	EC (ds m^{-1})	Avail. P (mg kg^{-1})	Elemental content (%)		OM (%)	C/N ratio	Ex. Cations (cmol$_c$ kg^{-1})			
				C	N			K^+	Ca^{2+}	Mg^{2+}	Na^+
Soil	6.4±0.0	0.16±0.01	12.3±1.04	0.07±0.01	0.06±0.00	0.11	1.15	0.18±0.02	6.6±0.3	11.0±0.5	0.21±0.05

Abbreviations: EC, Electrical conductivity; Avail. P, Available phosphorus; OM, Organic matter; C, Carbon; N, Nitrogen; Ex. cations, Exchangeable cation ons including (K^+, Ca^{2+}, Mg^{2+}, Na^+) analysed using inductively coupled plasma optical emission spectrometry (ICP–OES; GBC Scientific, Australia) after leaching with 1 N NH_4OA_C solution (pH 7.0). Total organic carbon, nitrogen and organic matter content (OM) analysed with a CN analyser (Eager 300; Thermo Scientific, Inc.), available (P) and total phosphorus (TP) by the Lancaster method using a UV–VIS spectrophotometer (Evolution 300; Thermo Scientific, Inc.). Biochar total element concentration (K, Ca, Mg, Na) was assessed with ICP (Icap 7000 Thermo Scientific, Inc.).

Agronomic and quality attributes of the crops

The varieties grown were sourced from local seed companies. These were Hongbitch 5 for lettuce and Daetong for Chinese cabbage. The crops were watered adequately to ensure proper growth and development. The parameters employed in the analysis of the effects of different biochar types on the productivity of Chinese cabbage and lettuce included; plant height, width and length of leaves (determined with help of straight metre rule), stem diameter (using vernier caliper), weights of shoots and roots (with laboratory scale balance), chlorophyll content of leaves (using SPAD– 502 Plus chlorophyll metre), number of leaves produced including their weight, sweetness (Brix). The resultant data from the measurement of these parameters were subjected to one–way analysis of variance (ANOVA) Post Hoc Tests by Duncan in SPSS version 24.0.

RESULTS

Effects on soil chemical properties

Changes in Soil pH and EC

Both biochar types induced increments in soil pH and EC. Soil pH and EC increments were highest where lettuce was grown. While B–C soil application triggered the highest soil pH increments, pellets occasioned the highest EC increments. Reinforcing biochar soil application with NPK fertiliser had no considerable effect on pH but prompted EC increments in comparison with when biochar was used alone. Solitary soil application of NPK fertiliser decreased soil pH with the soil under Chinese cabbage cultivation suffering the highest losses in pH as shown in tables 3 and 4. Contrary to soil pH, soil EC increments seemed ignited when NPK was used in conjunction with biochar. Generally, the soil EC positively responded to all the soil amendments including NPK fertiliser while the results of the un–amended soils turned out mostly negative.

Changes in total soil carbon, nitrogen and organic matter

Addition of biochar blended organic amendments into the soil triggered more than six–fold increments in soil organic matter (SOM) and between six fold to nine fold increases of organic carbon while the concentration of soil nitrogen was maintained or gradually increased in comparison with the soil concentrations before the

Table 3. Chemical properties of the soil under Lettuce cultivation

Treatment	pH (1:5)	EC (ds m^{-1})	Avail. P (mg kg^{-1})	Elemental content (%)		OM (%)	C/N ratio	Ex. Cations (cmolc kg^{-1})			
				C	N			K^+	Ca^{2+}	Mg^{2+}	Na^+
Control	6.2±0.2	0.17±0.03	35.61±0.6	0.05±0.01	0.04±0.00	0.08	1.36	0.10±0.02	6.4±0.4	2.3±0.1	0.13±0.04
N–P–K	6.3±0.1	0.17±0.02	32.71±1.5	0.06±0.00	0.04±0.00	0.10	1.40	0.09±0.05	6.1±0.1	2.3±0.1	0.18±0.06
B–C	7.7±0.1	0.9±0.1	281.0±17.1	0.45±0.05	0.06±0.01	0.77	6.90	0.10±0.02	7.5±0.2	2.8±0.1	0.31±0.06
B–C+ N–P–K	7.7±0.0	0.8±0.0	284.5±17.5	0.43±0.09	0.06±0.01	0.74	7.06	0.14±0.04	8.0±0.2	2.9±0.1	0.47±0.11
Pellet	7.5±0.1	1.5±0.1	144.7±43.1	0.41±0.02	0.09±0.02	0.71	4.50	0.16±0.01	7.1±0.7	2.7±0.1	0.22±0.12
Pellet+ N–P–K	7.3±0.1	1.67±0.02	147.2±23.5	0.55±0.15	0.10±0.00	0.95	5.64	0.15±0.03	7.2±0.4	2.7±0.1	0.13±0.09

Abbreviations: EC, Electrical conductivity; Avail. P, Available phosphorus; OM, Organic matter; C, Carbon; N, Nitrogen; Ex. cations, Exchangeable cation

Table 4. Chemical properties of the soil under Chinese cabbage cultivation

Treatment	pH (1:5)	EC (ds m^{-1})	Avail. P (mg kg^{-1})	Elemental content(%)		OM (%)	C/N ratio	Ex. Cations (cmolc kg^{-1})			
				C	N			K^+	Ca^{2+}	Mg^{2+}	Na^+
Control	6.1±0.1	0.08±0.01	24.4±1.1	0.04±0.01	0.05±0.00	0.08	0.96	0.20±0.10	6.0±0.2	1.9±0.1	0.43±0.15
N–P–K	5.3±0.1	0.37±0.12	25.1±3.2	0.05±0.01	0.05±0.00	0.09	1.01	0.18±0.05	6.6±1.0	1.9±0.1	0.39±0.20
B–C	7.5±0.1	0.32±0.05	347.9±65.6	0.40±0.28	0.08±0.02	0.69	5.18	0.18±0.09	6.8±0.4	2.5±0.1	0.45±0.14
B–C+ N–P–K	7.3±0.2	0.45±0.12	311.4±31.4	0.44±0.29	0.09±0.01	0.76	4.87	0.16±0.04	6.4±0.3	2.2±0.1	0.33±0.08
Pellet	6.8±0.1	0.72±0.22	124.0±29.3	0.66±0.32	0.10±0.00	1.14	6.95	0.17±0.10	5.9±0.3	2.0±0.1	0.28±0.30
Pellet+ N–P–K	6.8±0.1	0.92±0.25	110.7±28.2	0.63±0.06	0.10±0.00	1.09	6.38	0.18±0.02	6.1±0.60	2.1±0.2	0.35±0.47

Abbreviations: EC, Electrical conductivity; Avail. P, Available phosphorus; OM, Organic matter; C, Carbon; N, Nitrogen; Ex. cations, Exchangeable cation experiment. The best results were observed with the application of biochar pellets. The control and the soil where NPK fertiliser was added alone without biochar organic amendments, soil organic carbon, nitrogen and organic matter concentrations plunged.

Changes in available phosphorus and exchangeable cations

All the soil amendments plus the control experiment had their concentrations of available phosphorus increased. B–C application culminated into above twentyfold increment of P against the nine to eleven–fold increment observed in the soil amended with biochar pellets as indicated in tables 3 and 4. There were no considerable differences between the NPK treated soil and the control with regards to P concentration. Talking about exchangeable potassium, concentrations of exchangeable K plummeted in all soil amendments including the control. However, the decrements were slimmer in the soil amended with biochar pellets and or cultivated for Chinese cabbage.

Both biochar types enhanced the Ca concentration of the soil under lettuce cultivation while provoking slight Ca decrements, in Chinese cabbage. The Ca decrements were also observed in the control as well as the NPK fertiliser treatment.

The Mg concentration plummeted in all the treatments with severe losses registered in soils not amended with biochar or those used for Chinese cabbage cultivation.

All amendments enhanced Na concentration of the soil under Chinese cabbage cultivation. Conversely, however, Na concentration of the soil used for lettuce cultivation diminished aside from when B–C was used.

Effects on crop productivity

As shown in tables 5 and 6, for most of the analysed agronomic and quality parameters of the crops, the largest significant statistical differences were obtained between B–C+ NPK and the control. This is an indication that B–C+ NPK provided the most favourable conditions for crop growth and yield. This was closely followed by B–C and the two biochar pellet treatments i.e. Pellet+ NPK and Pellet. However, in Chinese cabbage, application of NPK fertiliser produced better results than biochar pellets and B–C in most of the analysed attributes. Chlorophyll development was boosted when either B–C or NPK were used. Biochar pellets negatively impacted root growth and development in lettuce. There was a negative correlation between vegetable sweetness and soil amendments i.e. un–amended soils produced vegetables with higher sugar.

NPK fertiliser application resulted into huge increments in leaf width and length in Chinese cabbage. All soil amendments aroused positive responses in weights of leaves.

Table 5. Agronomic and quality attributes of Chinese cabbage

Treatment	Fresh Weight		Leaf length	Leaf width	Number of leaves	Weight per leaf	Sweetness	Chlorophyll
	Shoot	Root						
	(g)		(cm)		(per plant)	(g/ea)	(Brix)	(SPAD)
Control	6.6±1.6^{a}	3.3±1.6^{a}	8.0±0.1^{a}	4.9±0.2^{a}	4.3±1.5^{a}	1.7±1.0^{a}	8.7±2.1^{c}	57.6±4.9^{a}
N–P–K	128.9±51.4^{bc}	15.6±5.5^{b}	24.5±2.3^{c}	14.8±1.5^{d}	19.7±6.8^{d}	6.4±0.9^{b}	5.5±2.1^{ab}	60.0±13.5^{ab}
B–C	80.8±22.9^{b}	13.4±2.1^{b}	20.9±2.7^{b}	12.4±0.5^{bc}	15.6±2.5^{cd}	5.2±1.3^{b}	7.7±2.6^{bc}	75.9±17.6^{b}
B–C+ N–P–K	226.3±51.2^{c}	17.6±5.5^{b}	31.9±1.4^{d}	20.0±0.5^{e}	18.4±2.8^{d}	12.2±1.1^{c}	4.1±0.3^{a}	66.4±11.4^{ab}
Pellet	61.5±14.0^{b}	6.8±0.8^{a}	13.8±1.7^{b}	13.3±1.1^{c}	12.0±2.1^{bc}	5.1±0.7^{b}	4.8±1.3^{a}	56.5±9.4^{a}
Pellet+ N–P–K	37.2±15.5^{ab}	7.7±3.3^{a}	18.7±2.1^{b}	11.4±1.3^{b}	7.6±3.2^{ab}	5.0±1.4^{b}	5.7±1.1^{ab}	68.7±7.4^{ab}

Values represent by means ± SD, One–way analysis of variance, ANOVA, Post Hoc Tests by Duncan in SPSS version 24.0.

Table 6. Agronomic and quality attributes of lettuce

Treatment	Fresh Weight		Leaf length	Leaf width	Number of leaves	Weight per leaf	Sweetness	Chlorophyll
	Shoot	Root						
	(g)		(cm)		(per plant)	(g/ea)	(Brix)	(SPAD)
Control	73.1±2.5^{a}	12.5±0.8^{b}	14.3±0.5^{a}	14.7±0.7^{a}	18.4±1.9^{a}	4.0±0.5^{a}	4.8±0.1^{c}	17.3±4.8^{a}
N–P–K	119.8±39.0^{b}	14.9±4.0^{b}	15.1±1.2^{ab}	15.2±1.5^{a}	19.6±3.5^{ab}	6.0±1.5^{bc}	3.7±0.6^{b}	27.4±6.1^{b}
B–C	135.2±35.4^{bc}	15.2±2.9^{b}	15.8±0.7^{b}	16.4±1.1^{ab}	26.0±4.7^{cd}	5.1±0.8^{ab}	2.9±0.1^{a}	18.8±0.9^{a}
B–C+ N–P–K	195.0±16.1^{d}	15.7±1.4^{b}	18.3±0.8^{c}	19.6±1.6^{c}	29.2±1.3^{d}	6.6±0.2^{c}	4.0±0.2^{b}	22.7±1.4^{ab}
Pellet	160.7±24.5^{c}	7.4±1.5^{a}	15.4±1.4^{ab}	17.2±1.1^{b}	22.6±1.5^{bc}	6.6±1.5^{c}	3.1±0.2^{a}	22.6±4.8^{ab}
Pellet+ N–P–K	163.7±13.2^{cd}	7.5±0.8^{a}	15.2±0.4^{ab}	17.1±1.0^{b}	27.6±1.5^{d}	5.9±0.5^{bc}	3.6±0.7^{b}	26.0±3.7^{b}

Values represent by means ± SD, One–way analysis of variance, ANOVA, Post Hoc Tests by Duncan in SPSS version 24.0.

DISCUSSIONS

Changes in Soil chemical properties

As the results indicated, both blended biochar types triggered increases in soil pH. This observation concurred with several formerly concluded biochar studies for example by Chan *et al.* (2007), Jien and Wang (2013), Abbasi and Anwa (2015). The ability of biochar to raise soil pH has been largely attributed to its alkalinity (Chintala *et al*., 2014; Cornelissen *et al*., 2018), an assertion that didn't conform with the trends observed in this study. This is because the two biochar blended organic amendments used were not alkaline but managed to stimulate considerable increases in soil pH. However, Novak *et al.* (2009) used a nearly neutral biochar and came up with the observations similar to the results obtained in this study. Steiner *et al.* (2007) attributed biochar's ability to raising soil pH on the high concentration of alkaline metal oxides. Another study by shen *et al.* (2016) indicated that the power of any biochar material to raise soil pH is incumbent on its liming potential, which was measured in terms of $CaCO_3$ equivalence. Possibly therefore, alkalinity was masked by the low concentration of biochar in the mixed organic amendments. One clear point to pick from this observation is that biochar's liming potential remains high even when biochar is blended with other materials in small quantities.

The biochar propelled increase in soil electrical conductivity is attributed to the increased exchange of ions triggered by its addition in the soil (Joseph *et al*., 2013). Chesworth (2004) regarded decomposing organic materials as electron pumps which supply electrons to oxidised elements in the soil. This could therefore explain why pellets that had a large chunk of easily decomposable materials (70% non–pyrolysed waste) caused the highest increases in EC. Also Cheng *et al.* (2008) termed fresh biochar applied in acidic environments a source of anions hence biochar's addition to the soil sparks off anion exchange with the soil solution. Although high temperature biochars such as the one we used, generally have aromatic carbon structures, they have redox activities mainly as reducing agents using oxygen as the electron acceptors (Joseph *et al*., 2010). Therefore, increases in electrical conductivity observed in this study were certainly a compounding effect of the redox reactions and anion exchange capacity of biochar, as well as the electron pumping effect of the non–pyrolysed decomposing materials. It is also clear that the type of crop grown influenced the increases in soil pH and EC with Soil under lettuce cultivation registering higher increases of pH and EC than the Chinese cabbage soil. Indeed, Joseph *et al.* (2010) stated that the plant type grown on the soil has an influence on the biochar reactions in the soil.

As many of the previous studies for example by Chan *et al.* (2007); Shen *et al.* (2016) and others indicated, addition of biochar organic amendments into the soil stimulated high increases in available phosphorus, with the highest increases produced by the application of B–C. This increase could have been prompted by the increased soil pH stimulating increased mobility and availability of phosphorus in the soil (Shen *et al*., 2016). Another reason for this increase could be the direct release of phosphorus from both compost (Horta, 2017) and biochar (Deluca *et al*., 2009). This is a possible explanation why B–C with both biochar and compost stimulated the highest increases in available phosphorus. The possible explanation for increases in available phosphorous in biochar non–amended soils is possibly the presence of symbiotic relationships between the crops grown and the Arbscular Mycorrhizal Fungi (Scervino *et al*., 2009) or the supply of phosphorus from NPK fertiliser.

The observed increases in soil organic carbon (SOC) and soil organic matter (SOM) were in agreement with the observations by for example Keith *et al.* (2006), Dong *et al.* (2018), Mensah and Frimpong (2018). The increase in soil organic carbon can be attributed to the refractory nature of biochar which renders resilience to oxidation of carbon (Steiner *et al*., 2007). The possible explanation for the increase in organic matter is its sequestering into biochar pores thereby protecting it from microbial degradation and abiotic oxidation (Zimmerman *et al*., 2011). The higher increases in both organic carbon and SOM caused by biochar pellets relative to B–C may be explained by the higher concentrations of carbon and organic matter in the pellets themselves.

Biochar immobilises or adsorbs NH_4^+ which in turn reduces the potential for leaching hence sustained higher nitrogen fertility over time in surface soils (Steiner *et al*., 2007). This can explain why biochar amended soils maintained or slightly increased the nitrogen concentration. The depletion of nitrogen from non–amended soils was probably due to leaching and volatilisation (Lehmann *et al*., 1999).

The changes in soil exchangeable cations largely depended on the type of crop grown since the responses highly varied between the two crops. This may be due to differences in interactions of roots of different crops with the applied biochar in the rhizosphere (Joseph *et al*., 2010).

Agronomic attributes of Lettuce and Chinese cabbage

Among all the amendments, a synchronized application of B–C with NPK fertiliser produced the highest yields in both lettuce and Chinese cabbage which conformed with the observation made by Naeem *et al.* (2017). NPK fertiliser application resulted into better root development than compared to when pellets were used. This can be ascribed to the low available phosphorus concentration in pellets since phosphorus is essential in root development and growth. The yield of Chinese cabbage was higher with NPK fertiliser than biochar pellets. This observation contravened the one made by Carter *et al.* (2013) where biochar increased yield in both lettuce and Chinese cabbage. In all other cases however, biochar organic amendments produced higher yields than NPK alone and or the control. A possible explanation for this positive observation can be the improved soil conditions created by biochar added to the soil enhancing nutrient uptake by the crops (Deluca *et al*., 2009; Shen *et al*., 2016; Naeem *et al*., 2017). Although biochar adsorbs plant nutrients, the adsorbed nutrients are bioavailable to plants. Also, biochar itself contains nutrients that it releases into the soil (Joseph *et al*., 2013) directly contributing to nutrient pool of the soil. B–C addition into the soil stimulated higher yields than pellets possibly because compost readily releases nutrients into the soil unlike the more recalcitrant biochar (Joseph *et al*., 2013). In conclusion, blended biochars are capable of replacing pure biochars if the positive results observed in this study are anything to go by. However, more studies are still needed to compare the efficacies of these blended biochars with those of pure ones, evaluate their long term effects under field conditions and identify the best combinations for achieving the higher agronomic values. As per this study, biochar–compost combination proved better than the pellets.

AUTHOR CONTRIBUTIONS

Jae–Han Lee, Deogratius Luyima, Ji–Yeon Lee, Sang–Jik Kim, Min–Ki Son, Chae–Won Yoon, You–Jin Choi, and Ha–Yeon Choi carried out analysis and interpretation of data. Yoshiyuki SHINOGI verified the data. Taek–Keun OH and Kee Woong Park supervised the project and wrote the paper. All authors commented on the manuscript.

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REFERENCES

Abbasi, M. K and A. A. Anwar 2015 Ameliorating Effects of Biochar Derived from Poultry Manure and White Clover Residues on Soil Nutrient Status and Plant Growth Promotion – Greenhouse Experiments. *PLOS ONE* **10**(6): e0131592.

Atkinson, C. J., J. D. Fitzgerald and N. A. Hipps 2010 Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. *Plant and Soil*, **337**(1–2): 1–18

Barrow, C. J. 2012. Biochar: Potential for countering land degradation and for improving agriculture. *Applied Geography*, **34**: 21–28

Beesley, L., E. Moreno–Jiménez and J. L. Gomez–Eyles 2010 Effects of biochar and greenwaste compost amendments on mobility, bioavailability and toxicity of inorganic and organic contaminants in a multi–element polluted soil. *Environmental Pollution* **158**(6): 2282–2287

Bogusz, A., P. Oleszczuk and R. Dobrowolski 2017 Adsorption and desorption of heavy metals by the sewage sludge and biochar–amended soil. *Environmental Geochemistry and Health*, pp. 1–12

Bonanomi, G., F. Ippolito G. Cesarano, B. Nanni, N. Lombardi, A. Rita and F. Scala 2017 Biochar As Plant Growth Promoter: Better Off Alone or Mixed with Organic Amendments? *Frontiers in Plant Science*, **8**: 1570

Cao, X., L. Ma, B. Gao and W. Harris 2009 Dairy–Manure Derived Biochar Effectively Sorbs Lead and Atrazine. *Environmental Science & Technology*, **43**(9): 3285–3291

Carter, S., S. Shackley, S. Sohi, T. Suy and S. Haefele 2013 The Impact of Biochar Application on Soil Properties and Plant Growth of Pot Grown Lettuce (Lactuca sativa) and Cabbage (Brassica chinensis). *Agronomy*, **3**(2): 404–418

Chan, K. Y., L. Van Zwieten, I. Meszaros, A. Downie and S. Joseph 2007 Agronomic values of greenwaste biochar as a soil amendment. *Australian Journal of Soil Research*, **45**(8): 629

Cheng, C. H., J. Lehmann and M. H. Engelhard 2008 Natural oxidation of black carbon in soils: Changes in molecular form and surface charge along a climosequence. *Geochimica et Cosmochimica Acta*, **72**(6): 1598–1610

Chesworth, W. 2004 Redox, soils, and carbon sequestration. *Edafología*, **11**: 37–43

Chintala, R., J. Mollinedo, T. E. Schumacher, D. D, Malo and J. L. Julson 2013 Effect of biochar on chemical properties of acidic soil. *Archives of Agronomy and Soil Science*, **60**(3): 393–404

Cornelissen, G., N. L. Jubaedah, S. E. Nurida, V. Hale, L. Martinsen and J. Mulder 2018 Fading positive effect of biochar on crop yield and soil acidity during five growth seasons in an Indonesian Ultisol. *Science of The Total Environment*, **634**: 561–568

Criscuoli, I., G. Alberti, S. Baronti, F. Favilli, C. Martinez, C. Calzolari and F. Miglietta 2014 Carbon Sequestration and Fertility after Centennial Time Scale Incorporation of Charcoal into Soil. *PLoS ONE*, **9**(3): e91114

Deluca, T. H., M. D. MacKenzie and M. J. Gundale 2009 Biochar effects on soil nutrient transformations. In: J. Lehmann, S. Joseph (Eds.), *Biochar for Environmental Management: Science and Technology*. Earth scan, London, 251–270

Dias, B. O., C. A. Silva, F. S. Higashikawa, A. Roig, and M. A. Sánchez–Monedero 2010 Use of biochar as bulking agent for the composting of poultry manure: Effect on organic matter degradation and humification. *Bioresource Technology*, **101**(4): 1239–1246

Ding, Y., Y. Liu, S. Liu, Z. Li, X. Tan, X. Huang, and B. Zheng 2016 Biochar to improve soil fertility. A review. *Agronomy for Sustainable Development*, **36**(2): 1–18

Dong, X., B. P. Singh, G. Li, Q. Lin and X. Zhao 2018 Biochar application constrained native soil organic carbon accumulation from wheat residue inputs in a long–term wheat–maize cropping system. *Agriculture, Ecosystems & Environment*, **252**: 200–207

Glaser, B., L. Haumaier, G. Guggenberger and W. Zech 2001 The Terra Preta phenomenon: a model for sustainable agriculture in the humic tropics. *Naturwissenschaften*, **88**: 37–41

Han, K. H., Y. S. Zhang, K. H. Jung, H. R. Cho, M. J. Seo and Y. K. Son 2016a Statistically estimated storage potential of organic carbon by its association with clay content for Korean upland subsoil. *Korean Journal of Agricultural Science*, **43**: 353–359

Han, S. H., J. Y. An, J. Hwang, S. B. Kim and B. B. Park 2016b The effects of organic manure and chemical fertilizer on the growth and nutrient concentrations of yellow poplar (Liriodendron tulipiferaLin.) in a nursery system. *Forest Science and Technology*, **12**(3): 137–143

Han, X., X. Sun, C. Wang, M. Wu, D. Dong, T. Zhong and W. Wu 2016 Mitigating methane emission from paddy soil with rice–straw biochar amendment under projected climate change. *Scientific Reports*, **6**(1): 24731–24740

Harter, J., H. M. Krause, S. Schuettler, R. Ruser, M. Fromme, T. Scholten and S. Behrens 2013 Linking N_2O emissions from biochar–amended soil to the structure and function of the N–Cycling microbial community. *The ISME journal*, **8**: 660–674

Horta, C 2017 Bioavailability of phosphorus from composts and struvite in acid soils. *Revista Brasileira de Engenharia Agrícola e Ambiental*, **21**(7): 459–464

Hu, Q., J. Shao, H. Yang, D. Yao, X. Wang and H. Chen 2015 Effects of binders on the properties of bio–char pellets. *Applied Energy*, **157**: 508–516

Hua, L., W. Wu, Y. Liu, M. B. McBride and Y. Chen 2008 Reduction of nitrogen loss and Cu and Zn mobility during sludge composting with bamboo charcoal amendment. *Environmental Science and Pollution Research*, **16**(1): 1–9

Hussain, M., M. Farooq, A. Nawaz, A. M. Al–Sadi, Z. M. Solaiman, S. S. Alghamdi and K. H. M. Siddique 2016 Biochar for crop production: potential benefits and risks. *Journal of Soils and Sediments*, **17**(3): 685–716

Inyang, M., B. Gao, Y. Yao, Y. Xue, A. R. Zimmerman, P. Pullammanappallil and X. Cao 2012 Removal of heavy metals from aqueous solution by biochars derived from anaerobically digested biomass. *Bioresource Technology*, **110**: 50–56

Jien, S.H and C. S. Wang 2013 Effects of biochar on soil properties and erosion potential in a highly weathered soil. *CATENA*, **110**: 225–233

Jones, D. L., P. Cross, P. J. A. Withers, T. H. DeLuca, D. A. Robinson, R. S. Quilliam and G. Edwards–Jones 2013 REVIEW: Nutrient stripping: the global disparity between food security and soil nutrient stocks. *Journal of Applied Ecology*, **50**(4): 851–862

Joseph, S. D., M. Camps–Arbestain, Y. Lin, P. Munroe, C. H. Chia, J. Hook and J. E. Amonette 2010 An investigation into the reactions of biochar in soil. *Australian Journal of Soil Research*, **48**(7): 501

Joseph, S., E. Graber, C. Chia, P. Munroe, S. Donne, T. Thomas and J. Hook 2013 Shifting paradigms: development of high–efficiency biochar fertilizers based on nano–structures and soluble components. *Carbon Management*, **4**(3): 323–343

Keith, A., B. Singh and B. P. Singh 2011 Interactive Priming of Biochar and Labile Organic Matter Mineralization in a Smectite–Rich Soil. *Environmental Science & Technology*, **45**(22): 9611–9618

Korai, P. K., X. Xia, X. Liu, R. Bian, M. O. Omondi, A. Nahayo and G. Pan 2018 Extractable pool of biochar controls on crop productivity rather than greenhouse gas emission from a rice paddy under rice–wheat rotation. *Scientific Reports*, **8**(1): 820

Laird, D. A. 2008. The Charcoal Vision: A Win–Win–Win Scenario for Simultaneously Producing Bioenergy, Permanently Sequestering Carbon, while Improving Soil and Water Quality. *Agronomy Journal*, **100**(1): 178

Lehmann, J., T. Feilner, G. Gebauer, W. Zech 1999 Nitrogen uptake of sorghum (Sorghum bicolor L.) from tree mulch and mineral fertilizer under high leaching conditions estimated by nitrogen¡15 enrichment. *Biol Fertil Soils*, **30**: 90–95

Lehmann, J. and S. Joseph 2015. *Biochar for environmental management*: An introduction, in biochar for environmental management: Science, Technology and Implementation. Earthscan, London. pp. 1–11

Lehmann, J., J. Gaunt and M. Rondon 2006 Bio–char sequestration in terrestrial ecosystems – a review. *Mitigation and Adaptation Strategies for Global Change*, **11**: 403–427

Lin, G., H. Yang, J. Hu, Y. Luo, J. Shao, X. Wang, and H. Chen 2016 Effects of the physicochemical properties of biochar and soil on moisture sorption. *Journal of Renewable and Sustainable Energy*, **8**: Article 064702

Liu, Z., B. Dugan, C. A. Masiello and H. M. Gonnermann 2017 Biochar particle size, shape, and porosity act together to influence soil water properties. *PLOS ONE*, **12**(6): Article e0179079

Lungu O. I and R. F. Dynoodt 2008 Acidification from long term use of urea and its effects on selected soil properties. *African Journal Food Agriculture Nutrition and Development*, **8**(1): 63–76

Ma, N., L. Zhang, Y. Zhang, L. Yang, C. Yu, G. Yin and X. Ma 2016 Biochar Improves Soil Aggregate Stability and Water Availability in a Mollisol after Three Years of Field Application. *PLOS ONE*, **11**(5): Article e0154091

Malghani, S., E. Jüschke, J. Baumert, A. Thuille, M. Antonietti, S. Trumbore and G. Gleixner 2014 Carbon sequestration potential of hydrothermal carbonization char 0(hydrochar) in two contrasting soils; results of a 1–year field study. *Biology and Fertility of Soils* **51**(1): 123–134

Martin, S. L., M. L. Clarke, M. Othman, S. J. Ramsden and H. M. West 2015 Biochar–mediated reductions in greenhouse gas emissions from soil amended with anaerobic digestates. *Biomass and Bioenergy*, **79**: 39–49

Mensah, A. K and K. A. Frimpong 2018 Biochar and/or Compost Applications Improve Soil Properties, Growth, and Yield of Maize Grown in Acidic Rainforest and Coastal Savannah Soils in Ghana. *International Journal of Agronomy*, **2018**: 1–8

Naeem, M. A., M. Khalid, M. Aon, G. Abbas, M. Amjad, B. Murtaza, W. D. Khan and N. Ahmad 2018 Combined application of biochar with compost and fertilizer improves soil properties and grain yield of maize. *Journal of Plant Nutrition*, **41**(1): 112–122

Novak, J. M., W. J. Busscher, D. L. Laird, M. Ahmedna, D. W. Watts and M. A. S. Niandou 2009 Impact of Biochar Amendment on Fertility of a South eastern Coastal Plain Soil. *Soil Science*, **174**(2): 105–112

Oo, A. Z., S. Sudo, H. Akiyama, K. T. Win, A. Shibata, A. Yamamoto and Y. Hirono 2018 Effect of dolomite and biochar addition on N_2O and CO_2 emissions from acidic tea field soil. *PLOS ONE*, **13**: Article e0192235

Oh, T. K., J. H. Lee, S. H. Kim and H. C. Lee 2017 Effect of biochar application on growth of Chinese cabbage (Brassica chinensis). *Korean Journal of Agricultural Science*, **44**: 359–365

Oh, T. K. and Y. Shinogi 2013 Characterization of the pyrolytic solid derived from used disposable diapers. *Environmental Technology*, **34**(24): 3153–3160

Oh, T. K., Y. Shinogi, S. J. Lee and B. S. Choi 2014 Utilization of biochar impregnated with anaerobically digested slurry as slow–release fertilizer. J. Plant Nutr. *Soil Sci.*, **177**: 97–103

Ouyang, L., F. Wang, J. Tang, L. Yu and R. Zhang 2013 Effects of biochar amendment on soil aggregates and hydraulic properties. *Journal of Soil Science and Plant Nutrition*, **4**: 991–1002

Paz–Ferreiro, J., A. Méndez, G. Gascó, M. Guo, Z. He and S. M. Uchimiya 2016 Application of Biochar for Soil Biological Improvement. *SSSA Special Publication*, **63**: 145–174

Ravi, S., B. S. Sharratt, J. Li, S. Olshevski, Z. Meng and J. Zhang 2016 Particulate matter emissions from biochar–amended soils as a potential trade off to the negative emission potential. *Scientific Reports*, **6**: Article 35984

Scervino, J. M., Ponce, M. A., Delia Monica, I., Vierheilig, H., Ocampo, J. A and Godeas, A. 2009. Development of arbuscular mycorrhizal fungi in the presence of different patterns of trifolium repens shoot flavonoids. *Revista de La Ciencia Del Suelo y Nutrición Vegetal*, **9**: 102–115

Shen, Q., M. Hedley, M. Camps Arbestain and M. U. F. Kirschbaum 2016 Can biochar increase the bioavailability of phosphorus? *Journal of Soil Science and Plant Nutrition*, **16**: 268–286

Singh, B., B. P. Singh, and A. L. Cowie 2010 Characterisation and evaluation of biochars for their application as a soil amendment. *Australian Journal of Soil Research*, **48**(7): 516

Sohi, S. P. 2012 Carbon storage with benefits. *Science*, **338**(6110): 1034–1035

Sombroek W. G. 1966 *Amazon soils. A reconnaissance of the soils of the Brazilian Amazon region*. Verslagen Landbouwkundige Onderzoekingen, **672**: 292

Steiner, C., W. G. Teixeira, J. Lehmann, T. Nehls, J. L. V. de Macedo, W. E. H. Blum and W. Zech 2007 'Long term effects of manure, charcoal, and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil'. *Plant and Soil*, **291**: 275–290

Sun, F and S. Lu 2013 Biochars improve aggregate stability, water retention, and pore–space properties of clayey soil. *Journal of Plant Nutrition and Soil Science*, **177**(1): 26–33

Waters, D., L. Van Zwieten, B. P. Singh, A. Downie, A. L. Cowie and J. Lehmann 2011 Biochar in Soil for Climate Change Mitigation and Adaptation. *Soil Health and Climate Change*, **29**: 345–368

Ye, J., R. Zhang, S. Nielsen, S. D. Joseph, D. Huang and T. Thomas 2016 A Combination of Biochar–Mineral Complexes and

Compost Improves Soil Bacterial Processes, Soil Quality, and Plant Properties. *Frontiers in Microbiology*, **7**: 372
Zimmerman, A. R., B. Gao and M. Y. Ahn 2011 Positive and negative carbon mineralization priming effects among a variety of biochar–amended soils. *Soil Biology and Biochemistry*, **43**(6): 1169–1179