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Single biochar application enhanced the effectiveness of organic fertilizers in a continuously cropped soil

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Abstract

Indiscriminate use of chemical fertilizers has profound environmental implications that organic fertility options can circumvent. Lower macronutrient contents that warrant higher tonnage application rates hinders achieving higher relative agronomic efficiencies (RAE) in these organic fertilizers. The effects of short-term usage of organic fertilizers on selected soil and plant parameters and the potential of harnessing biochar's unique characteristics to improve RAE of other organic fertilizers at reduced application rates were evaluated. The seven-year (2015 to 2021) field trial composed of two near raw organic fertilizers: *Gliricidia sepium* leaves (GL) and poultry manure (PM) and two composted organic materials: sole compost (SC) and bone meal fortified SC termed phosphocompost (PC). There were also two control treatments: chemical fertilizer (sole CF) and absolute control (AC). Each organic fertilizer was applied at 5 t ha^{-1} during 2015 to 2019 cropping seasons. In 2021, biochar was coapplied at 0.5 t ha^{-1} with the other organic fertilizer at a reduced rate of 2.5 t ha^{-1}. Data taken on soil organic carbon (SOC), available P, dry grain (DGY) shoot weights (DSW), and grain N and P contents at the end of the 2015, 2019, and 2021 cropping seasons were subjected to analysis of variance. Treatment means of the selected years were compared using Chi-square at $P<0.01$, followed by computation of the RAE of each organic fertilizer with and without biochar application. Sole CF reduced SOC and DSW of maize by 145.8 and 3.2%, respectively. Sole near raw organic fertilizers reduced SOC by 18.8% (GL) and 19.2% (PM), while SC increased it by 16.4%. One-time biochar spiking at reduced organic fertilizer rate increased SOC, available P, grain yield, P, and N contents. The RAE of the near to raw organic fertilizers were more responsive to biochar in enhancing SOC and grain P contents while biochar favored composted organic fertilizers for enhanced soil available P, grain, and shoot weights.

Keywords: Biochar, compost, green manure, organic fertilizers, poultry manure, relative agronomic efficiency.

Introduction

The Green revolution introduced in the early 1960s is characterized by technological advancement and intensive use of agrochemicals and genetically modified propagules. It has brought good and bad scenarios to crop production, food security, and environmental serenity. The initiative has increased crop production by developing high-yielding seeds, fast nutrient-releasing chemical fertilizers, and herbicides to reduce crop loss due to weed infestation. Despite these merits, the contributions of the initiative to over-dependence on external farm input by farmers, loss of traditional farming practices, crop biodiversity and beneficial soil macro and microorganisms demands attention. Its significant contribution to soil organic carbon depletion, nutrient leaching, surface and underground water pollution and greenhouse gas emissions (Jantke et al., 2020; Banerjee et al., 2021;) should also be considered if future food production and environmental safety will be secured. Consequently, it is essential to bring back traditional farming methods crucial in addressing

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the challenges posed by global climate change. This will help to achieve sustainable management of natural resources, conserve water, enhance biodiversity, and foster overall environmental harmony.

The potential of organic fertilizers to circumvent the adverse environmental effects of agrochemicals has been pinpointed in many reports (Assefa and Tadesse, 2019; Shang et al. 2020; Avery, 2021; Badagliacca et al., 2024). For instance, plain and phosphorus-fortified compost application improved soil organic carbon (Allam et al., 2022), available P (Bergstrand et al., 2020; Zhang et al., 2023), neutralized soil acidity (Oyeyiola, 2017) and improved microbial activities in the soils (Liu et al., 2022). The beneficial roles of near-raw organic fertilizers such as green manure and farmyard manure to enhance the soil nutrient pool for improved crop production had been reported (Bhunia et al., 2021; Allam et al., 2022). However, a few reports exist on potential adverse effects that some of these near-raw organic fertilizers could cause when used in their raw states (Lazcano et al. 2021; Bergstrand, 2022). Furthermore, most organic fertilizers have low macronutrient content (Bergstrand, 2022), leading to their higher tonnage application rates required to satisfy recommended nutrients. This limitation has consistently bedeviled their acceptance as fertility options among local farmers.

Relative agronomic efficiency measures the extent of nutrient response to crop yield in a test fertilizer compared to a conventional chemical fertilizer. It has been used to evaluate the nutrient supply efficacy of new fertilizers to support sustainable soil fertility management and crop production (Frimpong et al., 2021; Jia et al., 2021; Zhang et al., 2023; Manka'abusi et al., 2024). Adverse environmental impacts of intensive agrochemical use are becoming evident in the study area. The need to re-introduce and evaluate the potential of locally sourced organic fertilizers to circumvent these associated adverse effects are imperative.

Biochar, a carbon-rich, relatively new organic soil amendment, has gained global attention in mitigating various soil and water degradation conditions owing to its unique characteristics (Fungo et al., 2017; Oyeyiola et al., 2021; Kabir et al., 2023). Biochar's large surface area, porous structure, ash content, and variable functional and active sites have been explored in tackling various soil and environmental challenges (Tomczyk et al., 2020; Khawkomol et al., 2021; Sushkova et al., 2021; Yang et al., 2021; Minnikova et al., 2022; Oyeyiola et al., 2024). However, a few works have been reported on biochar use in improving nutrient composition and reactivity during compost production (Antonangelo et al., 2021). Biochar inclusion in composing feedstock improved microbial activities, reduced emissions of methane and N losses and bioavailability of heavy metals (Sanchez-Monedero et al., 2018; Guo et al., 2019; Nguyen et al., 2022; Jia et al., 2022). Its use as a coat for inorganic fertilizers to achieve slow-nutrient release conditions in the fast-nutrient-releasing inorganic fertilizer is also gaining attention (Jia et al., 2021; Wang et al., 2022; Long and Dung, 2023).

Information on the potential of biochar spiking to enhance the relative agronomic efficiencies of other organic fertilizers at reduced application rates in continuously cropped soil is limiting despite increasing research interests in biochar. Optimizing the efficiency of the commonly used organic fertilizer is imperative in achieving environmental benefits of these organic fertilizers. Therefore, harnessing the outstanding qualities of biochar in the face of increasing competitive use of feedstock required for organic fertilizer production is important for their enhanced efficiencies.

The fieldwork, therefore, assessed the effects of five-year continuous use of common organic fertilizers (green manure, animal dung, and compost) on selected soil and plant parameters. The potential of single biochar application into the existing organic plots for their improved agronomic efficiencies was also evaluated.

Material and Methods

Description of the experimental site and soil characteristics

The field trial was conducted at the Fertilizer Trial Site of the Department of Crop Production and Soil Science, Ladoke Akintola University of Technology, Ogbomoso, located on 8°08'49''N and 4°11'56''E. The soil of the studied site is alfisol using Soil Survey Staff (2003). It was continuously used for cassava and maize production before being opened for use in 2015. The field was randomly sampled at 0-15 cm depth and processed for routine analysis following standard procedures (IITA, 1978). The soil was near neutral, low in total N, organic carbon (SOC), and available P, but moderately sufficient in exchangeable bases. The soil belongs to the sandy loam textural category. (Table 1).

Field preparation, layout, treatment, and experimental design

The field was manually cleared and laid into plots measuring 2 m x 2.25 m with 1 m inter-row spacing. There were six treatment plots, which were two near raw organic materials- *Gliricidia sepium* leaves (tagged GL) and poultry manure (tagged PM) and two composted organic materials- sole compost produced from rice bran and poultry manure mix (tagged SC) and bone meal fortified SC termed phosphocompost (tagged PC).

There were also two control treatments- sole chemical fertilizer (tagged sole CF) using NPK 15:15:15 and urea mix and absolute control (tagged AC) that did not receive organic or chemical fertilizer. The treatments were replicated thrice and were laid in a randomized complete block design.

Table 1. Initial physical and chemical characteristics of the experimental field in 2015

Parameters		Values
pH (H_2O)		6.90
Total N (g kg^{-1})		0.66
Available P (mg kg^{-1})		3.17
Organic carbon (%)		0.64
Exchangeable bases (cmol kg^{-1})	Ca	2.39
	Mg	0.76
	K	0.33
	Na	0.08
Particle size (g kg^{-1})	Sand	780
	Silt	100
	Clay	120
Textural Class		Sandy loam

Each organic fertilizer was applied at 5 t ha^{-1} (equivalent to 2.25 kg plot^{-1}) via broadcasting and incorporation within 5 cm soil depth and was left to equilibrate for 2 weeks before seed sowing during the 2015 to 2019 cropping seasons. The sole CF treatment was achieved through NPK 15:15:15 application at 60 kg N ha^{-1} (equivalent to 180 g plot^{-1}) mixed with urea at 60 kg N ha^{-1} (equivalent to 60 g plot^{-1}). No cropping activity was done on all the plots in 2020. In 2021, however, biochar was introduced into all four organic plots.

The biochar tested was produced from the pyrolysis of composted groundnut husk and rat litter at 350 °C at 20 minutes residence time in a laboratory muffled furnace. The biochar was applied at 0.5 t ha^{-1} (equivalent to 225 g plot^{-1}) into all the existing organic fertilizer plots in 2021. During 2021 cropping season, the application rates of the other tested organic fertilizers were reduced to 2.5 t ha^{-1} (equivalent to 1.13 kg plot^{-1}) against the 5 t ha^{-1} rate applied from 2015 to 2019. The selected characteristics of the organic and inorganic fertilizers tested are presented in Table 2.

Table 2. Nutrient characteristics of the organic and inorganic fertilizers studied.

Fertilizers	N	P	C	Ca	Mg	K	Ash	C/N
							%	
Sole compost	5.90	10.21	22.50	3.36	0.85	2.36	75.81	4.44
Phosphocompost	5.21	26.62	25.21	2.13	0.79	2.54	ND	5.65
Poultry manure	19.50	19.41	37.50	ND	ND	ND	66.56	2.24
Gliricidia sepium leaves	32.02	27.03	91.02	0.29	1.13	5.05	ND	3.32
Biochar	2.46	2.08	19.62	9.22	1.41	3.01	49.20	9.30
Chemical fertilizer	20.00	10.00	ND	ND	ND	10.00	ND	ND

ND is not determined.

Seed sowing, agronomic practices, data collection, and statistical analysis

Oba super 2 maize variety was sown at 2 seeds per hole at a spacing of 25 cm by 75 cm to give 36 plant stands per plot during the selected cropping seasons. The selected cropping seasons were: 2015 (first year of organic fertilizer application), 2019 (fifth year of continuous use of organic fertilizer) and 2021 (single biochar application with reduced rate of other organic fertilizers). Thinning was done a week after sowing to achieve one plant per stand. Weeding was done manually as when it was due.

Data were taken on soil (SOC and available P) and plant (dry shoot weight, grain weight, grain N and P) parameters at crop harvesting. All data taken each year were subjected to one-way analysis of variance and means were separated by Duncans Multiple Range Test at $P < 0.05$. Treatment means of the selected cropping seasons: 2015, 2019, and 2021 were compared by Chi-square at a $P < 0.05$ using the Genstat statistical package. Selected soil and plant parameters were used for the computation of the relative agronomic efficiencies (RAE) of the biochar spiked organic fertility options relative to the sole chemical fertilizers. For example, RAE using soil organic carbon (SOC) data was estimated as:

$$\text{RAE of TOF} = \frac{\text{SOC content in TOF treated soil} - \text{SOC content in AC soil}}{\text{SOC content in sole CF} - \text{SOC content in AC soil}} \times 100$$

Where: TOF is testing organic fertilizer

Sole CF is a conventional chemical fertilizer.

AC is an absolute control soil that receives neither chemical nor organic fertilizer.

SOC is soil organic carbon.

Results and Discussion

Changes in soil organic carbon, dry shoot weight and grain yield of maize in soil under continuous organic fertilizer treatments

Immediate effects of the applied organic fertilizers on SOC during the 2015 cropping season were more evident in the near raw organic fertilizers such as the GL and PM and P fortified compost (PC). The SOC increased by 23.1, 20.0% and 9.2% in GL, PM and PC respectively, compared to AC while it reduced by 6.2% in SC (Table 3). Higher N and P contents in the near raw organic fertilizers led to lower C/N and C/P ratios. This facilitated faster mineralization of N, P, and labile C for use by the innate microorganisms in the nutrient-degraded soil studied (Ylivainio et al., 2021; Bergstrand, 2022). This ultimately led to the observed immediate enhanced SOC responses. Low macronutrient content in the SC compared to near raw organic fertilizers has been a major limiting factor associated with compost adoption and use by farmers. Thus, there is a need for N and P fortification of compost designed for use on degraded soil like the one studied.

Table 3. Changes in soil organic carbon, dry shoot weight and grain yield of maize in soil under continuous organic fertilizer treatments

Treatments	SOC (%)			DSW (t/ha)			DGY (t/ha)		
	2015	2019	2021	2015	2019	2021	2015	2019	2021
Sole CF	0.75a	0.57b	0.38c	15.40a	16.00a	14.90b	1.40a	4.01a	8.34b
SC	0.61b	0.71a	0.93a	12.40a	9.30b	18.38a	1.80a	2.79b	16.17a
PC	0.71a	0.63a	0.57b	10.70a	11.20b	16.33a	1.60a	3.47a	10.19a
GL	0.80a	0.65a	0.92a	11.30a	9.10b	13.60b	1.50a	3.15a	10.77a
PM	0.78a	0.63a	0.96a	10.70a	10.50b	20.39a	1.40a	2.91b	11.09a
AC	0.65b	0.61a	0.10d	6.50b	10.10b	12.46b	1.20b	2.55b	6.11b
Chi-square									
Sample size		6			6			6	
Degree of freedom		2			2			2	
p-value		0.44^{ns}			0.017*			<0.001***	

SOC is soil organic carbon, DSW is dry shoot weight of maize and DGY is dry grain yield of maize. Means followed by the same letter in the same column are not significantly different by DMRT at $p < 0.05$, * and *** significant at $p < 0.05$, and $p < 0.001$ levels while ns is not significant. Sole CF is sole chemical fertilizer (NPK 15:15:15 + urea mix), SC is sole compost, PC is phosphocompost, GL is *Gliricidia sepium* leaves, PM is poultry manure. AC is an absolute control that receives neither chemical fertilizer nor organic fertilizer.

All the soil (except SOC) and plant parameters measured differed significantly across the three selected cropping seasons (Table 3). Values of each parameter recorded across the different fertilizers were generally least during 2015 (first year of organic fertilizers application at 5 t ha^{-1}) and highest in 2021 (sixth year of organic fertilizer application at reduced rate of 2.5 t/ha spiked with biochar at 0.5 t ha^{-1}). The potential of each tested organic fertilizer to improve soil characteristics for enhanced maize yield and quality improved generally from 2015 to 2021. Concerning SOC, single biochar application had a more significant positive effect on the near raw organic fertilizers such as the PM and GL treated plots. The SOC increased by 2.4 and 41.5% in 2021 compared to 2019 observations when biochar was not used. Chen et al. (2024) also observed a drastic increase in SOC contents, its quality and macronutrient concentrations when testing biochar prepared from animal manure and crop residues. Conversely, lower increases in SOC were observed in biochar-spiked composted organic fertilizers such as SC (31.0%), while SOC was reduced by 6.3% in plots treated with PC. The generally lower N and P and higher C/N and C/P ratios of the composted organic material used as an amendment in the nutrient-degraded soil could be attributed to their reduced responsiveness to biochar spiking compared to the near raw organic fertilizers. More severe SOC degradation was, however, observed from plots under continuous use of chemical fertilizer (up to 33.3% reduction) and AC (up to 83. 6% reduction) in 2021. Similar organic carbon decomposition has been reported in other studies involving the sole continuous use of chemical fertilizers (Tang et al., 2020; Allam et al., 2022; Liu et al., 2022). These earlier studies indicated severe organic carbon depletion in chemical fertilizer treated sandy soils characterized by poor water and nutrient holding capacities. Xu et al. (2024) highlighted physiochemical properties of soil as major driver to the organic carbon dynamics in soils. This underlines the superior benefit of using an organic-based fertility option over the conventional chemical fertilizer in the nutrient-degraded sandy soil studied.

Five years of continuous sole use of other organic fertilizers (in 2019) increased the grain yield of maize by 55.0, 107.9, 110.0 and 116.9% in SC, PM, GL, and PC treated plots, respectively, compared to the 2015 cropping season when they were first applied (Table 3). These values increased dramatically by 5.8, 3.8, 3.4, and 2.9-fold in SC, PM, GL, and PC treated plots, respectively, after biochar inclusion into other organic fertilizers at reduced rates of 2.5 t ha^{-1} in 2021. These fold increases were lower in sole CF (2.1- fold) and AC (2.4- fold) plots in 2021. This directly followed the trend observed with organic carbon depletion and or sequestration in the soil studied. Biochar's potential to improve crop yield, especially in similar coarse-textured soil, was reported by Kabir et al. (2023). Frimpong et al. (2021) recorded higher maize yield after single biochar spiking into sandy loam soil earlier treated with compost and CF compared to soils with sole applications. They identified improved organic carbon, available P, total N, pH and cation exchange capacity in biochar spiked soil as pathway to the enhanced crop yield. Continuous use of sole CF however, depressed dry shoot weight (DSW) of maize in 2021 by 0.88-fold. Conversely, one-time biochar spiking increased DSW of maize by 2.0, 1.9, 1.5, and 1.4-fold in SC, PM, GL, and PC-treated plots, respectively.

Changes in soil available P, grain P, and N contents in maize in soil under continuous organic fertilizer treatments

Available P, grain P, and N contents in the maize varied significantly among the selected cropping seasons (Table 4). Available P enhancement was lowest during 2015 across all the organic fertilizers tested (except SC-treated soil) compared to the conventional CF. Five years of continuous use of organic fertilizers in 2019 improved soil available P by 178.6, 678.8, and 803.2% in PC, GL, and PM, respectively, compared to their initial values in 2015. The increases dramatically increased by up to 7.4, 6.5, 5.2, and 1.5- folds in SC, PC, GL, and PM in 2021 following a one-time biochar application. This enhanced soil labile P content was rightly indicated by the 8.3, 9.1, 12.9, and 10.8-fold increases in grain P contents in 2021 from plots respectively amended with SC, PC, GL, and PM compared to 2015 values. Similar enhanced trends were observed with grain N contents in 2021 compared to 2019 and 2015 values. The potential of biochar to improve nutrient uptake by plants through modification of the physicochemical and biological characteristics of soils has been highlighted by Lu et al. (2023), Razzaghi et al. (2020), and Adekiya et al. (2020).

Table 4. Changes in soil available P, grain P, and N contents in maize in soil under continuous organic fertilizer treatments

Treatments	Available P (mg/kg)			Grain P (%)			Grain N (%)		
	2015	2019	2021	2015	2019	2021	2015	2019	2021
Sole CF	8.61b	17.37b	21.16e	0.31a	2.83b	2.40e	1.26a	13.80a	13.62c
SC	32.16a	17.37b	129.37a	0.33a	3.41a	2.72d	1.16a	12.00a	14.31b
PC	5.74c	15.99c	104.25b	0.32a	3.51a	2.91b	1.18a	12.00a	12.42d
GL	1.65e	12.85d	65.27c	0.25b	2.50b	3.23a	1.10b	12.50a	14.82a
PM	2.88d	22.31a	34.60d	0.26b	2.53b	2.80c	1.11b	11.50b	12.31e
AC	2.47d	11.56d	17.15f	0.22c	2.40c	2.24f	1.12b	11.50b	11.91f
Chi-square									
Sample size		6			6			6	
Degree of freedom		2			2			2	
p-value		0.003**			0.003**			0.001**	

Means followed by the same letter (s) in the same column are not significantly different by DMRT at $p < 0.05$, **significant at $p < 0.01$ level. Sole CF is sole chemical fertilizer (NPK 15:15:15 + urea mix), SC is sole compost, PC is phosphocompost, GL is Gliricidia sepium leaves, PM is poultry manure. AC is an absolute control that receives neither chemical fertilizer nor organic fertilizer.

Relative agronomic efficiencies (RAE) of the tested organic fertilizers with and without biochar using the soil organic carbon content data.

One-time biochar application drastically increased the efficiencies of all the tested organic fertilizers to enhance SOC above the conventional chemical fertilizer compared to 2019 observations when biochar was not used (Figure 1). The near raw organic fertilizers (the PM and GL treatments) were more responsive to biochar treatment for improved efficiency to enhance SOC. Higher RAE values of 307.4 and 292.9% were observed for PM and GL respectively in 2021 compared to 50 and 100% RAE respective values recorded in 2019 when biochar was not used. Similar improved microbial biomass, which indicates enhanced organic matter condition in soil, was observed by Li et al. (2020) in degraded sandy soil following application of manure-based biochar produced at pyrolysis temperature below 550 °C with low C/N ratios. The composted organic fertilizers, however, were less responsive to biochar spiking in enhancing SOC. For instance, in the SC-treated plot, RAE using SOC data only increased from 250.0% in 2019 to 296.4% in 2021. The generally higher C/N ratio of the compost tested compared to the near-raw organic fertilizers could have resulted in the observed negative carbon sequestering priming effect. Conversely, the near-raw organic fertilizers conferred positive priming effects when spiked with the biochar (Majumder et al., 2019; Rehman et al., 2020). Biochar's capacity to improve SOC was associated with promoting soil microorganisms' activities (Tao et al. 2020; Jing et al. 2020; Zheng et al. 2022).

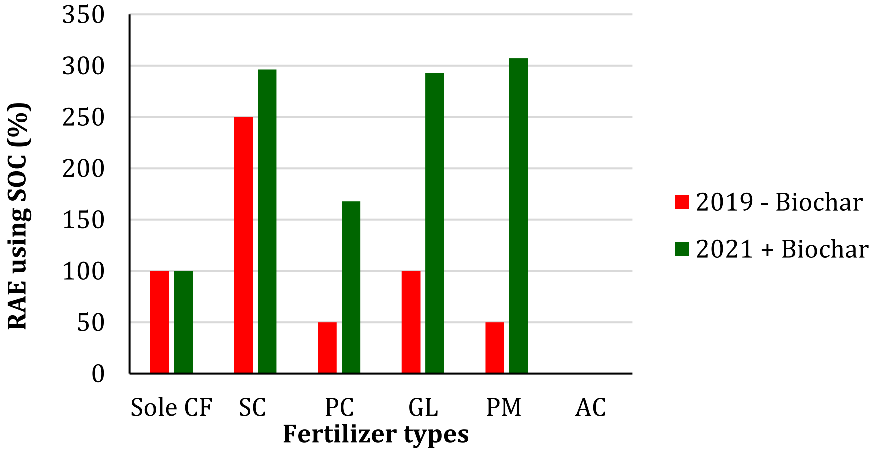

Figure 1. Relative agronomic efficiencies of the tested organic fertilizers with and without biochar relative to the conventional chemical fertilizer using the soil organic carbon contents.

RAE is relative agronomic efficiency, -Biochar is without biochar, +Biochar is with biochar, SOC is soil organic carbon, sole CF is sole chemical fertilizer (NPK 15:15:15 + urea mix), SC is sole compost, PC is phosphocompost, GL is *Gliricidia sepium* leaves, PM is poultry manure. AC is an absolute control that receives neither chemical fertilizer nor organic fertilizer.

Relative agronomic efficiencies of the tested organic fertilizers with and without biochar relative using the soil available phosphorus content data.

One-time biochar application again drastically increased the efficiency of all the organic fertilizers tested to improve soil available P (Figure 2). The trend was, however, opposite to what was observed using SOC data, such that higher RAE values were from composted organic fertilizers while lower values were from the near-raw organic fertilizers. This indicates differences in the response of the organic fertilizer forms to biochar spiking. The RAE of SC was 2798.5% > 2172.1% from PC > 1200.0% from GL > 435.2% from PM compared to 100, 76.3, 22.2 and 185% from SC, PC, GL, and PM respectively, in 2019 without biochar spiking. The potential of the biochar to significantly improve the soil available P underscored the high labile P pool in the biochar tested. Therefore, such biochar can be utilized in low-activity clay soils and high P-fixing soils peculiar to tropical soils. Biochar produced from crop residues and animal manure like the one studied, especially at pyrolysis temperatures below 400 °C, were found to support higher macronutrient pools in soils (Hossain et al. 2020; Li et al. 2023; Qi et al. 2024).

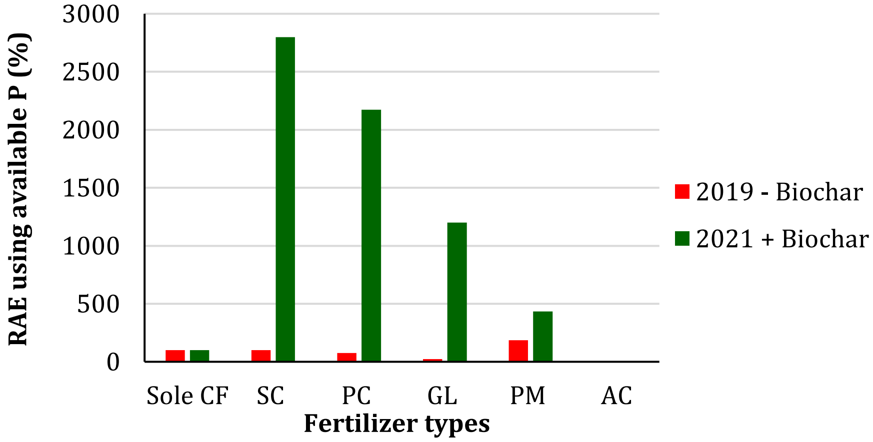

Figure 2. Relative agronomic efficiencies of the tested organic fertilizers with and without biochar relative to the conventional chemical fertilizer using the soil available P contents.

RAE is relative agronomic efficiency, -Biochar is without biochar, +Biochar is with biochar, sole CF is sole chemical fertilizer (NPK 15:15:15 + urea mix), SC is sole compost, PC is phosphocompost, GL is *Gliricidia sepium* leaves, PM is poultry manure. AC is an absolute control that receives neither chemical fertilizer nor organic fertilizer.

Relative agronomic efficiencies of the tested organic fertilizers with and without biochar using maize grain and shoot yields.

The RAE of all the tested organic fertilizers using their maize grain yield data drastically increased following the one-time introduction of biochar into the soil fertility management practices compared to 2019 when biochar was not used (Figure 3). Biochar spiking into other organic fertilizers served as biocatalyst in enhancing their efficiency to improve maize grain yield. The RAE of PC, GL, PM, and SC respectively increased to 140.3, 215.6, 257.1, and 916.9 in 2021 when spiked with biochar compared to their individual respective RAE values of 18.6, 16.9, 6.8, and 13.6% in 2019. Similar enhanced RAE values following the spiking of other organic fertilizers with biochar have been reported (Situmeang et al., 2019; Frimpong et al., 2021; Faye et al., 2021; Liu et al., 2022; Manka'abusi et al., 2024). Sole use of biochar under short-term cropping, however, was reported by Keller et al. (2023) and Frimpong et al. (2021) not to confer significant increase in crop yield.

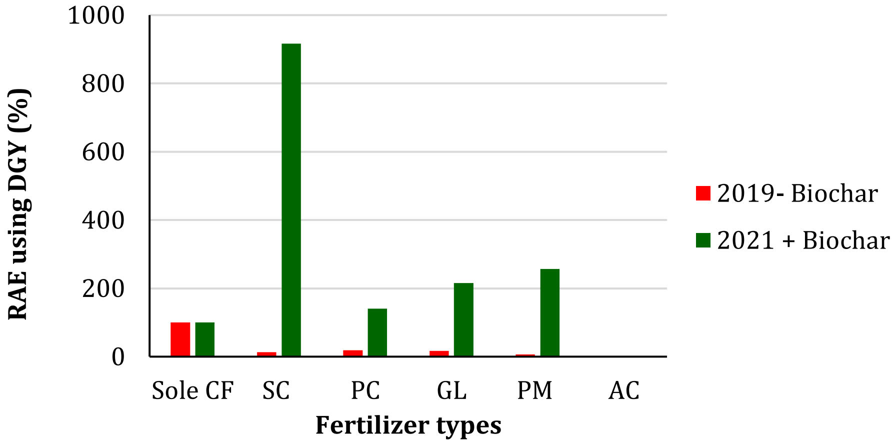

Figure 3. Relative agronomic efficiencies of the tested organic fertilizers with and without biochar relative to the conventional chemical fertilizer using the maize dry grain yield.

RAE is relative agronomic efficiency, -Biochar is without biochar, +Biochar is with biochar, DGY is dry grain yield of maize, sole CF is sole chemical fertilizer (NPK 15:15:15 + urea mix), SC is sole compost, PC is phosphocompost, GL is *Gliricidia sepium* leaves, PM is poultry manure. AC is an absolute control that receives neither chemical fertilizer nor organic fertilizer.

Spiking the tested organic fertilizers with biochar enhanced their efficacy to improve the dry shoot weight of the test crop (Figure 4). Biochar spiking increased the RAE of GL, PM, SC, and PC to 46.7, 158.1, 242.6, and 325.0% respectively from 41.0, 63.0, 16.4 and 24.7% in 2019 when they were applied solely. The biochar porous structure and silicon richness improved the nutrient holding capacities of the soil for efficient nutrient availability, uptake and translocation for improved biomass production (Matichenkov et al., 2020; Alkharabsheh et al., 2021). This was not the situation in soil continuously treated with sole CF as indicated by lower RAE value (100%) compared with the biochar spiked fertilizers. Indiscriminate use of CF is associated with reduced cation exchange capacity (Dubos et al., 2016; Balasuriya et al., 2022) nutrient leaching and volatilization (Liu et al., 2021; Krasilnikov et al., 2022) which significantly reduces nutrient concentrations available for plant uptake.

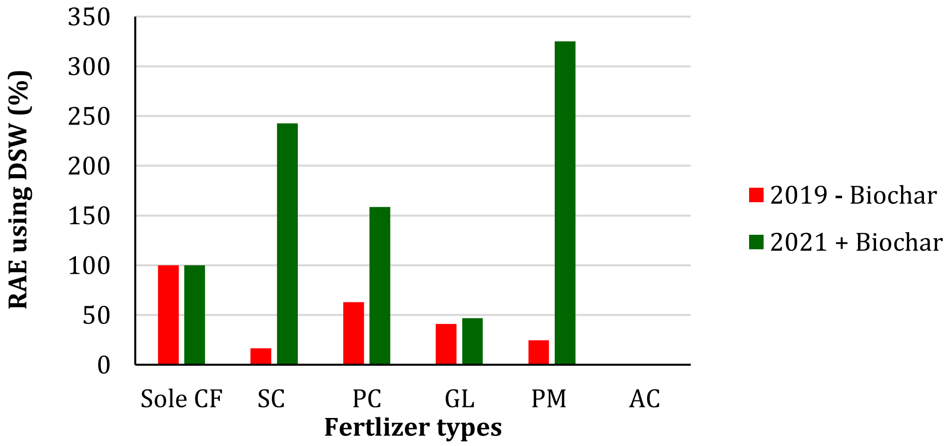

Figure 4. Relative agronomic efficiencies of the organic fertilizers relative to the conventional chemical fertilizer using dry shoot weight of maize.

RAE is relative agronomic efficiency, -Biochar is without biochar, +Biochar is with biochar, DSW is dry shoot weight, sole CF is sole chemical fertilizer (NPK 15:15:15 + urea mix), SC is sole compost, PC is phosphocompost, GL is *Gliricidia sepium* leaves, PM is poultry manure. AC is an absolute control that receives neither chemical fertilizer nor organic fertilizer.

Relative agronomic efficiencies of the tested organic fertilizers with and without biochar using the maize grain N and P contents.

Biochar inclusion into the plots under five years of continuous use of other tested organic fertilizers improved the RAE of the organic fertilizers (except GL) using the maize grain N contents compared to their respective values in 2019 (Figure 5). However, the RAE values recorded during both 2019 and 2021 in all the organic fertilizers tested (except PC in 2021) were below the threshold value of 100% from the conventional chemical fertilizers. This indicates lower contributions of the organic fertilizers with or without one-time spiking with biochar to improve N nutrition in the soil studied sufficiently and translocation into the maize grains. This is dominantly due to lower N contents in the organic fertilizers tested. This has been identified as a significant limitation to farmers' adoption of organic fertilizers as soil fertility options for crop production. The observed higher N content in maize grown on the PC plot in 2021 may be due to possible co-absorption of N along with the higher available P content recorded from this plot. Summarily, biochar spiking into existing organic plots increased RAE values of SC, PM, and PC using grain N content of maize by 63.2, 382.5, and 656.8%, respectively, in 2021 compared to 2019.

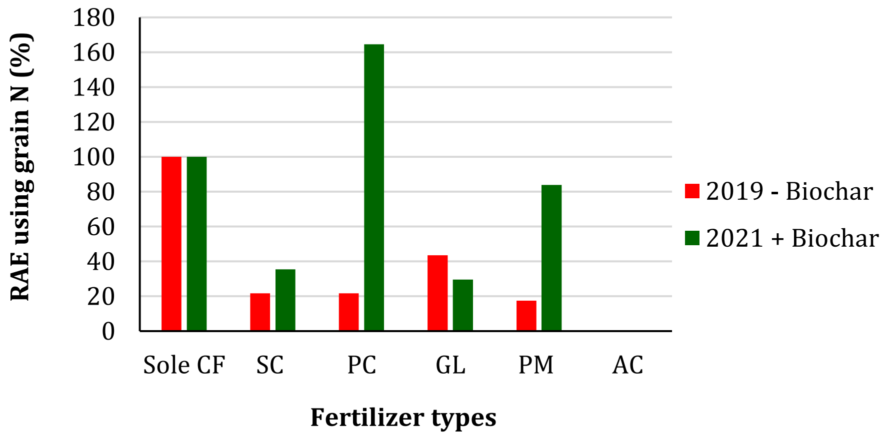

Figure 5. Relative agronomic efficiencies of the tested organic fertilizers with and without biochar relative to the conventional chemical fertilizer using the maize grain N contents.

RAE is relative agronomic efficiency, -Biochar is without biochar, +Biochar is with biochar, sole CF is sole chemical fertilizer (NPK 15:15:15 + urea mix), SC is sole compost, PC is phosphocompost, GL is *Gliricidia sepium* leaves, PM is poultry manure. AC is an absolute control that receives neither chemical fertilizer nor organic fertilizer.

The RAE of all the organic fertilizers tested using grain P content data also increased in 2021 when biochar was introduced (except in SC) compared to their 2019 values (Figure 6). Interestingly and contrary to observation under soil available P, higher RAE percentage increases of 672.5 and 383.4% were observed in the near raw organic fertilizers GL and PM respectively in 2021 following biochar spiking compared to their 2019 RAE values. Lower RAE increases, however, were observed from composted organic fertilizer-treated soil, such as a 4% increase from PC and a 13.2% reduction from SC-treated soil. Nevertheless, the RAE values of all the tested organic fertilizers using the grain P contents were superior to those of the conventional chemical fertilizers during 2019 and 2021 (except in GL and PM in 2019). Biochar's potential to improve the nutrient use efficiency of other fertilizers is attributed to its porous structure's ability to retain nutrients and prevent nutrient leaching and volatilization (Fungo et al. 2017; Liu et al. 2021; Jiang et al. 2024).

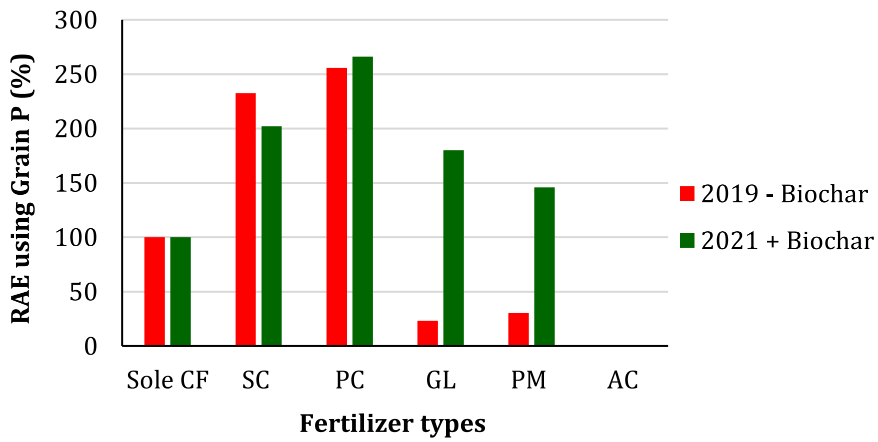

Figure 6. Relative agronomic efficiencies of the tested organic fertilizers with and without biochar relative to the conventional chemical fertilizer using the maize grain P contents.

RAE is relative agronomic efficiency, -Biochar is without biochar, +Biochar is with biochar, sole CF is sole chemical fertilizer (NPK 15:15:15 + urea mix), SC is sole compost, PC is phosphocompost, GL is *Gliricidia sepium* leaves, PM is poultry manure. AC is an absolute control that receives neither chemical fertilizer nor organic fertilizer.

Conclusion

The immediate, short-term use of different organic fertilizers and contributions of one-time co-application of biochar with other organic fertilizers in continuously cropped soil were evaluated. The work underlines the superior benefits of the organic-based fertility option over the sole use of conventional chemical fertilizer in the nutrient-degraded sandy loam soil studied. Soil and plant parameters generally improved with the continued use of organic fertilizers during the 2015 to 2021 cropping seasons. Severe reductions in organic carbon contents, grain yield and shoot weight were observed from plots continuously managed by sole chemical fertilizer. Near-raw organic fertilizers (poultry manure and *Gliricidia sepium* leaves) were instrumental in achieving immediate enhancement of soil organic carbon contents compared to composted organic fertilizers.

Biochar one-time spiking into the existing organic plots improved the RAE of all the other organic fertilizers at 50% reduced application rate. There were, however, differences in their responses to biochar spiking. Biochar's one-time application impacted higher responsiveness on RAE of near-raw organic fertilizers for SOC enhancement than composted organic fertilizers while RAE using available P data was higher in composted organic fertilizers. Variation also existed in the grain P contents in the different forms of organic fertilizer studied and responses to biochar spiking. Near- raw organic fertilizers translocated more P into maize grains above the composted organic fertilizers.

Spiking other organic fertilizers with biochar from composted crop residues and animal dung, therefore, provides a platform for reduction in the high tonnage application rates associated with the usage of organic fertilizers. It assures drastic improvement in soil properties, crop yield and quality. Biochar co-application with other organic fertilizers should be adopted for use in sustainable cultivation and amelioration of degraded sandy soils of the tropics. Potential of biochar to reduce application rates of other organic fertilizers will benefit local farmers desiring to convert from conventional farming into organic crop production. Future research work should be channeled into developing nitrogen fortified biochar and other organic fertilizers that will solve the limitation of poor grain N contents in the organically produced maize.

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