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Article

Assessing the effects of biochar, sewage sludge, and mineral fertilization on soil characteristics and maize yield

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ABSTRACT: Sewage sludge (SS) and biochar offer a sustainable approach for improving nutrient supply and soil characteristics, but more research is needed to compare their efficacy against mineral fertilizers. First, this study assessed the effects of rice husk biochar (RHB) rates (0, 5, 10, 15, and 20 $t \cdot ha^{-1}$) on the chemical, physical, and biological characteristics of a soil grown with maize. Then, the RHB rate providing the highest maize biomass was compared to SS and NPK fertilization. Maize yield and mineral composition were also evaluated. The results showed that the tested fertilizers had varying effects on increasing maize yield and altering soil properties. While RHB improved water retention capacity, cation exchange capacity, microbial biomass, and maize yield when compared to the control group, SS proved to be more effective in enhancing P availability. The maize yield with SS was five times greater than the regional maize productivity and equal to the performance of NPK fertilization. Considering the substantial positive impact of SS on soil characteristics, it is recommended that local farmers apply 20 $t \cdot ha^{-1}$ of this fertilizer. This not only has the potential to replace traditional mineral fertilization, but also offers the additional advantage of improving overall soil quality.

Key words: *Zea mays* L., organic fertilizers, soil conditioners, sustainable agriculture.

INTRODUCTION

Over the past five decades, the global population has increased by 196%, and it is anticipated to increase by an additional 65% by 2050 (United Nations Organization 2020). This demographic forecast has sparked a surge in the demand for food, exerting mounting pressure on natural resources, particularly soil and water, due to expanding arable land (Laghari et al. 2015). Such expansion has driven the increased consumption of mineral fertilizers, with adverse effects on the environment, including the release of reactive forms of N into the atmosphere (Liu et al. 2020), eutrophication, water and soil contamination (Withers et al. 2014), and the disruption of microbial community compositions (Geisseler and Scow 2014).

Simultaneously, the population's needs led to a surge in organic waste generation. Considering the environmental challenges to dispose of such wastes and the global crisis in the production and distribution of mineral fertilizers (USDA 2023), the use of organic wastes has become an even more imperative and cost-effective practice to enhance soil characteristics and increase crop yields (Da Silva et al. 2021, Lee et al. 2022).

In this scenario, the use of biochar and sewage sludge as soil amendments represents a sustainable approach to enhance soil fertility and mitigate the adverse environmental impacts associated with mineral fertilizers. Biochar, a carbon-rich, stable form of organic matter, improves soil structure, retains moisture, and sequesters carbon. Moreover, biochar can increase nutrient retention in the soil and promote microbial activity. Sewage sludge (SS), a byproduct of wastewater treatment, has become an attractive alternative since it provides organic matter and nutrients that positively affect the soil quality and crop yield while reducing risks with inadequate SS disposal (Da Silva et al. 2021). Furthermore, the organic compounds in the sludge enhance the stability of soil aggregates, increasing the total soil porosity able of retaining water (Sharma et al. 2017).

This study compared the efficacy of biochar, SS, and mineral fertilizer on maize yield and nutrition and soil chemical, physical, and biological characteristics. Our goal was providing insights into sustainable agricultural practices, aiming to optimize crop yield while enhancing soil quality. We hypothesized that organic fertilizers can give equal or even greater crop yields than traditional mineral fertilizers used by small farmers of Northeast Brazil and similar regions in the tropics.

MATERIALS AND METHODS

The commercial rice husk biochar (RHB) used in this experiment was derived through the controlled process of pyrolysis, which involved subjecting rice husks to the temperature of 400°C. Meanwhile, SS used was obtained by a sewage treatment plant. The materials were dried in an oven at 60°C and chemically analyzed using standard methods, including heavy metal concentrations (CONAMA 2006) (Table 1). All metals evaluated were within permissible concentrations to soil application. The experiment was carried out in the field between March to June, in Moreno, Pernambuco state, Brazil (08°07’07”S and 35°05’32”W). The precipitation during the experiment was around 770.1 mm. The soil in the study area was classified as Acrisol (FAO 2015; Table 2).

Table 1. Chemical and physical characteristics of rice husk biochar and sewage sludge used in the experiment.

Characteristics	Rice husk biochar	Sewage sludge
Density ($g \cdot cm^{-3}$)	1.0	---
Pore volume ($cm^3 \cdot g^{-1}$)	0.0044	---
pH (H_2O)	5.73	7.62
Organic carbon (%)	47.67	31.06
Total N ($g \cdot kg^{-1}$)	1.40	18.5
C/N	34.50	16.79
P ($g \cdot kg^{-1}$)	1.90	9.94
K ($g \cdot kg^{-1}$)	2.23	0.42
Ca ($mg \cdot kg^{-1}$)	1.62	57.64
Mg ($mg \cdot kg^{-1}$)	0.71	1.57
Mn ($mg \cdot kg^{-1}$)	713.07	109.98
Fe ($mg \cdot kg^{-1}$)	351.27	5,083.70
Cu ($mg \cdot kg^{-1}$)	4.28	52.67
Zn ($mg \cdot kg^{-1}$)	15.40	418.62
As ($mg \cdot kg^{-1}$)	ND	2.93
Cd ($mg \cdot kg^{-1}$)	0.45	0.27
Cr ($mg \cdot kg^{-1}$)	1.77	0.41
Ni ($mg \cdot kg^{-1}$)	0.77	36.45
Pb ($mg \cdot kg^{-1}$)	0.65	9.30

ND: non detectable; P, Ca, Mg, Cu, Zn, Fe, Mn, As, Cd, Cr, Ni, and Pb content was extracted with HNO3 + HCl according to method 3051a (USEPA 1998) and analyzed by colorimetry (P), flame photometry (K), and inductively coupled plasma–atomic emission spectrometry. RHB pore volume e density were determined according to Brewer et al. (2014).

Table 2. Chemical and physical characteristics of the soil (0–20 cm) from the experimental site.

Characteristics	Soil
Chemical	
pH (H_2O)	6.00
P (mg·kg^{-1})	9.80
Total organic carbon (g·kg^{-1})	18.1
N (g·kg^{-1})	1.09
K (cmol$_c$·kg^{-1})	0.06
Ca (cmol$_c$·kg^{-1})	0.75
Mg (cmol$_c$·kg^{-1})	2.26
Al (cmol$_c$·kg^{-1})	0.21
Cation exchange capacity (cmol$_c$·kg^{-1})	7.19
Physical	
Bulk density (g·cm^{-3})	1.45
Total porosity (%)	43.46
Sand (g·kg^{-1})	500.00
Silt (g·kg^{-1})	400.00
Clay (g·kg^{-1})	100.00

Ca^{2+}, Mg^{2+} e Al^{3+} extracted by KCl 1 mol·L^{-1}; K^+, and available P by Melich-1.

The experimental area encompassed 316.8 m^2, with individual experimental units spanning 7.2 m^2 (2.4 × 3 meters). Each plot consisted of four maize (hybrid AG 1051) rows, each measuring 3 m in length, with row spacing at 0.80 m and plant-to-plant spacing set at 0.20 m. In total, the study had 28 experimental units (seven conditions × four replicates) distributed in four blocks, which were randomized, as experimental design. For data collection, only the two central rows were taken into account.

The treatments consisted of four RHB rates, single rates of SS and NPK fertilizer, and a control. The RHB rates were 0, 5, 10, 15, and 20 t·ha^{-1}. The SS rate (20 t·ha^{-1}) was selected based on a previous study (Gomes et al. 2007). Mineral fertilization followed the fertilizer recommendations of Pernambuco state: urea (70 kg·ha^{-1} = 30 kg·ha^{-1} at planting and 40 kg·ha^{-1} at the 40th day after planting), MAP (30 kg·ha^{-1}), and KCl (30 kg·ha^{-1}). The SS used was treated with 10% of CaO to raise the SS pH to 12 for 2 h in order to reduce pathogenic organisms (CONAMA 2006). RHB and SS were manually incorporated into the soil to the depth of 10 cm across the entire plot, while mineral fertilizer was applied within the maize planting rows. The plants were cultivated for 90 days until grain maturation.

For physical attributes, undisturbed samples were collected, with the aid of volumetric cylinders (5 × 5 cm) and an Uhland-type sampler, at the depth of 0–5 cm, collecting one sample per plot, totaling 28 samples. Bulk density (BD) and total porosity (TP) were determined (EMBRAPA 2017). The soil water retention curve was constructed using the tension table to equilibrate the samples at low potentials (1, 6, and 10 kPa); and Richards chamber (Richards 1965) for medium and high potentials (33, 80, 300, and 1,500 kpa). The curve adjustment was performed by applying Van Genuchten's model (1980). The pore-size distribution of the soil was determined based on Prevedello (1996). Mesoporos values was not discussed, because no differences were identified.

Carbon (Cmic) from soil microbial biomass was estimated by the irradiation-extration method (Mendonça and Matos 2017). Microbial activity was assessed through basal soil respiration (BSR), in which the C-CO_2 emission of soils incubated with sodium hydroxide.

Total organic carbon (TOC) was obtained using the Walkley–Black method, while the cation exchange capacity (CEC) was obtained using the sodium and ammonium acetate method. The soil pH (H_2O) was also determined. Available P and K^+ were determinated after extraction with Mehlich-1.

Three plants were randomly collected within the useful area of each plot. In the laboratory, the grains were separated from the ears and placed in paper bags, to then be taken to dry in an oven at 65°C for 72 hours. In the leaves and grains, the concentrations of P and K were determined after nitroperchloric digestion. N extract was obtained by digesting 0.2 g of the plant material in sulfuric acid at 350°C (Kjeldahl method). P content was determined by colorimetry and K content by flame photometry. All analysis were performed according to standard protocols (EMBRAPA 2009). There was no difference between treatments regarding N concentration, so this data was not shown.

The selection of the optimal RHB rate was predicated on the rate that yielded the highest maize yield. We also conducted a Pearson's linear correlation analysis to examine the relationships between biological and physical soil attributes. Afterward, we compared the chosen RHB rate with the other treatments (SS, NPK, and control) using an analysis of variance (ANOVA) and the Tukey's test ($p < 0.05$).

RESULTS AND DISCUSSION

Effects of rice husk biochar on soil chacteristics and maize yield

Rice Husk Biochar application had significant effects on soil properties and maize yield, with exponential, polynomial, or linear trends with RHB increasing rates (Fig. 1). The alteration in soil physics resulted from changes in BD, which decreased as RHB rates increased. This decrease can be attributed to the lower density of biochar (1 g·cm^{-3}) compared to BD (1.45 g·cm^{-3}), and the interaction between biochar and soil mineral particles, particularly in sandy soils, which enhanced the formation and stability of larger soil aggregates.

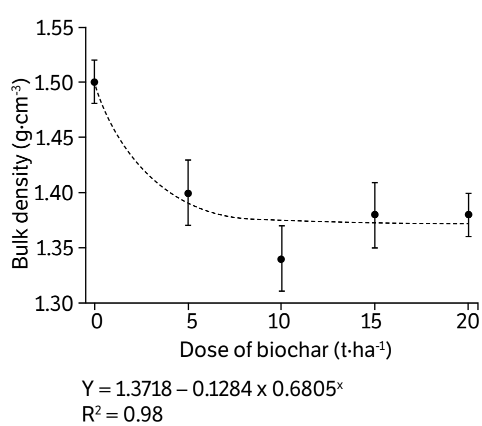


Figure 1. Bulk density (± deviation standard) at 90 days of planting considering the rice husk biochar rates applied. Significant at 1% probability by analysis of variance.

We found an increase in both macro and microporosity of the soil (Fig. 2), which influenced water retention. Increased moisture with RHB application rates of 5, 10, and 15 t·ha^{-1} can be attributed to the pores on the biochar's surface. After carbonization, various-sized pores develop on the biochar surface due to the volatilization of organic compounds (Singh et al. 2018). The application of 20 t·ha^{-1} RHB significantly increased soil criptoporosity and wilting point. This increment is mainly due to the appearance of very small intrapores within the biochar (Fig. 3) and the interaction between coarse soil particles (silt and sand) and biochar, forming interpores (Liu et al. 2017).

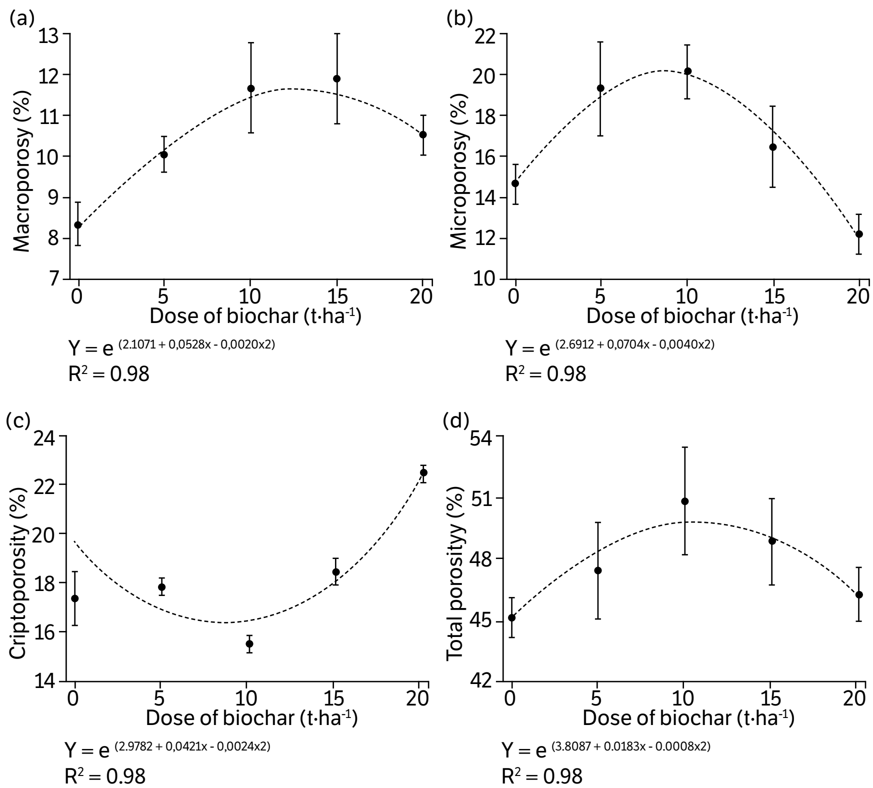


Figure 2. Pore size distribution and total porosity of soil (± deviation standard) considering the rice husk biochar rates applied. Significant at 1% probability by analysis of variance. (a) Macroporosity; (b) microporosity; (c) criptoporosity; (d) total porosity.

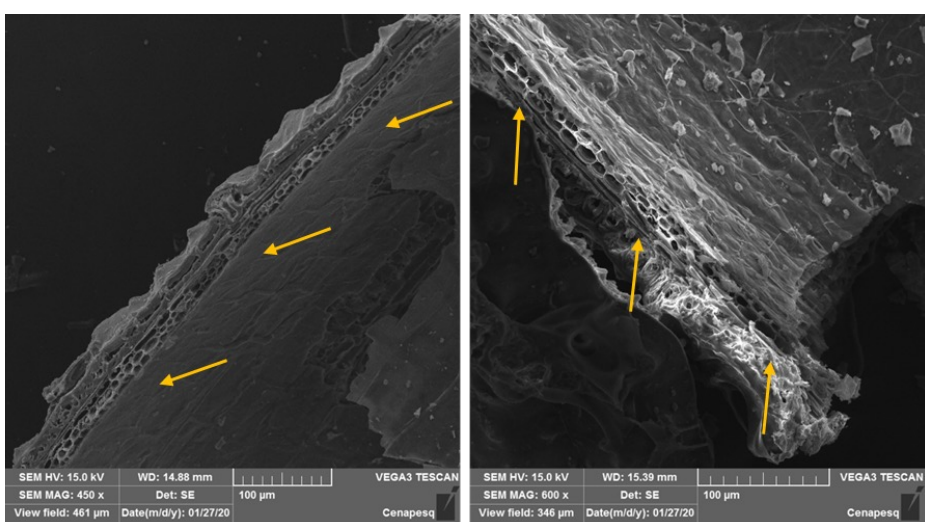


Figure 3. Scanning electron microscopy of the rice husk biochar, with arrows indicating the presence of pores surface close to the edges in cross-section.

All alterations in field capacity (FC), wilting point (WP), and available water (AW) were influenced by the alterations in soil pore network (Fig. 4). The soil texture plays a significant role in improving moisture in RHB-treated soil (Esmaeelnejad et al. 2016). This effect is attributed to increased soil microporosity resulting from RHB's internal microporosity and pore shrinkage–a process involving smaller RHB particles filling interpores located between coarse particles (silt and sand), reducing pore size.

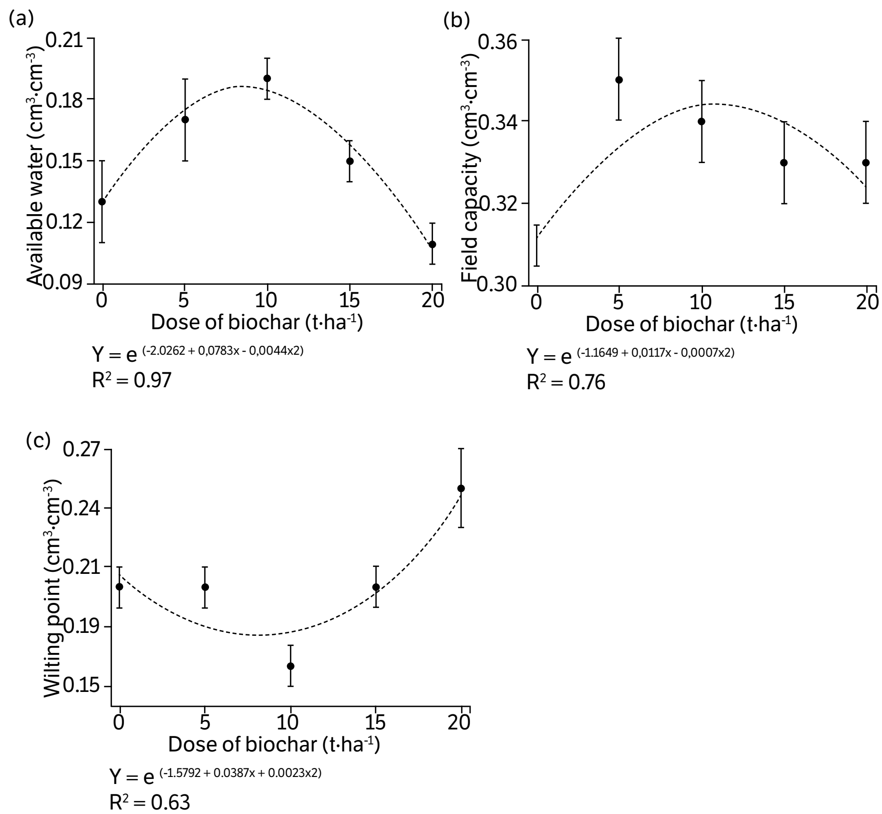


Figure 4. Available water, field capacity, and wilting point of soil (± deviation standard) considering the rice husk biochar rates applied. Significant at 1% probability by analysis of variance. (a) Available water; (b) field capacity; (c) wilting point.

While most plants cannot access moisture at the WP, the most crucial changes for maize development were the increases in FC and AW. The rise in AW and FC benefits maize growth, as these improvements translate to increased water storage and availability, ultimately contributing to higher dry mass and grain yield. Nevertheless, even if the increase in WP after 20 t·ha^{-1} applied is considered a moisture inaccessible to plants, it could support soil microbial biomass (Lima et al. 2018).

The alteration of moisture in the different pore size, combined with the introduction of carbon into the soil, led to an increase in MBC and CO_2 releasing across all RHB rates assessed (Fig. 5). A portion of C biochar can persist in a labile form post-pyrolysis, primarily the bio-oil formed during pyrolysis and absorbed by the biochar during cooling. This labile fraction is common, especially in biochars produced at lower temperatures (200–500°C), and this carbon can be oxidized by microorganisms (Smith et al. 2010, Chagas et al. 2022).

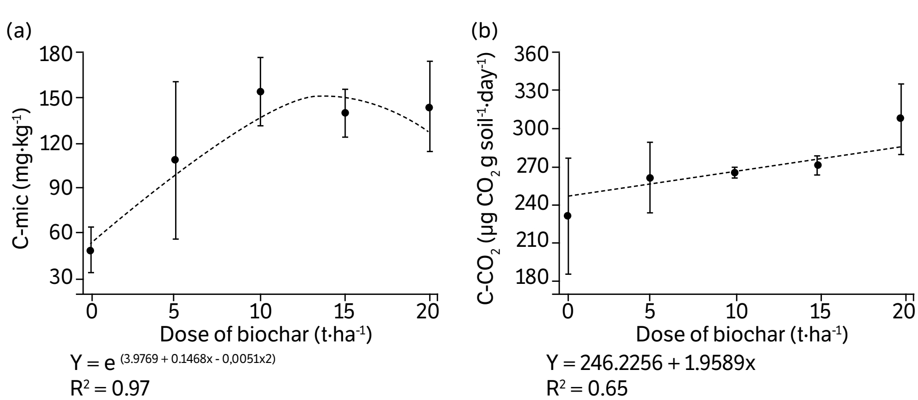


Figure 5. Microbial biomass carbon and basal respiration of soil (± deviation standard) considering the rice husk biochar rates applied. Significant at 1% probability by analysis of variance. (a) Microbial biomass; (b) basal respiration.

The correlations demonstrate that increased microbial activity depends not only on carbon supply, but also on changes in several soil physical attributes, including macroporosity [(MBC = 0.57 ($p < 0.01$)], criptoporosity [(BSR = 0.45 ($p < 0.05$)], field capacity [(BSR = 0.52 ($p < 0.05$)], and wilting point [(BSR = 0.47 ($p < 0.05$)], as well as a decrease in bulk density [(MBC = -0.62 ($p < 0.01$)]. Some authors report that the increase in soil respiration is not correlated with physical alterations resulting from biochar addition (Jones et al. 2011), while others sustain that biochar's physical changes, such as enhanced oxygen diffusion, moisture retention, and nutrient availability foster a hospitable environment for microorganisms (Liu et al. 2017, Singh et al. 2018).

RHB application induced significant alterations in soil chemical properties (Fig. 6. The linear increase in CEC can be attributed to the surface area of biochar, especially in the low CEC soil we studied (7.19 $cmol_c \cdot kg^{-1}$). The carboxylate groups on biochar play a significant role in nutrient retention (Adekiya et al. 2019). It's noteworthy that CEC increased significantly within just 90 days of the experiment.

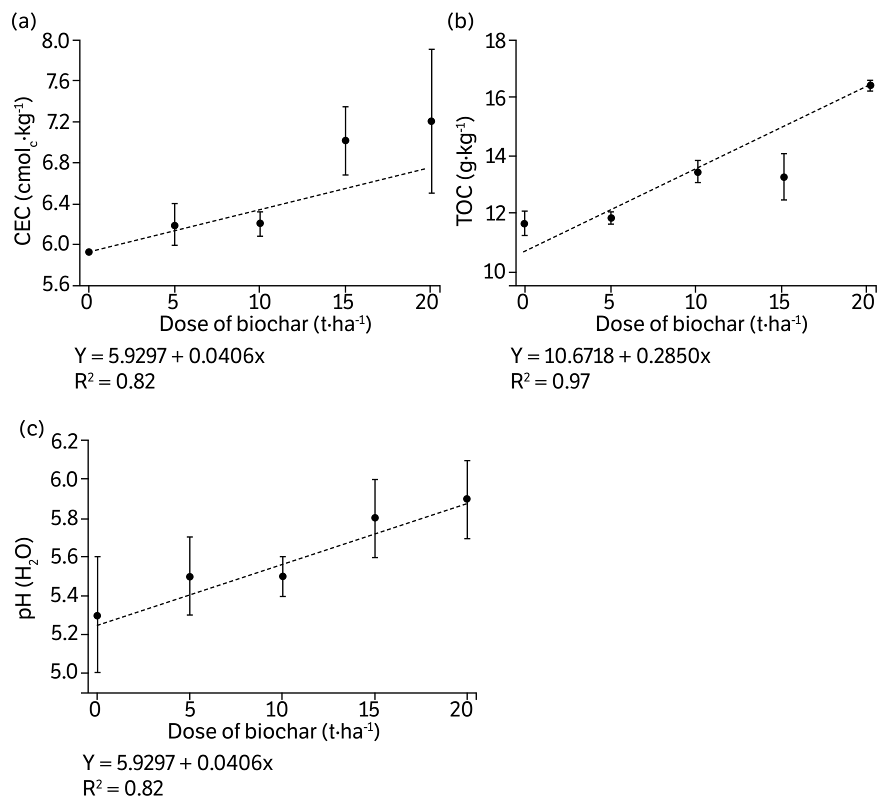


Figure 6. Cation exchange capacity, total organic carbon and pH of soil (± deviation standard) at 90 days of planting considering the rice husk biochar rates applied. Significant at 1% probability by analysis of variance. (a) Cation exchange capacity; (b) total organic carbon; (c) pH of soil.

The rise in soil pH increased the availability of P and K (Fig 7). The increase in available P was linear, suggesting that higher application rates (> 20 $t \cdot ha^{-1}$) could further enhance P availability. The RHB used contains approximately 1.90 $g \cdot kg^{-1}$ of P, and application rates such as 20 $t \cdot ha^{-1}$ provide about 38 kg of P. Eduah et al. (2019) suggested that RHB produced at low temperatures (350 to 400°C) retains acidic groups (carboxylic and phenolic groups) that release P from clay particles, making P more available (Torres et al. 2020).

RHB is among the primary organic sources with the highest K levels in its composition (Andrews et al. 2021). Furthermore, the increase in soil pH and CEC played crucial roles in the K^+ increased availability (Fig. 7), particularly CEC, as the negative charges generated on biochar surfaces reduced K leaching losses (Tanure et al. 2019). K exhibites a different pattern compared to N and P, with maximum absorption occurring during the vegetative development phase, indicating a higher demand for K in the initial growth stage (Coelho 2006). Despite being considered a recalcitrant source of organic matter, RHB provides a portion of the K required for maize.

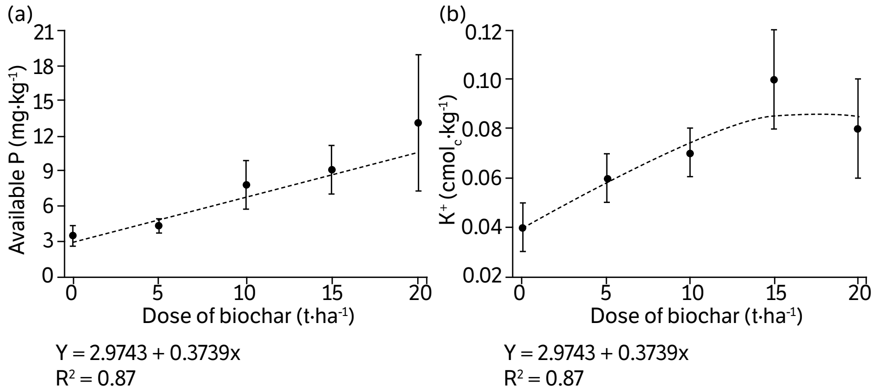


Figure 7. Available P and K^+ of soil (± deviation standard) considering the rice husk biochar rates applied. Significant at 1% probability by analysis of variance. (a) Available P; (b) K^+ of soil.

Despite the increased uptake of macronutrients, RHB at the rates used was not sufficient as a fertilizer to maize. The optimum leaf K and P contents for maize should range from about 17 to 35 and 2 to 4 $g \cdot kg^{-1}$, respectively (Fig. 8). In this study, both element values were below these ranges. However, a 208% maize yield increase was observed with the application of 10 $t \cdot ha^{-1}$ compared to the control (Fig. 9). The effect of RHB in improving water retention, CEC, TOC, pH, and increased K and P availability played a pivotal role in enhancing grain yield.

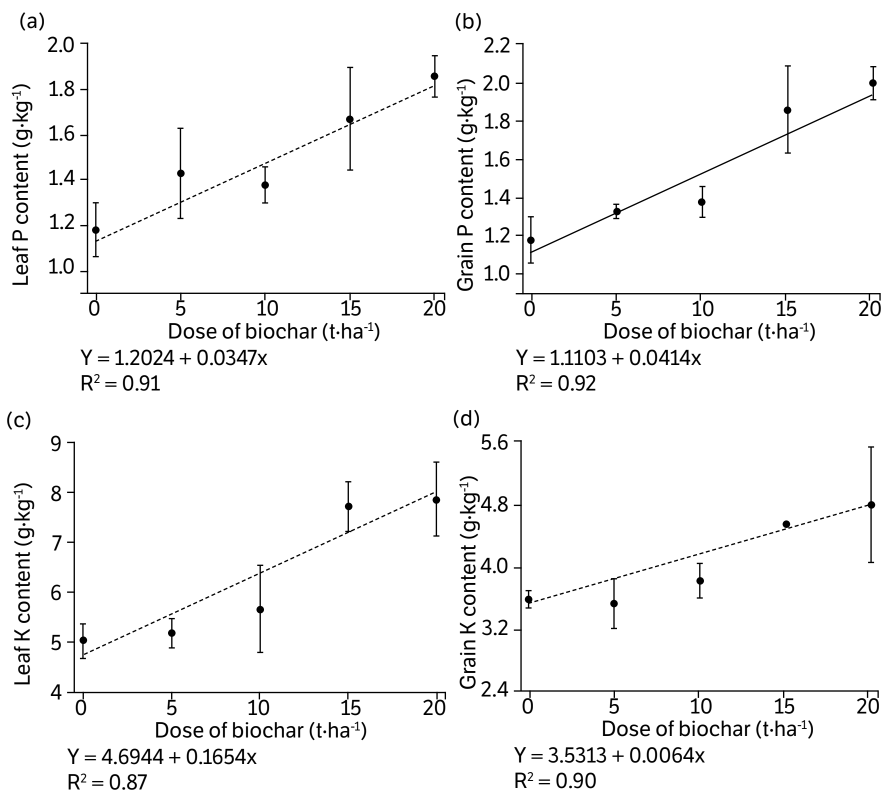
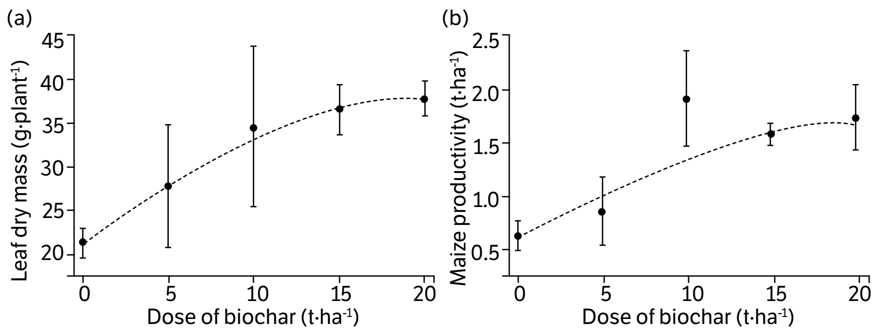


Figure 8. P and K content (leaf and grain) of maize plants (± deviation standard) considering the rice husk biochar rates applied. Significant at 1% probability by analysis of variance. (a) Leaf P content; (b) grain P content; (c) leaf K content; (d) grain K content.



$Y = e^{(3.0614 + 0.597x - 0.0015x2)}$
$R^2 = 0.99$

$Y = e^{(-0.4598 + 0.1031x - 0.0027x2)}$
$R^2 = 0.94$

Figure 9. Leaf dry mass and maize productivity (± deviation standard) considering the rice husk biochar rates applied. Significant at 1% probability by analysis of variance. (a) Leaf fry mass; (b) maize productivity.

Comparing rice husk biochar, sewage sludge, and NPK effects on the soil characteristics and maize yield

The 10 t·ha^{-1} rate of RHB caused the highest maize yield increase. Interestingly, the 10 t·ha^{-1} rate of RHB and SS exhibited a similar effect on soil BD (Table 3). Both organic materials have low densities compared to sandy soils. The RHB and SS densities are near 1 g·cm^{-3}. Therefore, adding such material to a soil with 1.45 g·cm^{-3} density lowers BD. Water retention, on the other hand, showed distinct behavior. RHB promoted greatest improvements on TP, macroporosity, microporosity, and AW. The 10 t·ha^{-1} RHB rate was more efficient for improving water retention compared to SS, owing to its inherent porosity and its potential to enhance soil aggregation (Herath et al. 2013). However, SS and RHB showed a similar effect in increasing TP and FC.

Table 3. Effect of rice husk biochar, sewage sludge, and NPK fertilizer on soil physical attributes at 90 days of plating.

Characteristics	Treatment			
	Control	NPK	Rice husk biochar	Sewage sludge
Bulk density (g·cm^{-3})	1.50 ± 0.0 a	1.48 ± 0.0 a	1.34 ± 0.0 b	1.37 ± 0.0 b
Total porosity (%)	45.17 ± 0.1 c	46.23 ± 0.8 c	52.62 ± 0.9 a	48.34 ± 0.5 b
Macroporosity (%)	8.33 ± 0.5 b	7.85 ± 0.1 b	11.67 ± 1.1 a	6.68 ± 1.0 b
Microporosity (%)	14.69 ± 1.0 b	15.52 ± 1.7 b	20.13 ±1.3 a	16.03 ± 2.0 b
Criptoporosity (%)	18.34 ± 1.7 ab	20.61 ± 1.8 ab	15.52 ± 0.0 b	21.81 ± 3.2 a
Field capacity (cm·cm^{-3})	0.31 ± 0.0 c	0.32 ± 0.0 bc	0.34 ± 0.0 ab	0.36 ± 0.0 a
Available water (cm·cm^{-3})	0.12 ± 0.0 b	0.13 ± 0.0 b	0.19 ± 0.0 a	0.14 ± 0.0 b
Wilting point (cm·cm^{-3})	0.19 ± 0.0 ab	0.19 ± 0.0 ab	0.15 ± 0.0 c	0.22 ± 0.0 a

Values followed by the same letters, within rows, are not significantly different at $p < 0.05$ according to the Tukey's test. Mesoporous was also calculated to determine total porosity, but no differences were identified. Mesoporous values were (%): control = 3.81; NPK = 2.24; rice husk biochar = 5.30; sewage sludge = 3.82.

TP values around 50% are crucial for crops, especially for improving root system aeration and water retention. Baver et al. (1972) identified that optimum aeration conditions for plants are met when macroporosity exceeds 10%. Only the soil treated with RHB reached this threshold. Therefore, RHB can be a valuable asset, particularly during dry seasons by enhancing water retention and during wet seasons by facilitating proper drainage of excess water.

When assessing SS application on TP and pore size distribution, it is essential to emphasize the impact of the increase in criptoporosity on microbial activity (Table 4). SS acted as a rich source of labile carbon, and its enhancement of water content at the WP enables microorganisms to decompose organic carbon and expand their population within soil pores, despite the relatively short time of our experiment. Sampaio et al. (2012) stressed the need for a longer evaluation period. In their work, significant differences were observed six months after incorporating 20 t·ha^{-1} of SS.

Table 4. Effect of rice husk biochar, sewage sludge, and NPK fertilizer on soil biological attributes at 90 days of plating.

Treatments	Soil basal respiration μg CO_2 g·soil^{-1} day^{-1}	Microbial biomass carbon	Microbial coefficient	Metabolic coefficient
		----------------mg·kg^{-1}--------------		
Control	228.94 ± 4.0 b	40.25 ± 15.6 c	3.46 ± 1.0 c	7.75 ± 1.0 a
NPK	262.01 ± 7.7 a	144.66 ± 21.3 b	11.98 ± 2.2 ab	1.75 ± 0.1 b
Rice husk biochar	266.47 ± 4.1 a	154.44 ± 22.8 ab	9.04 ± 2.9 bc	1.78 ± 0.3 b
Sewage sludge	258.33 ± 1.6 a	196.40 ± 24.7 a	16.36 ± 1.73 a	1.18 ± 0.1 b

Values followed by the same letters, within columns, are not significantly different at $p < 0.05$ according to the Tukey's test.

Organic fertilizers were the primary contributors to microbial growth, particularly SS, which has a substantial portion of this carbon in labile form, readily metabolized by microorganisms (Scotti et al. 2016). Dhanker et al. (2021) also found an increase in C-mic and noted that the greatest contribution occured in SS-treated soil. In their study, the highest C-mic value was observed after two weeks of incubation, gradually declining over 90 days. The C:N ratio of SS (16.79) indicates a faster organic matter decomposition compared to RHB (34.50). In contrast, pyrolysis leaves only a small fraction of biochar carbon in easily degradable forms (Singh et al. 2018) when compared to SS (Scotti et al. 2016). However, despite the limited C pool accessible to microbes in biochar, its porous structure and the improvement in soil aggregate yield similar results to SS addition on microbial growth (Table 4).

Soil chemical changes showed differences between RHB, SS, and NPK. RHB primarily acts as a soil conditioner by providing OC and increasing CEC. NPK, on the other hand, enhances the availability of macronutrients, although a significant increase was observed only for P (Table 5). SS had the most significant effects on the soil chemistry, probably due to its liming effect attributed to the application of CaO for sludge stabilization (Da Silva et al. 2021). The reduction in acidity can enhance nutrient availability, particularly for P, which exhibited the most substantial increase. Moreover, SS is recognized as a significant source of P as it provided at least 200 kg·ha^{-1} of P in the present study. The P and K contents were similar in the SS and NPK treatments (Table 6). The increased dry leaf mass, especially with the application of RHB, was dependent on the increase of K uptake observed in the organic treatments. In contrast, P uptake significantly increased in the NPK-treated soil, playing a pivotal role in enhancing biomass.

Table 5. Effect of rice husk biochar, sewage sludge, and NPK fertilizer on soil chemical attributes at 90 days of plating.

Treatments	pH (H_2O)	Total organic carbon	Cation exchange capacity	Available P	K^+
		g·kg^{-1}	cmol$_c$·kg^{-1}	mg·kg^{-1}	cmol$_c$·kg^{-1}
Control	5.33 ± 0.3 c	11.66 ± 0.1 ab	6.69 ± 0.4 ab	3.54 ± 0.8 b	0.04 ± 0.0 b
NPK	5.76 ± 0.1 ba	11.79 ± 0.1 b	6.03 ± 0.3 b	18.55 ± 5.0 a	0.07 ± 0.0 a
Rice husk biochar	5.51 ± 0.1 bc	13.14 ± 0.5 a	8.18 ± 1.1 a	7.84 ± 2.1 b	0.08 ± 0.0 a
Sewage sludge	6.07 ± 0.2 a	12.60 ± 0.1 ab	7.09 ± 0.7 ab	22.85 ± 5.5 a	0.1 ± 0.0 a

Values followed by the same letters, within columns, are not significantly different at $p < 0.05$ according to Tukey's test.

Table 6. Effect of rice husk biochar, sewage sludge, and NPK fertilizer on macronutrient content and dry leaf mass.

Treatments	Leaf P content	Grain P content	Leaf K content	Grain K content	Dry leaf mass g·plant^{-1}
	--------------------------------g·kg^{-1}----------------------------------				
Control	1.18 ± 0.1 b	1.3 ± 0.2 a	5.52 ± 0.3 ab	38.35 ± 2.3 b	27.88 ± 9.41 b
NPK	7.23 ± 0.5 a	0.78 ± 0.1 a	3.70 ± 0.7 b	41.61 ± 6.0 ab	51.14 ± 0.87 a
Rice husk biochar	1.38 ± 0.1 b	1.35 ± 0.1 a	6.30 ± 1.5 a	38.35 ± 2.3 b	44.13 ± 8.95 a
Sewage sludge	1.4 ± 0.6 b	1.41 ± 0.6 a	7.8 ± 1.3 a	48.12 ± 3.0 a	39.97 ± 3.46 ab

Values followed by the same letters, within columns, are not significantly different at $p < 0.05$ according to the Tukey's test.

Considering the losses of P from the soil-plant system through leaching and fixation onto soil colloids, a gradual release of P into the soil solution as provided by SS in contrast to mineral fertilizers is essential for efficient nutrient utilization (Da Silva et al. 2021). Given the low contribution of P to leaves and grain tissues, two possibilities emerge. First, the majority of P in the composition of SS and RHB is either in unavailable forms (such as heterocyclic P) or immobilized through physicochemical sorption and interactions with microorganisms, especially P from RHB, given its recalcitrance. Secondly, this sets the stage for potential later P release for future crop cycles.

Biochar and SS are often considered promising alternatives to replace mineral fertilizers in agriculture. Given the maize yield (Fig. 10), several noteworthy points should be emphasized. When evaluating each treatment, RHB significantly enhanced maize yield compared to untreated soil. The increase is more than twofold, resulting in a remarkable 223.72% gain in relation to the average maize yield in the region. Despite the primary contribution of RHB lies in soil-conditioning effects (Lima et al. 2018, Villagra-Mendoza and Horn 2018, Tanure et al. 2019). Medyńska-Juraszek et al. (2021), on other hand, identified an increase in maize growth, but limited effects on soil properties. The biomass chosen for biochar production and the pyrolysis temperature are crucial for improving the entire soil-plant system. Some biomass sources provide most of the nutrients plants require, but they have limited soil-conditioning potential, and viceversa. The primary limitation of RHB in comparison to other treatments likely lies in the lower avalability of nutrients.

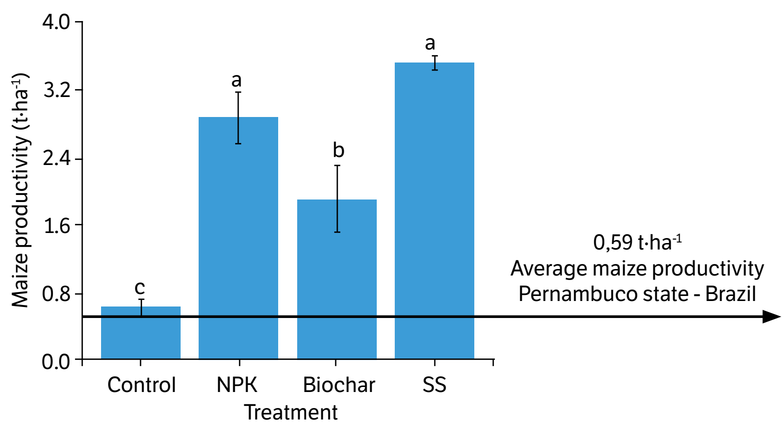


Figure 10. Maize yield (± deviation standard) considering the rice husk biochar, NPK, and sewage sludge application. Above the black arrow is written the average maize productivity of Pernambuco state, Brazil. Different letters above the bars of each treatment represent significant differences between various treatments following two-way analysis of variance (Tukey's test, $P < 0.05$).

The application of SS to the soil resulted in significant gains in grain yield, increasing it nearly sixfold compared to the control (Fig. 10). Zuo et al. (2019) stated the higher crop yield is a cumulative result of enhancements in soil's physical, chemical, and biological attributes. Additionally, Da Silva et al. (2021) added that using sludge treated with CaO led to yields similar to or greater than mineral fertilization.

NPK fertilizer also increased maize yield (compared to RHB and control, but not differed from SS application (Fig 10). It is important to notice that mineral fertilizer application solely had no significant effects on soil characteristics that are essential to maintain soil sustainability. On the other hand, especially for the small farmers of the studied region, SS application can represent a alternative to increase maize yield while improving soil quality as long as it is applied adequately (CONAMA 2006).

CONCLUSION

The tested fertilizers had varying effects on increasing maize yield and altering soil properties. While RHB improved water retention capacity, cation exchange capacity, microbial biomass, and maize yield when compared to the control group, SS proved to be more effective in enhancing P availability than biochar. The maize yield with SS was five times greater than the regional maize productivity and equal to the performance of NPK fertilization. Considering the substantial positive impact of SS on soil characteristics, it is recommended that local farmers apply 20 t·ha^{-1} of this fertilizer. This not only has the potential to replace traditional mineral fertilization, but also offers the additional advantage of improving overall soil quality with no risks regarding heavy metals cotamination.

CONFLICT OF INTEREST

Nothing to declare.

AUTHORS' CONTRIBUTION

Conceptualization: Silva, G. H. M. C., Nascimento, C. W. A., Souza, E. R., Almeida Junior, A. B., Biondi, C. M.; **Methodology:** Silva, G. H. M. C., Silva., W. R., Ximenes, D. H. S. V., Vieira, C. B.; **Investigation:** Silva, G. H. M. C., Silva, W. R., Ximenes, D. H. S. V., Vieira, C. B.; **Resources:** Nascimento, C. W. A., Biondi, C. M.; **Writing – Original Draft:** Silva, G. H. M. C.; **Writing – Review & Editing:** Nascimento, C. W. A., Souza, E. R.; **Supervision:** Biondi, C. M.

DATA AVAILABILITY STATEMENT

Data are available upon reasonable request.

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