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Management alternatives for sandy soils to overcome edaphic limitations in irrigated okra cultivation

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Abstract. Sandy soils are often unsuitable for agriculture due to their poor physical and chemical properties. However, using conditioners can improve these parameters, making these soils viable for cultivation. This study evaluated Red-Yellow Argisol (Clay), Biochar, and Ceramic residues as soil conditioners for Planosol. The experiments were conducted in pots in a greenhouse and the experimental design was completely randomized with three treatments and five replications, compared to a control (100% P). Treatments included Clay (50% P + 570.6 t ha^{-1} A), Biochar (50% P + 189.9 t ha^{-1} B), and Ceramic (50% P + 459.9 t ha^{-1} C). Okra (*Abelmoschus esculentus* L.) was used to assess the impact on development and productivity over 90 days from transplanting (DAT). Granulometry of conditioners, and the carbon, hydrogen, nitrogen, and ash content were analyzed. For constructed soils, granulometry, bulk density, particle density, and water retention capacity (CRA) were measured before planting. Chemical parameters, including Ca^{2+}, Mg^{2+}, K^+, Na^+, Al^{3+}, H^+, pH, and others, were measured at 0 and 90 DAT. Okra growth parameters, such as height, stem diameter, leaf number, leaf area, stomatal conductance, and chlorophyll a fluorescence dry biomass and leaf nutrient contents (N, P, K, Ca, Mg, Na) were assessed at 90 DAT. Results indicated that conditioners improved the physical and chemical properties of the Planosol and the physiological parameters of okra. Biochar increased phosphorus and potassium, while Clay enhanced nitrogen and sodium for okra cultivation.

Key words: *Abelmoschus esculentus* L., horticulture, soil conditioners.

INTRODUCTION

Global food demand is expected to increase by 1.3% annually over the next decade due to population growth and rising incomes, primarily in low- and middle-income countries. According to estimates from the OECD (Organisation for Economic Co-operation and Development) (2022), a 20% increase in global food production is needed over the next decade to provide enough food for the world's population, expected to rise from 7.7 billion in 2020 to 8.5 billion in 2030 (OECD-FAO Agricultural Outlook 2022–2031). With agricultural land expansion contributing only 6% to this growth, light sandy soils, which lack nutrients and water retention, are increasingly incorporated into agriculture for crops other than pastures.

These sandy soils pose challenges due to their low fertility, organic matter, acidity, and water retention capacity (Santos et al., 2015). Research is needed to address these issues, as improving soil management practices can mitigate their inherent fragility. Practices that enhance organic matter, cation exchange capacity, nutrient content, and vegetative cover are crucial for sustainable agriculture (Lamarca, 1996; Amado et al., 1999; Aita et al., 2004; Mafra et al., 2008).

In order to increase the organic matter content, CEC, pH, Water Retention Capacity (WRC), improve structure, increase microbiota, etc., several techniques can be evaluated individually or in combination. Among them, the use of conditioners to improve the chemical, physical, and biological characteristics of the soil is noteworthy, especially with the joint application of fertilizers, manures, and amendments (Shinde et al., 2019; Babla et al., 2022).

Conditioner selection should consider soil properties, potential benefits, and logistical and economic feasibility. Many conditioners such as zeolite, biochar, organic materials, peat, humic and fulvic acids, sludge have been evaluated for soil regeneration (Babla et al., 2022). However, few studies explore using construction residues like ceramics and clayey soils removed from other areas. Biochar is a material composed of carbon of high stability and chemical recalcitrance, characterized by possessing complex organic structures (Singh et al., 2022).

The use of biochar as a soil conditioner for the improvement of physical-hydraulic and nutritional properties can be visualized in the so-called Terra Preta de Indio (TPI), an anthropogenic formation in which, over the years, people buried organic and inorganic materials in the soil (Glaser et al., 2003). After the action of biotic and abiotic factors on these soils, significant visual, biological, physical-hydraulic, and fertility changes were observed (Neves Junior, 2008). These lands are characterized by dark-coloured soil patches, high fertility, nutrient retention, presence of ceramics, and lithic artifacts in the surface horizons (Neves Junior, 2008) and consist of 35% to 45% pyrogenic or charcoal carbon (Glaser et al., 2000).

However, the biochar use does not present a consensus regarding the results on the physical and chemical parameters of the soil, as some authors point out positive results such as its ability to mobilize Pb, carbon sequestration (Gurwick et al., 2013; Igalavithana et al., 2019), influence on hydraulic parameters and water retention in the soil (Razzaghi et al., 2020), nutrient availability (Hussain et al., 2020), pH increase (Xu et al., 2014), reduction of Al^{3+} levels (Falcão et al., 2013), improvement of aggregate stability (Yang & Lu, 2021), and reduction of trace elements in contaminated soils (Riedel et al., 2015). The literature also presents negative results such as reduced productivity and increased greenhouse gas emissions (Mukherjee & Lal, 2014) or even indifferent, without significant effects, for sandy soils (Jeffery et al., 2015).

Ceramics, present in the TPI from buried artifacts, are a poorly evaluated conditioner. Traditionally, red ceramics mainly use clay as raw material in the manufacture of ceramic pieces. The production of red ceramic pieces presents significant environmental impacts due to failures in the production process. In addition to the waste generated in the production process, there are also those generated in logistics, construction, and demolition forming part of the so-called Construction and Demolition Waste (CDW). There is, therefore, a global trend towards mitigating the generation and maximising the resource efficiency of these CDWs, driven by more stringent environmental regulations, public policies, and increased societal awareness (Akhtar & Sarmah, 2018).

Among the few properties studied when applied to soil, low toxic contents, a tendency to increase soil pH, potential use as a soil conditioner (Ramalho & Pires, 2009), and a source of potassium (Nobre et al., 2011; Nobre et al., 2012) can be mentioned. Rodrigues et al. (2021) described the composition of ceramics, emphasizing that it may vary according to the region, consisting mainly of silica (SiO_2), alumina (Al_2O_3), and hematite (Fe_2O_3).

The addition of clay to sandy soils, according to Hall et al. (2010), can lead to an increase in agricultural production. This can occur due to changes in stability and the formation of new aggregates (Silva et al., 2014). Thus, the presence of clay modifies the texture and its relationship with the amount of retained water, as well as factors such as orientation and shape of the grains (Donagemma et al., 2016). Research indicates that it becomes an important ally for C sequestration (Shi & Marschner, 2013), greater retention of nutrients such as Nitrogen and Potassium, and decreased natural leaching of sandy soils (Tahir & Marschner, 2017).

Due to this, one of the crops that can be associated with sandy soils in tropical climate regions due to its hardiness is Okra (*Abelmoschus escurentes* L.), a vegetable of the *Malvaceae* family (Santos et al., 2020). Its origins are attributed to Ethiopia (Sathish Kumar et al., 2013) and it has applications in various sectors, including food, pharmaceutical, and paper. The green pod of okra is a great source of fiber, minerals, vitamins C, proteins, and lipids (Ofori et al., 2020; Paul et al., 2023; Paul et al., 2024). The ideal soils for the crop are those with clayey-sandy (light) textures, pH between 6.0 and 6.5, and rich in organic matter (CATI, 1999).

The hypothesis of this research is that incorporating clay, biochar, or ceramic residue into sandy soils will improve soil fertility and structure, thereby enhancing okra cultivation. The objectives are to evaluate the effects of these soil conditioners on sandy soils and determine the optimal conditioner for successful irrigated okra cultivation.

MATERIALS AND METHODS

Soil and conditioners selection and characterization

The Haplic Planosol used in this research was chosen as the target of this study due to its textural composition of 643 g kg^{-1} coarse sand (2–0.2 mm), 234 g kg^{-1} fine sand (0.2–0.05 mm), 63 g kg^{-1} silt (0.05–0.002 mm), 60 g kg^{-1} clay (< 0.002 mm), and 0.8 g kg^{-1} organic carbon. Thus, this soil, totaling almost 88% sand in its pedological profile in depth, is classified in the textural triangle proposed by the United States

Department of Agriculture (USDA) (SOIL SURVEY STAFF, 1951) as Loamy Sand, which is highly representative in Brazilian soils. In order to improve the physical characteristics, and consequently chemical, nutritional, etc., of this soil, three conditioners were tested: Clay (argisol), Biochar, and Ceramic.

Table 1. Analysis of the soils collected in Seropédica - RJ

Analysis	Unity	Argisol	Planosol
pH (water)		5.3	5.1
pH (KCl)		4.9	4.2
Ca^{2+}	cmol$_c$ kg^{-1}	1.2	0.1
Mg^{2+}	cmol$_c$ kg^{-1}	0.6	
K^+	mg kg^{-1}	3.9	3.9
Na^+	mg kg^{-1}	13.8	2.3
S Value	cmol$_c$ kg^{-1}	1.9	0.1
Al^{3+}	cmol$_c$ kg^{-1}	0	0.1
H^+	cmol$_c$ kg^{-1}	2.0	0.4
T Value	cmol$_c$ kg^{-1}	3.9	0.6
V Value	%	49	17
P[1]	mg kg^{-1}	< 1	1

[1] Assimilable P.

This soil (Planosol) was collected in a soil toposequence in Seropédica, Rio de Janeiro, Brazil (S22°46'11"), and the Red-Yellow Argisol was also collected in this toposequence in Seropédica, Rio de Janeiro, Brazil (O43°42'28") presenting 361 g kg^{-1} coarse sand (2–0.2 mm), 77 g kg^{-1} fine sand (0.2–0.05 mm), 55 g kg^{-1} silt (0.05–0.002 mm), 507 g kg^{-1} clay (< 0.002 mm), and 1.9 g kg^{-1} organic carbon. Both soils were initially characterized regarding their chemical parameters (Table 1) according to Teixeira et al. (2017).

The biochar was obtained from commercial charcoal, derived from the pyrolysis of eucalyptus wood at approximately 400ºC, and the ceramic was obtained from construction waste, specifically from the disposal of red ceramic bricks collected at a brickyard in the municipality of Itaboraí/RJ - Brazil.

For the biochar, elemental analyses of carbon (C), hydrogen (H), and nitrogen (N) contents were also performed, determined by dry combustion in a CHN elemental analyzer (Perkin Elmer 2400), in triplicate. The ash content of the biochar was determined in triplicate by weighing 0.5 g of biochar sample in porcelain crucibles, which were heated in a muffle furnace at 800 °C for six hours. After this period, the samples were placed in a desiccator for one hour to cool down and then weighed on an analytical balance with an accuracy of four decimal places (ASTM D1762-84) (ASTM, 2007). The oxygen (O) content was obtained by the difference between 100 and the sum of the contents of C, H, N, and ash (KIM et al., 2012).

Therefore, the elemental characterization of the biochar was 70.44 ± 1.25% carbon, 2.62 ± 1.14% hydrogen, and 0.56 ± 0.01% nitrogen. The ash content obtained was 7.11%, totalling 19.27% oxygen (O). The molar ratios of H/C and O/C in the biochar are 0.03 and 0.27, respectively.

Conduction of the experiment and experimental design

The study was conducted at the Gragoatá campus of the Federal Fluminense University in Niterói - RJ, Brazil, 22°54'S latitude, 43°08'W longitude, and 8 m elevation with an Aw climate, according to the Köppen classification, meaning a tropical climate with a dry winter and rainy summer, with an average annual temperature of 23 °C and average annual precipitation of 1,200 mm, during the period from December 14, 2021, to April 13, 2022.

The experiments were conducted inside a greenhouse, in plastic pots with a volume of 4 dm³, using 5 kg of soil with conditioners per pot. The experimental design was completely randomized with four treatments segregating each of the aforementioned conditioners and the control, with 5 replications, totalling 20 experimental units. The percentage composition of the conditioners for each treatment was 50% of the volume of Planosol and 50% of the volume of the conditioner (Table 2).

Table 2. Treatment Description % (v/v) Tonnes per hectare

Treatment	Original soil	Conditioner	
	%	t ha^{-1}	%
Planosol	100	-	0
Clay	50	570.6	50
Biochar	50	189.9	50
Ceramic	50	459.9	50

To ensure the homogeneity of the experiment, the conditioners and soils were passed through a 2 mm sieve, then weighed for the individual preparation of each experimental unit. After weighing, they were placed in plastic bags and shaken for 2 minutes.

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Soil correction and fertilization were carried out according to the Liming and Fertilization Manual of the State of Rio de Janeiro (Freire et al., 2013), where each treatment had its pH corrected to a range between 6.0 and 6.5. The same fertilization was applied to all treatments considering the needs of okra plants. Thus, at planting, 20 kg ha^{-1} of nitrogen was incorporated through urea, 80 kg ha^{-1} of phosphorus through single superphosphate, and 40 kg ha^{-1} of potassium through potassium chloride.

The assembly of the pots was carried out by weighing each component individually, homogenizing them in plastic bags, and incubating them for 30 days, with the moisture maintained at 70% of field capacity.

After this period, two *Santa Cruz* 47 okra seedlings were transplanted, with 20 days after seedling (DAS). At 40 DAS, thinning was carried out, leaving only one plant per pot.

Irrigation during the experiment was carried out using the gravimetric method, considering the water retention capacity (CRA) and soil density of each treatment estimated by the Soil Analysis Methods Manual of Embrapa Solos (Teixeira et al., 2017).

Soil Treatments Analysis

Undisturbed soil samples from the experiments were collected before the okra transplanting (40 DAS) and after harvest (110 DAS). The samples were taken from each experimental unit and later mixed to obtain composite samples per treatment. They were then directed for chemical and physical analysis at Embrapa Solos laboratories, following the methodologies described by Teixeira et al. (2017).

At the end of the experiments (110 DAS), undisturbed samples from each treatment were taken using a cylindrical ring with a known volume to determine the final soil density by the volumetric ring method. The samples were dried in a forced air circulation oven at 105 °C for 24 hours, and after this period, weighed to determine the soil dry mass.

Plant growth and okra analysis

At 110 DAS, the following parameters were collected: plant height (H), stem diameter (SD), number of leaves (NL), and leaf area (LA). Stem diameter was measured at a height of three centimeters from the plant collar using a digital caliper graduated in millimeters; plant height was measured from the plant collar (soil surface) to the tip of the main stem, using a tape measure graduated in centimeters; the leaf area of each experimental unit, expressed in cm^2, was determined by averaging the area of two fully expanded young leaves using a tape measure graduated in centimeters to measure length versus width (x) versus a correction factor of 0.63, specific to okra cultivation (Oliveira et al., 2014); in addition to leaf number (NL).

The leaves and stems were separated with pruning shears, placed in paper bags, properly identified, and directed for drying in a forced air circulation oven at 65 °C for 72 hours. After drying, the samples were weighed on an analytical balance to determine the dry leaf mass (DLM) and dry stem mass (DSM) in grams for each experimental unit.

In the greenhouse, after removing the aboveground plant material, the roots were removed from the pots by soil disaggregation and passing through a 2 mm sieve. Then, the collected roots were washed in running water using a sieve and placed in paper bags, properly identified, for subsequent drying in a forced air circulation oven at 65 °C for 72 hours. After drying, the samples were weighed on an analytical balance to determine the dry root mass (DRM) in grams.

The dried leaf and root material were ground in a Wiley-type knife mill and directed for determination of N, P, K contents using the methodology described in the Manual of Soil, Plant, and Fertilizer Chemical Analysis (EMBRAPA, 2009).

After the beginning of fruiting, the number of fresh fruits was counted, and successive harvests of fruits were carried out considering the commercial harvest point where they were tender, fiberless, and had an intense green color. The fruit length (FL) was determined with a ruler graduated in cm, the fruit diameter (FD) with the use of a digital caliper in mm, and the fruit mass using a precision balance in grams. Productivity was determined by the total fruit production per plant and transformed from g $plant^{-1}$ to t ha^{-1}.

Chlorophyll (Greenness) fluorescence parameters

The measurements were taken on the upper middle third of the plants on young, fully expanded, and non-detached leaves. Evaluations were conducted on 3 leaves from each sample unit, which were previously adapted to dark conditions for 30 minutes using a portable fluorometer Model Handy-PEA (Hansatech Instruments, King's Lynn, Norfolk, UK). Determinations were made after the dark period, followed by a saturating pulse of 3,400 μmol photons m^{-2} s^{-1}, which was applied to induce the OJIP transient fluorescence. Transient fluorescence intensities were measured between 50 μs (initial fluorescence - F0) and 1 second; after obtaining the values of transient fluorescence, the JIP Test parameters were calculated (Table 3) (Strasser & Strasser, 1995; Tsimilli-Michael & Strasser, 2008). The analyses were performed at the end of the experiment (110 DAS).

Table 3. JIP Test Parameters

	Fluorescence parameters extracted
tFm	Time (in ms) to reach F_m
	Fluorescence parameters calculated from primary data
FV/FM	Maximum quantum yield of PSII
FV/F_0	Quantum yield of primary photochemistry of PSII
	Specific activity per reaction center (RC)
ABS/RC	Apparent size of the antenna system or the absorption flux per RC
TR_0/RC	Maximum rate at which an exciton is trapped by the RC resulting in plastoquinone (QA-) reduction
ET_0/RC	QA- reoxidation via electron transport at an active RC
DI_0/RC	Total dissipation ratio of unquenched excitation energy per total RC, with dissipation in this case being energy loss in the form of heat
RE_0/RC	Reduction of the final electron acceptor on the electron acceptor side of PSI by RC
	Energy efficiencies and flux rates
φP_0	Maximum photochemical quantum yield
φ_{E0}	Quantum yield of electron transport from QA- to the intersystem electron acceptors
φ_{R0}	Quantum yield of electron transport from QA- to the final electron acceptor of PSI
ψ_{E0}	Probability (at time 0) that an exciton captured can move an electron in the electron transport chain after QA-
δ_{R0}	Efficiency with which an electron can move from reduced intersystem electron acceptors to the final electron acceptors of PSI
	Performance Index
PI_{ABS}	Total performance index
PI_{TOTAL}	Total performance index, measuring performance up to the final electron acceptors of PSII

[1] (Sousa, 2012. Adapted from: Strasser et al., 2004 and Yusuf et al., 2010).

Data analysis

The results were subjected to the Shapiro-Wilk test to check for data normality and subsequently submitted to analysis of variance to determine significance. Afterwards, the Tukey's test for mean comparison was conducted at a 5% probability level using the R® software (R Core Team, 2024).

RESULTS AND DISCUSSION

The planosol and biochar were classified texturally as sandy loam; the argisol was classified as sandy clay loam; and the Ceramic as loamy sand (Table 4). The Available Water Capacity was respectively 0.66 mm cm^{-1} for the planosol; 0.93 mm cm^{-1} for the argisol; 0.61 mm cm^{-1} for the Biochar and 0.52 mm cm^{-1} for the ceramic residue. It was observed that the addition of ceramic resulted in worsened granulometric conditions, as a large percentage (81%) of this material was in the form of gravel and could effectively be disregarded in the granulometry used.

The biochar had a significant impact on soil density, as its individual application led to a 28% decrease in density. This result was also observed by Esmaeelnejad et al. (2016), who found a reduction in soil density in all treatments with different types of biochar applied to a sandy clay loam soil.

Table 4. Physical analyses of treatments

Analysis	Unity	Control	Clay	Biochar	Ceramic
Coarse sand	g kg^{-1}	602	456	617	690
Fine sand	g kg^{-1}	164	123	172	134
Silt	g kg^{-1}	72	135	109	75
Clay	g kg^{-1}	162	286	102	101
Particle density	g cm^{-3}	2.54	2.55	2.00	2.46
Bulk density	g cm^{-3}	1.42	1.29	1.02	1.22
Total porosity	cm^3 100 cm^{-3}	84.4	84.58	80.44	83.88
Water retention capacity	%	26	33	43	23

Total porosity decreased with the addition of biochar, due to its low density and presence of fine particles, leading to the filling of macropores in the Planosol and an increase in micropores. Carvalho et al. (2020) reported that the addition of 25 t ha^{-1} of biochar resulted in a 63% reduction in density compared to the control, affecting mainly the volume of soil micropores.

The incorporation of ceramic and clay into the planosol showed similar behaviors, resulting in a reduction in soil density. This practice may have also influenced the micropores, as observed by Primo (2020), where the addition of clay resulted in significant improvements in microporosity, making it the most beneficial parameter.

Since the conditioners impacted porosity and density, they consequently modified the soil's water retention capacity. Biochar promoted an increase of about 65.4% in Available Water Capacity (AWC), while Clay showed an increase of 26.9% and ceramic a decrease of 11.5%. Other authors support the results found for biochar incorporation, as in the case of Lucon (2019) who found values of 63.73% (kg dm^{-3}) and Bibar (2014) values of 80 and 81% (kg dm^{-3}), with biochar pyrolysis temperatures of 400 and 700 °C, respectively. However, there are no references that contextualize the incorporation of ceramic and clay.

Despite the negative results of ceramic, literature has shown that the specific surface area of these ceramic materials and biochars has the potential to increase their efficiencies as they degrade in the soil, promoting increased fertility, nutrient cycling, microbiota activity, and water and air availability, as these factors are intrinsically interconnected (Petter, 2010) and can provide greater benefits to sandy soils (Troeh & Thompson, 2005). Probably a greater crushing of the ceramic residue, providing finer particles, can increase the contribution of this conditioner.

Therefore, nutritional parameters in the soil were evaluated before transplanting (40 DAS) and at the end of the experiment (110 DAS) to verify the behavior of nutrients in the different treatments (Table 5).

Through the solution fertilizations carried out, it was found that biochar showed a greater tendency to retain phosphorus. However, the same did not occur for potassium, as there was a decrease with a similar trend to potassium, nitrogen, calcium, and magnesium.

The conditioners tend to promote greater nutrient retention. The presence of more stable materials in the soil promotes interaction sites that can influence carbon storage and nutrient retention, significantly altering the soil's cation exchange capacity (CEC).

Table 5. Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), organic carbon (C), C/N ratio, and pH of the treatments at 40 DAS (i) and 110 DAS (f)

Analyses		---------------- 40 DAS ----------------				---------------- 110 DAS ----------------			
		Control	Clay	Biochar	Ceramic	Control	Clay	Biochar	Ceramic
N	g kg^{-1}	0.7	1.1	0.8	0.7	0.8	1.3	1.2	1.0
P[1]	mg kg^{-1}	1,213	1,152	1,195	1,113	1,199	1,325	1,820	1,240
K^+	cmo_{lc} kg^{-1}	1.67	2.02	1.83	1.80	0.41	1.14	0.53	0.65
Ca^{2+}	cmo_{lc} kg^{-1}	12.0	15.3	11.8	9.5	8.0	13.9	12.2	8.8
Mg^{2+}	cmo_{lc} kg^{-1}	1.3	3.1	1.3	1.2	1.0	1.5	0.3	0.7
C[2]	g kg^{-1}	11.5	13.3	23.4	8.7	8.3	12.8	22.4	9.9
C/N	-	16	12	29	12	10	10	19	10
pH	Água	6.5	6.1	5.6	6.1	6.0	5.9	5.5	5.2
	KCl	6.4	6.0	5.3	6.0	6.0	5.2	6.0	5.8

According to IBI (2015), the H/C molar ratio should be less than 0.7, ensuring a large proportion of aromatic rings in the biochar structure. This value is still used to distinguish biochar from other biomasses that have not undergone partial thermochemical alteration or have been only partially altered.

In addition to biochar, the clay promotes mineral interactions, where there is a greater specific surface area and, in a basic medium, there is deprotonation and binding with cations from the soil solution. The ceramic, despite originating from clay, undergoes mineralogical and chemical changes according to the temperature used during the calcination process, which promotes the combustion of organic matter and pyrite (200 °C – 400 °C), allotopic transformation of crystalline silica (573 °C), changes in crystalline structures (800 °C – 930 °C) (Souza Santos, 1989), and vitrification process (900 °C) (Callister, 2006).

The processes involved in ceramic formation modify the active sites capable of establishing ionic exchanges and, therefore, modify their adsorptive properties. This was verified in the treatment where ceramic was inserted, making the results even lower than the control treatment. Thus, the material in this granulometry does not have a specific enough surface to adsorb cations and improve the soil's CEC. Therefore, it is not indicated individually for this purpose.

Total organic carbon was widely influenced by the addition of conditioners, with the treatment with biochar showing a greater tendency to introduce carbon into the soil. It is worth noting that the treatment with ceramic had a lower carbon content. Petter (2010) reported on the increasing linearity of soil C content with increasing doses of applied biochar. However, Hamer et al. (2004) described that despite the higher amount of carbon, it is highly aromatic and not readily accessible as an energy source for the microbiota; therefore, the effects of the material occur due to the greater surface area it promotes microbial growth and activity.

The chlorophyll *a* transient parameter of the treatments with conditioner compositions (Fig. 1), referring to the sequential energy transduction indicated by reaction centers (RC), showed an increase in the reduction of the final electron acceptor on the PSI acceptor side (RE0/RC) for all conditioners, along with an increase in energy dissipated as heat per RC (DI0/RC), leading to a decrease in performance indices (PI).

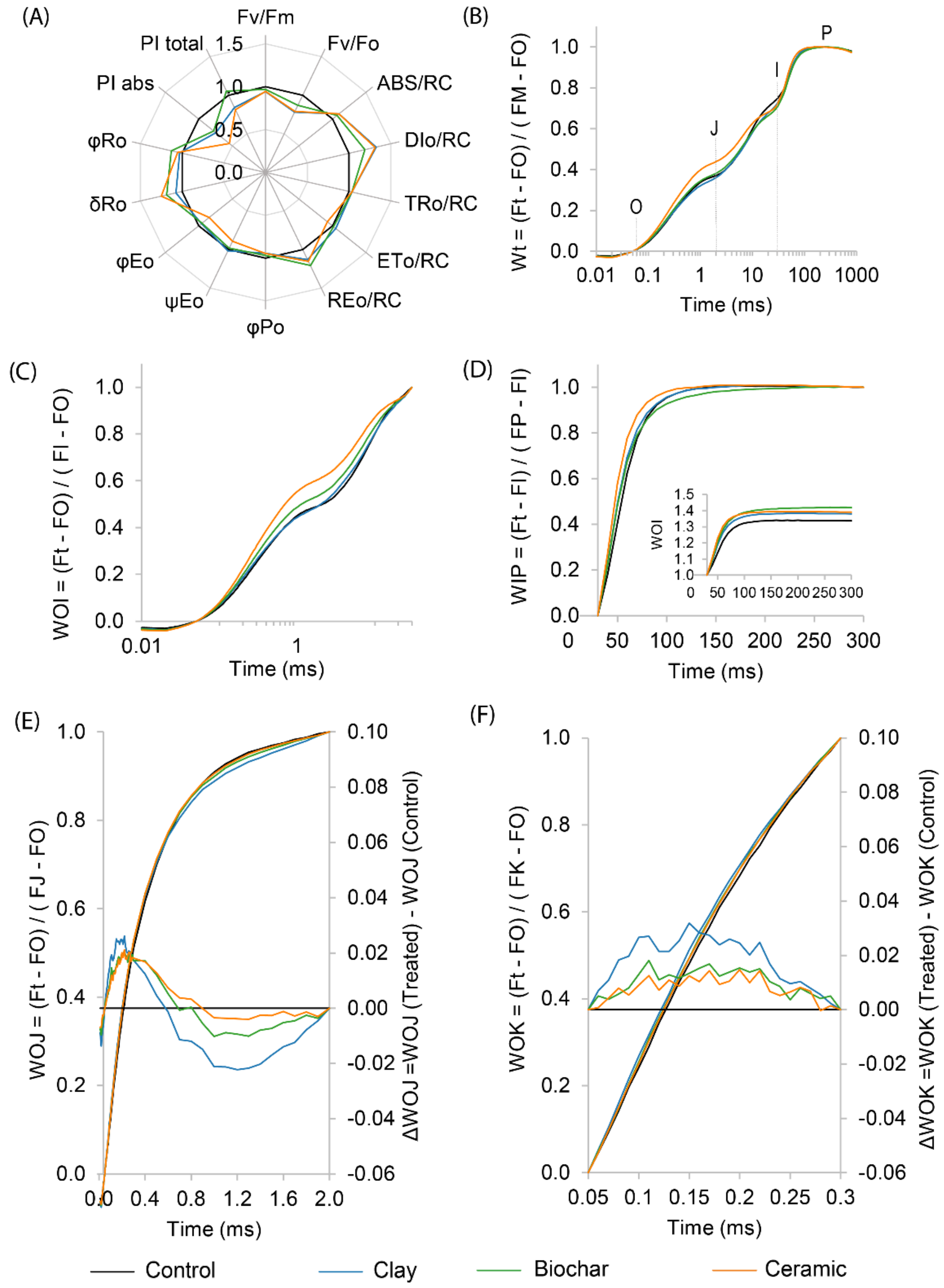

Figure 1. Chl α fluorescence transients of dark-adapted leaves of Okra (*Abelmoschus esculentus* L.) grown in different soil conditioners at 110 DAS.

Parameters of the JIP Test, in relation to the respective control, obtained from the transient OJIP fluorescence of rice plants grown under different extracts applied to the leaves and roots (A). Relative variable fluorescence between the steps O and P (Wt; B) on logarithmic time; Relative variable fluorescence between the steps O and I (WOI; C) on logarithmic time; Relative variable fluorescence between the steps I and P (WIP; D) and WOI in the insert. Relative variable fluorescence between the steps O and J (WOJ; E) and average kinetics (right vertical axis) depicted between the steps O and J (ΔWOJ), revealing the K-band; Relative variable fluorescence between the steps O and K (WOK; F) and average kinetics (right vertical axis) depicted between the steps O and K (ΔWOK). N = 15.

The decrease in both the performance index (potential) for energy conservation of the exciton for the reduction of electron acceptors of the intersystem (PIABS) and in the performance index (potential) for energy conservation of the exciton for the reduction of electron acceptors of photosystem I (PItotal) indicates a decrease in the functionality of the electron transport chain of the plants, resulting in increased energy flows for absorption (ABS/RC; which measures the apparent size of the antenna (total absorption or total chlorophyll per active RC)) mainly for the ceramic and clay, since the biochar showed no differences in PItotal when compared to the control. Regarding quantum yields and efficiencies, no significant differences were observed in the maximum quantum yield for primary photochemistry (φPo). Ceramic was the only one that showed a decrease in electron transport from QA^- to the intersystem (ψEo and φEo). However, the final electron acceptor of PSI (φRo and WIP phase) showed an increase. Another evidence of electron flow interruption is the intensity of fluorescence levels in the J step, which demonstrates that most of the QA^- is completely reduced (Strasser & Strasser, 1995). This results in a decrease in the photosynthetic performance (PItotal) of the plants, and energy loss through fluorescence (Wt) and heat (DI0/RC).

The chlorophyll *a* fluorescence transients (Fig. 1, b) exhibited typical polyphasic OJIP chlorophyll *a* fluorescence transient (Wt), increasing from initial fluorescence (FO) to maximum fluorescence (FM). However, a slight decrease in fluorescence was observed, demonstrated by a decrease in relative variable fluorescence curves in step I and, specifically for ceramic, an increase in step J. The normalization between steps O and I (WOI) mainly affected the ceramic and, subsequently, the biochar in events from exciton capture by PSII to plastoquinone (PQ) reduction (Fig. 1, c). On the other hand, Figure 1d (with its respective insertion graph) shows an increase in the sequence of events from PSI-driven electron transfer to the final electron acceptor on the PSI acceptor side, starting from PQH2 (plastoquinol) (WIP).

The kinetic evaluations revealed the presence of the L band (ΔWOK) and the K band (ΔWOJ). The positive K band (Fig. 1, e) could mean that the oxygen-evolving complex (OEC) becomes permeable and offers access to non-aqueous electron donors evidenced by a reduced quinone (QA) reduction rate, the primary electron acceptor of PSII, from QA to QA-. The presence of a positive K band reflects an increase in the functional antenna size of PSII and/or an inactivation of the oxygen-evolving complex (Yan et al., 2013), as evidenced by an increase in ABS/RC. The presence of a positive L band (Fig. 1, f) indicates lower energy connectivity and more inefficient consumption of excitation energy, giving lower stability (Pollastrini et al., 2017).

Thus, any disorder in these factors promoted by stress will be observed by the alteration of the vitality index (Han et al., 2009). According to Novák et al. (2020), under regular conditions, biochar-enriched soils promote photosynthesis and stomatal conductance. Therefore, the evaluation of these indices showed that the crop underwent biotic and abiotic stresses, and it can be observed that the lower the PIABS at the end of the experiment, and possibly the greater the stress it was subjected to, mainly evidenced for the ceramic treatment.

Plants under stress exhibit several key responses, such as stomatal closure to minimize transpirations, reduced cell growth, and decreased turgor pressure. Theses physiological changes lead to lower water content, reduced dry weight, and diminished plant height (Guo et al., 2018). Thus, such factors related to chlorophyll *a* directly impact the growth parameters of okra (Table 6).

Biochar significantly impacted okra cultivation, as the plants exhibited smaller size, reduced leaf area, and more leaves, this is likely due to biochar's capacity to enhance initial plant growth by effectively retaining and storing water, while also contributing essential nutrients (Syaranamual et al., 2024). This finding aligns with Petter (2010), who noted that charcoal also had significant effects on the height parameter of soybeans, and with Melo (2016), who observed similar effects on cowpea beans. However, it contrasts with Liu et al. (2021), who found no significant height differences in okra when biochar was applied. These results may be linked to the stress factors observed in chlorophyll *a* fluorescence parameter, which altered the crop parameters for better performance, as indicated by the increase in PItotal.

Table 6. Growth parameters of okra (*Abelmoschus esculentus* L.) at 110 DAS under different soil compositions

Treatments	Plant height, cm	Leaf area, cm^2	Stem diameter, mm	No of leaves per plant, un
Control	161.6 a	186.6 ab	15.32 ab	14.6 b
Clay	151.8 ab	209.8 a	15.08 b	14.0 b
Biochar	144.2 b	154.4 c	15.94 ab	16.4 a
Ceramic	158.6 a	160.1 bc	16.21 a	15.2 ab
CV (%)	4.01	9.80	6.56	5.56

[1] Same letters in the column, for the same day of analysis, in each parameter, do not differ statistically from each other at a 5% probability level according to Tukey's test. Values represent means of *n* = 15.

The other treatments and the control displayed more similar behaviors to each other, as observed by Nobre et al. (2012), who found that adding ceramic powder to banana seedling production did not enhance height, as this material lacks essential macro and micronutrients.

Consequently, these factors directly influenced the dry mass production of each part of the okra plant (Fig. 2). The increased root production in the treatments Control > Biochar > Ceramic may be related to the amount of macropores and resistance to root penetration in the constructed soil and/or the low nutrient availability, prompting greater root exploration in the soil volume in search of nutrients. Liu et al. (2021) did not corroborate the data found, as they identified a 40% increase in root biomass in the biochar treatment compared to the control. Milla et al. (2013) also reported increases in biomass factors, root depth, leaf width, and stem size with the application of rice husk charcoal. Ismail & Ozawa (2007) observed an increase in biometric attributes of cucumber and corn with the addition of clay, particularly in roots.

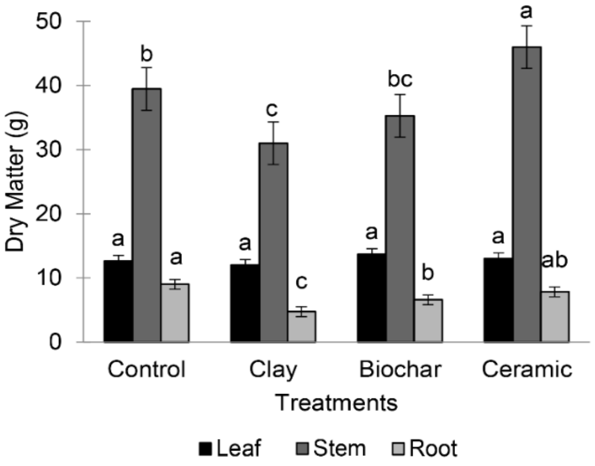

Figure 2. Dry mass of leaves, stems, and roots of okra for the treatments at the end of the experiment (110 DAS).

*Same letters among treatments for the same parameter do not differ statistically from each other at a 5% probability level according to the Tukey test. The values represent the means of *n* = 5.

Regarding the aerial part, Primo (2020) reported that increasing the percentage of clay in the soil did not significantly affect the dry matter of sorghum. However, Song et al. (2020) obtained higher corn biomass in soils with 40% clay content due to higher water retention. Lucon (2019) and Petter (2010) did not observe a relationship between charcoal levels in the soil and increased dry matter in corn and soybean crops, respectively.

Thus, since there were differences in the photosynthetic factors and the parameters related to the physiology of okra, it is necessary to evaluate its foliar contents to check for nutritional differences (Table 7).

Table 7. Foliar contents of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na), in g kg^-1, of okra (Abelmoschus esculentus L.) subjected to different soil compositions

Treatments	N	P	K	Ca ^{ns}	Mg ^{ns}	Na
	--- g kg^{-1} ---					
Control	17.86 c	9.58 b	41.01 b	48.60	9.33	0.28 b
Clay	25.35 a	9.49 b	41.77 b	43.84	9.26	0.32 a
Biochar	21.83 b	12.21 a	44.30 a	41.97	9.25	0.28 b
Ceramic	21.00 b	9.11 b	41.86 b	42.87	9.58	0.28 b
CV (%)	5.92	5.12	2.77	9.60	9.60	4.45

[1] Same letters in the column, for the same day of analysis, in each parameter, do not differ statistically from each other at a 5% probability level according to Tukey's test; Values represent means of *n* = 15; ns = not significant.

It was found that there was a significant difference for nitrogen, phosphorus, potassium, and sodium. The treatment composed of clay stood out in the promotion of nitrogen (N) and sodium (Na), while biochar stood out in the promotion of potassium (K) and phosphorus (P). Hussain et al. (2020) described that the use of biochar promotes higher concentrations of nitrogen (N), phosphorus (P), and potassium (K), and, in combination with other conditioners, promotes greater productivity, nutrient absorption, and growth for maize.

Moreover, biochar's influence manifests through the generation of anionic species via complex oxidation-reduction interactions with soil oxygen. Consequently, biochar demonstrates significant efficacy in nutrient retention for enhanced plant assimilation (Joseph et al., 2010; Bolan et al., 2022). Primo (2020) corroborates these results by reporting that in soil with 26% clay, there was greater nitrogen absorption by plants compared to levels of 10%, 15%, and 31%.

Thus, the use of biochar can be a good ally for phosphate and potassium fertilization, as phosphorus plays a significant role in the flowering and fruiting of plants, promoting good development of the root system and increased production (Raij, 1991), participating in the regulation of enzyme activity, synthesis of sucrose, phospholipids and cellulose, and the release of energy from ATP (Malavolta, 2008). Potassium, in turn, acts as an enzyme activator in the synthesis and degradation of organic compounds, in the processes of stomatal opening and closing, and osmoregulation (Marschner, 1995).

Consequently, this culminated in the productivity of the crop (Fig. 3), where about 99% of the harvested fruits were classified as Prime, i.e., fruits over 12 cm in length, regardless of the treatment (data not shown) (Filgueira, 2005). Productivity was significantly affected by the inclusion of conditioners; however, there were no significant differences between them, only compared to the control.

However, these values may present different results in subsequent harvests, as biochars can undergo biodegradation and transformation (Madari et al., 2006), potentially resulting in an increase in the availability of electrochemical sites. The utilization of biochar in nutrient-deficient soils represents a potential strategy to enhance agricultural productivity (Widiasri et al., 2022; Xu et al., 2017). This was observed by Yakubu et al. (2020), who reported an increase in productivity starting from the second year of okra cultivation, and by Major et al. (2010), who noted an increase in corn productivity in the second year of planting. Melo (2016) observed an increase of up to 60% in the productivity of dry caupi beans in Fluvic Neosol between the application of zero dose and a dose of 10.5 t ha^{-1}.

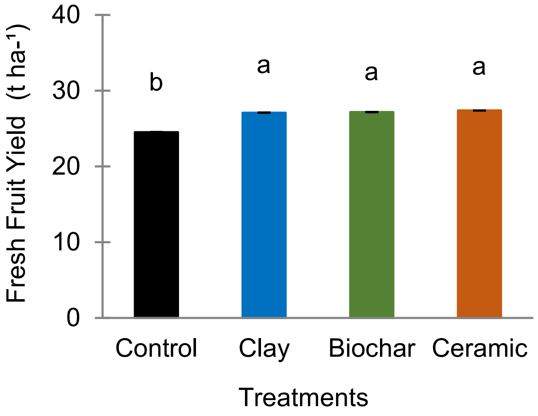

Figure 3. Productivity of okra (*Abelmoschus esculentus* L.) for treatments.

Values followed by the same letter within the same column are not significantly different from each other at a 5% probability level according to Tukey's test. Values represent the means of $n = 5$.

CONCLUSIONS

As the conditioners are highly stable materials, it is natural for the modifications to take time to appear over time. However, it was found that ceramic induced greater photosynthetic stress, was not efficient in retaining nutrients in the soil, nor did it promote chemical and/or physical qualities. Despite this, it significantly increased productivity. Biochar, on the other hand, was effective in retaining more water in the soil, retaining phosphorus, making it available for okra cultivation, increasing its absorption along with potassium, and increasing organic carbon content. Clay increased the levels of sodium and nitrogen in the crop. There was no difference between the conditioners in increasing productivity, only compared to the control.

Given that these results are preliminary, for future research, it is recommended to conduct experiments with doses and combinations of conditioners. Additionally, should be made experimentation in an open system (field) and medium and long-term trials.

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