








Enhancing food waste compost with sewage sludge biochar: impacts on stability, nutrient dynamics, and agronomic performance in maize

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ABSTRACT

The sustainable management of organic waste, including food waste (FW) and sewage sludge (SS), is crucial for mitigating environmental impacts and promoting nutrient recycling. This study investigated the effect of sewage sludge biochar (SSB) on FW composting, specifically regarding the quality, stability, and agronomic performance of the resulting co-compost. SSB, produced at 300 °C (BC300) and 500 °C (BC500), was mixed with FW at various proportions (0 %, 5 %, 10 %, 15 %, 20 % w/w). Adding SSB enhanced the physical and chemical properties of the co-composts, notably increasing phosphorus (P), calcium (Ca), sulfur (S), and zinc (Zn) levels, and improving nutrient retention. Moreover, higher biochar levels, especially BC500, lowered volatile matter and increased ash content, indicating greater compost stability. Importantly, heavy metal levels remained within regulatory limits, ensuring the environmental safety of the co-composts. Co-composts with higher biochar additions (15 %–20 %) notably increased chlorophyll content in maize plants, with a 49 %–60 % rise in the SPAD index compared to the unfertilized control. However, maize dry matter production was not affected by biochar addition, probably because the nutrient solution supplied to the plants limited the effect of the co-compost. Conversely, combining co-compost with mineral fertilization significantly boosted plant dry matter yield, exceeding both fertilized and unfertilized controls. These findings suggest that incorporating biochar into co-composts can improve soil nutrient availability and promote plant health, supporting more sustainable farming methods. Future research should focus on assessing the long-term impacts of this co-compost, particularly under field conditions, to better understand its role in gradual nutrient release and crop growth.

1. Introduction

About one-third of all food produced worldwide is wasted along the supply chain, significantly impacting the environment due to ineffective waste management [1]. Food waste (FW) is one of the largest components of municipal solid waste, with global estimates showing roughly 1.3 billion tons generated annually [2]. This volume is expected to rise because of population growth and changing eating habits, which are likely to increase food demand until 2050 [3]. The inadequate management of these waste materials is a major environmental problem, especially in countries where landfill disposal remains a common issue. This practice not only produces greenhouse gases (GHG) but also wastes valuable nutrients that could be reused in agriculture [4].

Among the options for organic waste treatment, aerobic composting

emerges as an affordable and environmentally sustainable solution. This process promotes the biological degradation of organic matter, reducing waste volume and recovering nutrients in the final compost. Although composting is generally considered an environmentally friendly practice, it is inevitably associated with odor emissions, greenhouse gases (CO₂, N₂O, and CH₄), leachate production, and nutrient runoff losses [5, 6]. In particular, using FW as feedstock presents significant concerns because it is often highly varied, has a low C:N ratio, low pH, high moisture content, and high fat levels, all of which can hinder the composting process or affect the quality of the final product [7,8]. An alternative way to boost composting efficiency is by adding amendments, which can speed up decomposition, retain nutrients, decrease gaseous emissions, and improve the quality of the final compost [9,10]. Among these amendments, biochar has demonstrated particular

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effectiveness not only by enhancing the composting process and improving compost quality, but also by reducing nitrogen losses and lowering undesirable gaseous emissions [11,12].

Biochar is a solid material rich in carbon, produced by the thermal decomposition of biomass in a pyrolysis reactor under limited oxygen supply [13]. It has unique properties such as high surface area, porosity, water retention, surface charge, and nutrient retention [14–16], which can enhance the aeration and potentially accelerate the composting process [17,18] and reducing greenhouse gas emissions, such as CH₄ and N₂O, during organic matter decomposition. Additionally, biochar can reduce the greenhouse gas emissions [19] and increase nutrient retention, improving the quality of the final compost as a fertilizer [20,21]. However, the properties of biochar vary depending on the feedstock and pyrolysis conditions, making each type of biochar a unique amendment [14,16,22]. Additionally, the amount of biochar applied can affect the co-composting process. High biochar doses can hinder biodegradation, decrease enzymatic activity, and reduce process efficiency [10,17].

Sewage sludge (SS) is another urban waste generated in large volumes and that can provide organic matter and plant nutrients, such as nitrogen, phosphorus, calcium, and zinc [23,24]. Its direct use as soil fertilizer is prohibited in several countries because it can contain a complex mixture of heavy metals, emerging contaminants, and other harmful substances and pathogens [25]. As a result, SS should be processed before use, with pyrolysis emerging as a promising method [26]. In this study, we used domestic SS biochars, which generally contain lower levels of heavy metals. Our previous research showed that sewage sludge biochars (SSB) produced at 300 °C and 500 °C did not significantly increase the bioavailability of harmful elements such as Cd, Cr, Ni, and Pb in soil over five years [27]. Instead, the biochars improved the availability of plant micronutrients like Cu, Mn, and Zn, indicating that biochar made from domestic SS can be safely used in agriculture and environmental applications. Therefore, SSB can be co-composted with FW, contributing to an integrated and sustainable waste management. Recent studies indicate that adding SSB to the composting process can improve the C:N ratio, pH, moisture, stability, and reduce GHG emissions [28–30], enhancing the quality of the final product. Additionally, the organic matter in conventional compost mineralizes quickly in the soil, breaking down within months or a few years. In contrast, co-composting with biochar includes resistant fractions that can last for decades or even centuries [31], leading to greater accumulation of stable carbon and reducing GHG emissions.

Research has extensively explored the use of biochar in co-composting through its combination with various feedstocks, such as animal manure and field or woody residues [32], wheat straw [33], and green residues [34]. Most research has focused on core composting metrics such as the microbial community structure, enzyme activity, compost maturity, germination index, greenhouse gas emissions, nitrogen losses, formation of humic substances, and the extent of organic matter degradation [35]. To our knowledge, no studies have evaluated the co-composting of FW with SSB produced at different pyrolysis temperatures and applied in varying proportions, aiming to optimize nutrient retention and influence the physical, chemical, and mineralogical properties of the resulting co-compost, as well as its agronomic value performance. As a result, this study aims to evaluate the impact of combining FW and SSB in aerobic composting, assessing the effectiveness and environmental implications of the resulting co-compost. Specifically, it will examine the effects of SSB produced at pyrolysis temperatures of 300 and 500 °C, applied at different proportions during the co-composting of restaurant-derived FW, on the physical, chemical, and mineralogical properties of the co-compost, as well as maize biomass production. Based on this framework, the following hypotheses are proposed: i) incorporating SSB into FW compost improves the physicochemical properties related to stabilization and nutrient content; ii) adding SSB reduces the total and available concentrations of heavy metals in the co-compost; and iii) the resulting co-compost can be used as a fertilizer.

2. Materials and methods

2.1. Study area

After preparing all the substrates, FW and biochar were thoroughly mixed and formed into individual piles, each weighing approximately 300 kg, in a composting shed at Fazenda Água Limpa (FAL), University of Brasília (UnB), Brasília-DF, Brazil. The experimental farm is located at coordinates 15°56'58.16" S and 47°55'49.54" W, at an elevation of 1098 m. The region has a tropical savanna with a rainy season from October to March and a dry season from April to September.

2.2. Acquisition, production, and characterization of feedstocks

Samples of sewage sludge were collected from the Samambaia Sewage Treatment Plant, owned by the Environmental Sanitation Company of the Federal District (CAESB). This treatment plant employs a tertiary-level system that, in addition to anaerobic waste decomposition, removes specific nutrients, such as N and P, from the liquid effluent. These elements remain in the final solid wastewater mass, which is then dried in covered warehouses with free air circulation and masonry floors to prevent contact with the soil. After collecting, the dry SS (containing about 8 % moisture) was crushed and sieved through a 4 mm mesh. Samples of SS were placed in a metal container specifically adapted to fit inside a muffle furnace (Linn Elektro Therm, Eschenfelden, Germany). The container was equipped with a gas and bio-oil exhaust system, a mechanism to prevent oxygen ingress, and a digital thermostat for temperature regulation. The SS samples were then pyrolyzed at 300 °C (BC300) and 500 °C (BC500), with the temperature increasing at an average rate of 2.5 °C min⁻¹ and a residence time of 5 h. After pyrolysis, the biochars were stored in plastic containers until used for forming composting windows. The characterization of the residues (SS and FW) and biochars (Table 1) was performed as described in Sections 2.4 and 2.5, with additional procedural details in Text S1 (Supplementary Material).

Food waste (FW) was provided by the startup “Projeto Compostar” (Brasília, Federal District). The waste was collected from kitchens in homes and restaurants in Brasília, Federal District of Brazil (15°41'0.5"S, 47°51'44.6"W). This material included pre- and post-consumer organic waste, such as leftover fruits, vegetables, dairy products, and fats and was initially stored in a covered area to prevent moisture loss. It was then arranged in piles, undergoing a two-month pre-composting process before being transported to FAL, where the piles were set up. This pre-composting step was applied solely to adjust moisture, reduce initial

Table 1

Characterization of the feedstocks (sewage sludge - SS and food waste - FW) and biochars (BC300, BC500) used in co-composting.

Properties	SS	BC300	BC500	FW
pH	6.40	6.00	6.40	7.22
Moisture (%)	8.5	6.60	1.50	10.0
OC (g kg ⁻¹)	288	250	231	244
P (g kg ⁻¹)	22.0	39.0	46.0	8.60
K (g kg ⁻¹)	2.40	2.40	4.30	nd
N (g kg ⁻¹)	3.70	42.1	34.0	27.9
Ca (g kg ⁻¹)	5.00	6.40	8.50	2.60
Mg (g kg ⁻¹)	2.10	2.50	2.90	2.10
S (g kg ⁻¹)	8.20	7.50	11.8	3.50
C:N ratio	7.80	5.90	6.80	8.74
Cu (mg kg ⁻¹)	105	115	168	24
Fe (mg kg ⁻¹)	19,800	20,500	20,490	34,218
Mn (mg kg ⁻¹)	100	105	149	138
Zn (mg kg ⁻¹)	460	480	690	72.1
Cd (mg kg ⁻¹)	3.00	3.00	2.00	nd
Ni (mg kg ⁻¹)	13.0	15.0	12.0	19.1
Pb (mg kg ⁻¹)	63.0	32.0	44.0	4.50

OC: organic carbon; BC300 and BC500 were derived from sewage sludge at 300 °C and 500 °C; nd: not detected.

volume, and stabilize the highly labile organic fraction, and it did not aim to achieve compost maturity. After this stage, FW still had a low C:N ratio (8.74; Table 1), high biodegradability, and active microbial metabolism, indicating it was an unstable organic substrate. The experimental co-composting process evaluated in this study began only after this pre-composting step, when FW was mixed with SS biochar to form the composting piles. Additionally, although below the conventional optimal range, the low initial C:N ratio reflects the intrinsic composition of nitrogen-rich feedstocks, such as FW or SSB, and is consistent with previous composting studies [36].

2.3. Installation of piles and setting up treatments

The piles were composed of a mixture of FW and biochar, added in specific proportions (mass/mass, dry-weight basis; see Table 1 for moisture contents): 0 % (control - no biochar), 5 %, 10 %, 15 %, and 20 % biochar. The cone-shaped piles were randomly distributed throughout the composting shed. Nine piles were arranged on an impermeable surface base. Each pile measured 1.0 m high, 1.0 m wide, and 0.8 m long. The exact masses of FW and biochar used in each treatment, calculated on a dry-weight basis to ensure the intended biochar proportions (0–20 %) and consistency across treatments, are detailed in Table 2.

During the composting process, moisture levels were checked at least three times a week, maintaining them between 50 % and 70 %, using a portable meter (Thermo, H50N). When values dropped below this range, humidification was performed with a watering can until the correct level was reached. Pile temperature was measured three times a week throughout the composting period using a portable thermometer (Instrutherm, pH-3000). The co-composting piles were turned and evenly mixed on days 0, 22, 47, 71, 88, 112, and 133 after the process started. Operations were carried out manually using a shovel and a hoe. The temperature and moisture variations of compost piles during the co-composting are illustrated in Fig. S1. The initial and final masses of the piles for each treatment are presented in Table S1. In this study, during composting, the elements lost through volatilization or leaching were not quantified.

2.4. pH, elemental composition and proximate analysis

At 133 days after pile assembly, three composite samples per pile, each based on 10 subsamples, were collected to assess the pH, elemental composition, and proximate analysis of the compost. Compost pH was measured in a CaCl₂ solution at a sample-to-solution ratio of 1:2.5 (m/v) using a pH meter (model Tec5, TECNAL) with a glass electrode, following the protocol described by Tedesco et al. [37].

The carbon (C), hydrogen (H), and N contents in the co-composite samples (dry and ground) were measured using an elemental analyzer (Euro EA 3000, EuroVector, Italy). The oxygen (O) content was calculated by subtracting the combined percentages of C, H, N, and ash content from the total mass of the sample, as described by Enders et al.

Table 2
Description of the treatments applied in the composting experiment.

Treatment code	Description	Composition (kg)
0%BC	Control (no biochar)	300 FW + 0 BC
5%BC300	5 % biochar at 300 °C	285 FW + 15 BC300
10%BC300	10 % biochar at 300 °C	270 FW + 30 BC300
15%BC300	15 % biochar at 300 °C	255 FW + 45 BC300
20%BC300	20 % biochar at 300 °C	240 FW + 60 BC300
5%BC500	5 % biochar at 500 °C	285 FW + 15 BC500
10%BC500	10 % biochar at 500 °C	270 FW + 30 BC500
15%BC500	15 % biochar at 500 °C	255 FW + 45 BC500
20%BC500	20 % biochar at 500 °C	240 FW + 60 BC500

FW: food waste used as composting base; BC300 and BC500: sewage sludge biochar produced at 300 and 500 °C, respectively.

[38].

For moisture determination, 1 g of the sample was placed in a silica crucible and dried in a muffle furnace at 110 ± 5 °C for 24 h, after which the final weight was recorded. To determine volatile material (VM), the dried sample was heated at 925 °C for 7 min, and its weight was then measured. Ash content was determined by weighing the samples after heating at 750 °C, for 6 h. The fixed carbon (FC) content was then calculated by subtracting the moisture, ash, and VM contents from the initial sample weight.

2.5. Total and available heavy metal contents

To determine total heavy metals (HMs), samples were subjected to acid digestion following the USEPA SW-846 3051 A method [39]. Additionally, available HMs were determined after extraction with diethylenetriaminepentaacetic acid (DTPA) solution. Details of the HMs analyses can be found in Text S1 in the supplementary material.

2.6. X-ray diffraction (XRD) and energy dispersive X-ray spectroscopy (EDX)

Samples of the co-composts were also analyzed using X-ray diffraction (XRD) on a D8 Focus diffractometer (Bruker, Billerica, MA, USA). The diffraction patterns of the powdered samples were obtained using monochromatic Cu K α radiation at 40 kV and 30 mA. Measurements were carried out over a 2θ range from 10° to 70°, with increments of 0.05° and a scan rate of 1 min⁻¹. The samples were also analyzed using energy-dispersive X-ray spectroscopy (EDS) with the EDX 720HS equipment from Shimadzu.

2.7. Maize pot experiment conducted under greenhouse conditions

Soil samples were collected from the UnB experimental farm. The soil is classified as a Rhodic Haplustox (clay) [40], with 817 g kg⁻¹ of clay, 89 g kg⁻¹ of silt, and 94 g kg⁻¹ of sand. Surface-layer samples (0–20 cm) were homogenized to ensure representativeness. Then, soil chemical properties were determined, and soil acidity was corrected with lime to raise base saturation (V%) to 60 %, as recommended by Rajj et al. [41]. After correction, the soil was moistened to field capacity and incubated for 149 days.

The experiment was conducted in a greenhouse, using plastic pots with a total volume of 3.6 L. Each pot was filled with a mixture consisting of 90 % soil and 10 % co-compost. The selected rate (90 % soil + 10 % co-compost) was based on earlier greenhouse pot studies that successfully applied compost or co-compost with biochar at similar proportions [42,43]. The experiment was conducted in a completely randomized design, with nine treatments (as presented in Table 2), two controls (fertilized and unfertilized), and three replicates, resulting in a total of 33 experimental units. Treatments with compost, co-compost, and fertilized control received the nutrient solution immediately after germination, as recommended by Novais and Smyth [44]. The concentrations, expressed in mg kg⁻¹ of soil, were: N (100), P (300), K (150), S (40), B (0.81), Cu (1.33), Fe (1.55), Mn (3.66), Mo (0.15), and Zn (4). Irrigation was performed daily by drip, in two periods (6:00–6:04 a.m. and 6:00–6:04 p.m.), with a flow rate of 35 mL min⁻¹, maintaining soil moisture close to field capacity (0.30 cm³ cm⁻³).

The corn variety used was the hybrid PEN.22M (seeds provided by Sementes Alfa Eireli®). Three seeds were sown per pot, and after emergence, thinning was performed to maintain one plant per experimental unit. On day 47, the relative chlorophyll content was measured using the single-photon avalanche diode (SPAD) index, a widely used indicator of leaf chlorophyll content that is closely linked to biomass production. Measurements were taken with a MultispeQ device (PhotosynQ INC, USA) via the PhotosynQ platform (<http://www.photosynq.org>) on the third fully expanded leaf from the top of each maize plant. The plants were harvested immediately after the SPAD measurements,

rinsed with tap water, and their shoots were weighed. To measure the dry biomass of plant samples, tissues were dried in an air-circulating oven at 65 °C for 3 d, then weighed to determine the maize dry shoot matter, following procedures described by Loomis and Connor [45].

2.8. Statistical analysis

The variables were evaluated for normality of residuals and homoscedasticity of variance according to the Shapiro-Wilk and Levene tests, respectively. When data showed a normal distribution, they were subjected to analysis of variance (ANOVA), and the means were compared using Fisher's LSD test ($p < 0.05$).

3. Results and discussion

3.1. pH changes in the final co-compost

The pH of CaCl_2 ranged from 6.70 (20%BC300) to 7.80 in the control (0%BC) (Fig. 1). Notably, 0%BC, 5%B300, and 5%BC500 showed higher values ($p < 0.05$) than the other treatments, while the highest biochar concentrations (15%BC300, 20%BC300, 15%BC500, and 20%BC500) resulted in the lowest pH values of the co-composts. Because of the low pH of the BC300 (6.00) and BC500 (7.22) used in the study, the pH reductions observed in the biochar co-composts were expected. Despite this, the values remained within the ideal pH range (5.50–8.00) [46]. The differences between the combinations indicate changes in the chemical composition of the medium and possible process of H^+ ion release, which are important factors in determining the chemical stability of the substrates. Additionally, continuous mineralization of organic matter may have produced organic acids and phenolic compounds, further boosting the buffering capacity of the compost mixture [47]. Notably, no significant difference in pH was observed between biochar produced at 300 °C and 500 °C at each biochar dose (5 %, 10 %, 15 %, and 20 %). This shows that, at these specific proportions, the production temperature does not ($p > 0.05$) influence the pH of the co-compost.

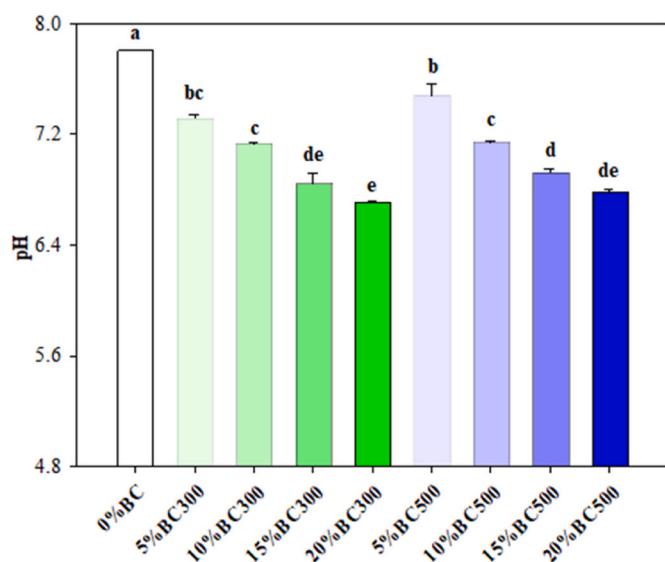


Fig. 1. pH (CaCl_2) of the final co-compost made from mixtures of food waste and sewage sludge biochar produced at 300 °C (BC300) or 500 °C (BC500), applied at different proportions (0, 5, 10, 15, and 20 % w/w). Different letters above the bars indicate significant differences among treatments (Fisher's LSD test, $p < 0.05$).

3.2. Elementary composition

Table 3 shows the concentrations of C, N, H, and O in the co-composts after 133 days of composting. The contents of C and N were not affected by the SSB addition ($p > 0.05$). The C content in the FW was about 20 %, similar to that in the biochars, which may explain why adding biochar did not cause noticeable changes during composting.

The 15%BC300 showed a higher H concentration than 15%BC500 and 20%BC500 ($p < 0.05$). The decrease in H content in the co-composts samples with SSB produced at 500 °C at higher concentrations is directly related to the thermal degradation of volatile organic compounds, resulting in more condensed and less hydrogenated materials [48]. This behavior reinforces the formation of more aromatic and stable structures, characteristic of biochars produced at higher temperatures [49]. This pattern directly correlates with the VM results, which showed lower values in the SSB co-composts at 500 °C, confirming that higher pyrolysis temperatures promote the development of more aromatic, stable, and biologically resistant structures.

The contents of O were similar in the co-composts with SSB at 300 and 500 °C. The reduction of O is characteristic of pyrolyzed materials, which results in the removal of oxygenated functional groups and the enrichment of more inert fractions [50]. This transformation promotes the formation of recalcitrant C and reduces the availability of biodegradable organic compounds in the final compost [51].

The C:N ratio is a key factor in composting because it directly affects the mineralization of organic matter and N availability in the finished compost [52]. The results showed that the C:N ratio of the co-composts remained nearly stable throughout the incubation period (Table S2). At the beginning of the process (time 0), the values ranged from 8.54 to 9.47, with 5%BC300, 15%BC300, and 5%BC500 showing the highest values ($p < 0.05$). From 0 to 113 days, this ratio remained mostly constant, indicating that composting did not result in significant changes in this measure.

The low C:N ratio observed since the beginning of composting is directly linked to the waste composition used (Table 1). The FW had a low C content (244 g kg^{-1}) and a high N content (27.9 g kg^{-1}), while the biochars, although rich in C, contained significant N concentrations (42.1 g kg^{-1} in BC300 and 34.0 g kg^{-1} in BC500). This profile, also shown in the SS (C:N = 7.8), consistently resulted in low initial C:N values, limiting the variation of this parameter throughout the process, even with the addition of SSB [53]. Composts with a low C:N ratio tend to release N more immediately, promoting plant growth, although they have a lower potential for organic carbon accumulation in the soil [54].

Table 3

Elemental composition (%) of co-composts from food waste mixed with sewage sludge biochar produced at 300 °C (BC300) or 500 °C (BC500), applied at different proportions (0, 5, 10, 15, and 20 % w/w), after 133 days of composting.

Treatment	C	N	H	O
	<i>ns</i>	<i>ns</i>	*	*
0%BC	20.6 ± 0.64	2.31 ± 0.05	4.40 ± 0.15abc	24.8 ± 0.84a
5%BC300	23.5 ± 2.00	2.75 ± 0.25	4.72 ± 0.18 ab	20.5 ± 3.10 ab
10%BC300	20.4 ± 0.25	2.96 ± 0.68	4.41 ± 0.03abc	23.0 ± 1.30 ab
15%BC300	23.3 ± 0.73	2.70 ± 0.04	4.77 ± 0.08a	18.0 ± 0.81b
20%BC300	21.9 ± 0.77	2.57 ± 0.10	4.57 ± 0.06abc	20.8 ± 0.94 ab
5%BC500	22.5 ± 0.59	2.52 ± 0.08	4.51 ± 0.06abc	18.8 ± 0.75 ab
10%BC500	21.2 ± 0.48	2.43 ± 0.07	4.40 ± 0.08abc	20.0 ± 1.10 ab
15%BC500	20.2 ± 0.87	2.18 ± 0.10	4.29 ± 0.05bc	20.5 ± 1.10 ab
20%BC500	20.2 ± 0.26	2.39 ± 0.08	4.21 ± 0.07c	19.8 ± 0.50 ab

Means followed by the same letters in the column are not significantly different according to Fisher's LSD test ($p < 0.05$); mean values ± standard error of the mean ($n = 3$). * indicates a 5 % (0.05) level of significance, and *ns* indicates non-significant.

3.3. Proximate analysis

The results of the proximate analysis of the co-composts are shown in Fig. 2. The pyrolysis temperature and the amount of SSB added to the FW affected the levels of volatile material (VM), ashes, and fixed carbon (FC). The VM concentrations decreased as the percentage of SSB in co-compost increased with the addition of BC500. Furthermore, the reduction in VM was aligned with an increase in ash mass (BC500 treatments), highlighting a direct relationship between the two parameters. Pyrolysis stabilizes organic compounds and decreases volatile material levels. Adding biochar, especially that produced at 500 °C, which is more stable, helped decrease the VM content in the mixture. This is because biochar made at higher temperatures tends to be more stable, containing more FC and ash [14,55,56], which helps reduce volatile compounds during composting.

On the other hand, the ash content increased with the rising percentage of biochar obtained at 500 °C in the co-compost. The ash levels ranged from 47.8 % (0%BC) to 53.3 % (20%BC500), further emphasizing the role of BC500 in improving the stability and ash content of the co-compost. This increase in ash content is associated with the concentration of mineral components during the volatilization of organic compounds in pyrolysis [57,58]. Sewage sludge biochars produced at higher temperatures have a greater inorganic content, including elements like Ca, boron (Bo), manganese (Mn), Zn, and especially P [59]. This P can serve as a slow-release fertilizer, providing long-term advantages for crop growth and soil health [60].

Co-composts made with higher BC500 incorporate at the highest rates (15 % and 20 %) show higher fixed carbon (FC) content ($p < 0.05$). However, the 15 % incorporation is significantly higher than 5% BC300 and 15%BC300. This suggests that adding BC500 at these doses improves stability and resistance to decomposition of the co-compost.

3.4. Energy dispersive X-ray (EDX) and X-ray diffraction (XRD) analysis of co-composts

The EDX analysis of co-composts formed from mixtures of FW and SSB heated at 300 °C (BC300) or 500 °C (BC500) showed notable changes in elemental composition, as illustrated in Fig. S2, especially for aluminum (Al), Ca, iron (Fe), P, and silicon (Si). The intensity of these elements increased with higher biochar levels, especially at 15 % and 20 %, mainly for Al and Fe, which are commonly present in sludge. Conversely, potassium (K) decreased, probably due to its lower concentration in SSB. The presence of P-rich SSB further enhanced nutrient quality. As demonstrated by Figueiredo et al. [61], Fachini & Figueiredo [62], and Santos et al. [63], these elements contributed to the nutritional enrichment, especially at higher biochar proportions. These findings suggest that using biochar, particularly in higher proportions, may enhance soil quality by improving the nutrient profile of the co-composts. The X-ray diffraction (XRD) analysis, including mineral identification and crystallinity patterns, is detailed in the Supplementary Material, with Text S3 and Fig. S3.

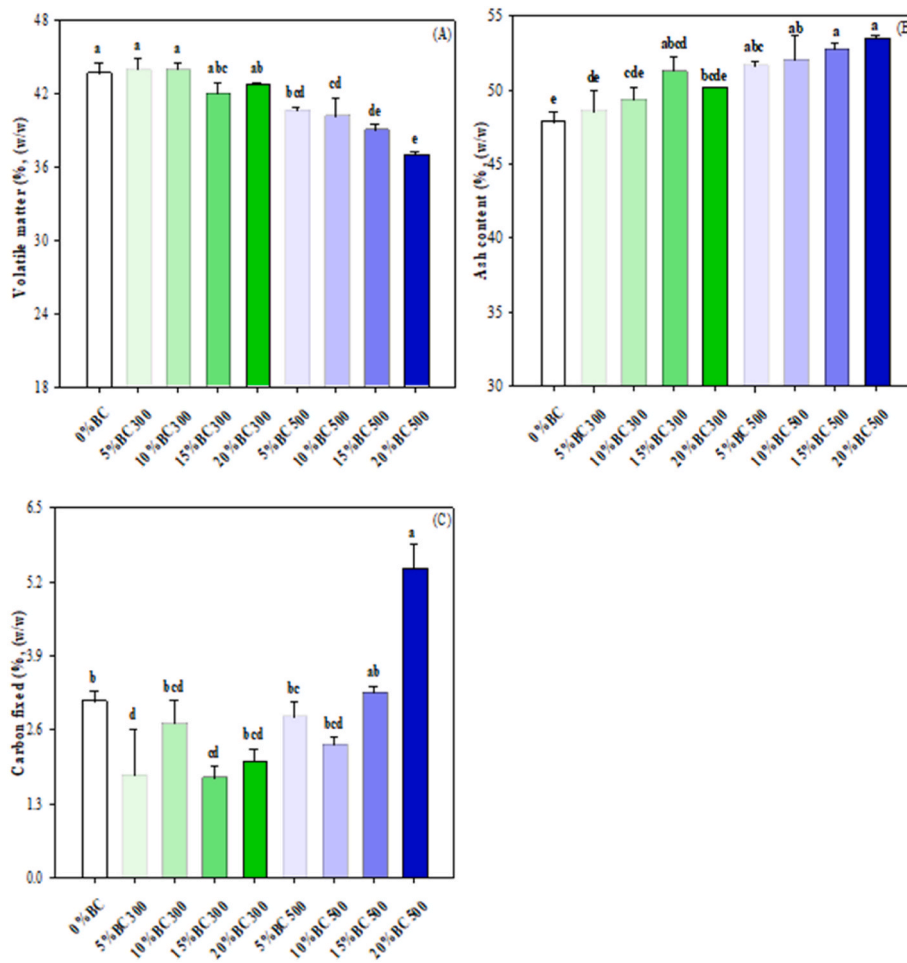


Fig. 2. Proximate composition analysis of co-composts made from mixtures of food waste (FW) and biochar produced from sewage sludge at 300 °C (BC300) or 500 °C (BC500), applied at different proportions (0, 5, 10, 15, and 20 % w/w): volatile matter (A), ash (B), and fixed carbon (C). Values are shown as mean ± standard error of the mean. Different letters above the bars indicate significant differences among the co-composts (Fisher's LSD test, $p < 0.05$).

3.5. Nutrient levels in co-compost

The application of different proportions of BC300 and BC500 affected the nutrient concentrations in the final co-compost (Table 4 and Table S3; and Fig. 3). Overall, adding SSB increased Ca, Mg, and S levels and decreased K levels in the co-compost. Specifically, the co-compost made with 5%BC500 had the highest levels ($p < 0.05$) of Ca and Mg compared to other treatments. This result suggests that higher pyrolysis temperatures favor increased Ca and Mg levels in biochar and, consequently, in the final co-compost. Additionally, increasing the dose of 500 °C biochar did not lead to a significant increase in Ca and Mg levels in the co-composts, possibly due to the dilution of these elements as a result of the higher proportion of carbonized material with low immediate nutrient availability.

Samples of 5%BC300 showed the highest levels of K, followed by the control (0%BC), both higher ($p < 0.05$) than the other treatments. Conversely, co-composts with 15 % and 20 % biochar had the lowest K levels, showing a reduction as biochar proportion increased. This is due to the nature of the raw material used, since K, being highly soluble in water, is removed in the form of mineral salts along with the liquid effluent during the final treatment of SS [64]. As observed in Table 1, the SS has low K content, since this element is not retained in the dry solid fraction after treatment. Similarly, the SSB has a low concentration of K. Therefore, the addition of SSB to FW composting reduces K levels in the final co-compost. Regarding S, co-composts containing biochar, especially at higher doses (15 % and 20 % of BC500 and 20%BC300), showed the highest concentrations ($p < 0.05$). This is probably due to the greater nutrient retention capacity of biochar at these higher doses [65]. In contrast, the control (0%BC) had significantly lower S levels, emphasizing the positive effect of SSB addition on the final S concentration in the co-compost. Details and interpretations of the micronutrient data are available in the Supplementary Material, including text S2 and Table S3.

Phosphorus (P) levels in the co-composts increased with the addition of biochar, especially at higher doses (15 % and 20 % of both BC500 and BC300) ($p < 0.05$). The greatest P increases were observed, with values rising from 8.6 g kg⁻¹ in the control (0 % BC) to 25.7 g kg⁻¹ in the 20% BC500 treatment (Fig. 3). This illustrates biochar's ability to improve P retention in the co-compost, which is particularly important for enhancing nutrient availability. Since biochar naturally has a high P content (Table 1), the rise in P levels in the amended co-composts was expected. During pyrolysis, the transformation of P into more stable mineral forms, particularly apatite P, reduces immediate P solubility while enabling gradual release over time [66], thereby allowing SSB-amended co-composts to function as a slow-release P source [60]. This feature is particularly relevant for long-term soil fertility management in clay-rich soils dominated by Fe and Al oxides, where P availability is often constrained by strong P fixation through adsorption onto

Table 4

Macronutrient levels in the final co-composts made from food waste mixed with sewage sludge biochar produced at 300 °C (BC300) or 500 °C (BC500), applied at various proportions (0, 5, 10, 15, and 20 % w/w).

Treatments	Ca	Mg	K	S
	g kg ⁻¹			
0%BC	2.9 ± 0.61bc	2.3 ± 0.48bc	8.9 ± 0.14a	4.9 ± 0.45d
5%BC300	3.0 ± 0.34bc	2.4 ± 0.26bc	9.6 ± 0.43a	6.2 ± 0.77bc
10%BC300	2.9 ± 0.37bc	2.3 ± 0.25bc	7.8 ± 0.96b	6.4 ± 0.12b
15%BC300	2.7 ± 0.18c	2.1 ± 0.19c	6.3 ± 0.61d	6.7 ± 0.73b
20%BC300	3.1 ± 0.83bc	2.4 ± 0.66bc	7.3 ± 0.22bc	7.9 ± 0.25a
5%BC500	4.7 ± 0.26a	3.8 ± 0.20a	7.6 ± 0.19bc	5.7 ± 0.69c
10%BC500	3.3 ± 0.16b	2.6 ± 0.12b	7.8 ± 0.94b	6.3 ± 0.19bc
15%BC500	3.4 ± 0.38b	2.7 ± 0.30b	7.7 ± 0.41b	7.6 ± 0.83a
20%BC500	3.3 ± 0.49b	2.6 ± 0.38b	7.1 ± 0.10c	8.1 ± 0.13a

Means followed by the same letters in the column are not significantly different according to Fisher's LSD test ($p < 0.05$); mean values ± standard error of the mean (n = 3).

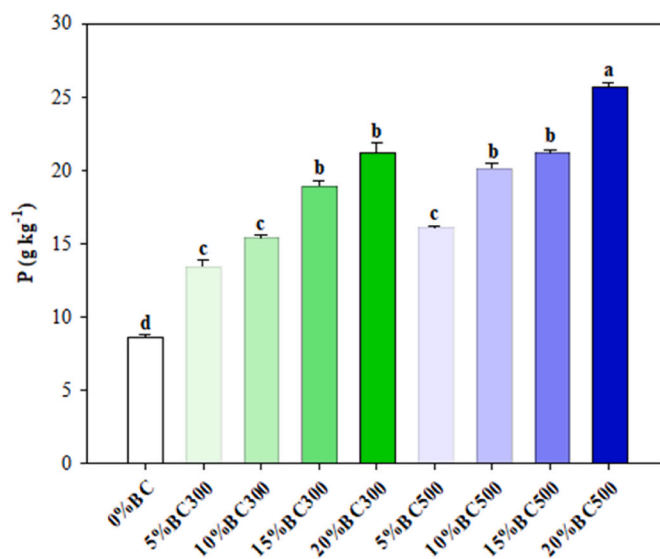


Fig. 3. Total phosphorus (P) contents in co-composts made from mixtures of food waste and biochar produced from sewage sludge at 300 °C (BC300) or 500 °C (BC500), applied at different proportions (0, 5, 10, 15, and 20 % w/w). Values are shown as mean ± standard error of the mean. Different letters above the bars indicate significant differences among the co-composts (Fisher's LSD test, $p < 0.05$).

oxide surfaces. Under field conditions, biochar's ability to retain P has been shown to sustain soil P availability and plant P uptake over multi-year periods (4–5 years), despite a progressive decrease in P availability over time [61,67].

When applied to soil, these biochar-enriched co-composts can significantly increase P availability, helping to address P deficiencies, especially in tropical and acidic soils [68]. The slow-release mechanism offers a continuous nutrient supply, promoting steady plant growth and productivity [60].

A key concern when mixing food waste with sewage sludge-derived materials is the potential immobilization of P by Fe and Al, which may reduce short-term P availability. However, a global meta-analysis by Lustosa Filho et al. [60] shows that pyrolysis converts water-soluble P into acid-extractable forms, enabling medium- to long-term P supply despite lower immediate solubility. This mechanism explains why SSBs can sustain crop productivity in acidic, Fe- and Al-rich soils rather than acting as counterproductive amendments [61,69].

3.6. Concentration of total and available heavy metals (HMs)

Some heavy metals (HMs) are considered nutrients for plants at trace levels, but excessive amounts can harm plants metabolism. In this study, we measured the total and available levels of eight heavy metals —Ni, Cu, Cr, As, Ba, Hg, Pb, and Cd — to evaluate how different biochar additions to FW during composting affect the passivation of these metals compared to an unamended mixture. Table 5 shows the results of total HMs concentrations in the co-composts produced. No significant differences ($p > 0.05$) were observed between treatments for Ni, Cr, As, Hg, and Pb, whereas Cd concentration was below the detection limit (0.05 mg kg⁻¹) (Table 5). However, adding 10 %, 15 %, and 20 % of both biochars (BC300 and BC500) resulted in higher Cu concentrations ($p < 0.05$) in the co-composts than in the control (0 % BC). For Ba, the 20% BC500 had higher levels compared to the control (0%BC) ($p < 0.05$).

Regarding available HMs, Ni, Cr, and Hg had concentrations below the detection limit (BDL) across all treatments (Table 6). No significant differences ($p > 0.05$) were found among treatments for As and Pb. However, adding 15 % of both biochars (BC300 and BC500) to FW increased Cu concentrations than 0%BC and 5%BC300 ($p < 0.05$). This

Table 5

Concentration of total heavy metals in the final co-composts made from food waste mixed with sewage sludge biochar produced at 300 °C (BC300) or 500 °C (BC500), applied at various proportions (0, 5, 10, 15, and 20 % w/w).

Treatments	Ni	Cu	Cr	As	Ba	Hg	Pb
0%BC	24.3 ± 1.43a BDL	36.7 ± 1.61d	94.3 ± 3.47a	3.10 ± 1.62a 0.71a	40.8 ± 0.63f 0.37e	1.13 ± 0.24a 0.29a	BDL ± 1.49 ± 1.49 ab 3.67 2.26 2.26 5.53 0.47 BDL
5%BC300	BDL	50.9 ± 0.63cd	BDL	7.70 ± 0.71a	55.2 ± 0.37e	0.29 ± 0.29a	1.49 ± 1.49 ab 3.67 2.26 2.26 5.53 0.47 BDL
10%BC300	BDL	68.1 ± 1.86c	BDL	2.99 ± 0.74a	65.1 ± 0.71d	0.35 ± 0.35a	3.67 ± 3.67 ab 12.1 5.18a 6.41 1.46 ab
15%BC300	27.1 ± 0.87a	89.4 ± 2.32b	103 ± 5.30a	3.34 ± 2.25a	74.8 ± 1.45c	0.69 ± 0.55a	2.26 ± 2.26 ab 5.53 0.47 BDL
20%BC300	BDL	92.8 ± 2.79b	BDL	8.05 ± 1.43a	97.4 ± 0.95b	0.57 ± 0.35a	5.53 ± 0.47 ab BDL
5%BC500	BDL	60.5 ± 1.40c	BDL	5.80 ± 2.04a	66.8 ± 3.12d	1.12 ± 1.12a	BDL ± 1.49 ± 1.49 ab
10%BC500	24 ± 7.26a	86.4 ± 6.37b	94.0 ± 21.4a	2.21 ± 0.58a	77.2 ± 1.35c	0.74 ± 0.73a	1.49 ± 1.49 ab
15%BC500	BDL	127 ± 7.26a	BDL	2.54 ± 1.33a	92.7 ± 1.04b	1.52 ± 0.59a	12.1 ± 5.18a 6.41 1.46 ab
20%BC500	35.7 ± 1.97a	132 ± 0.90a	116 ± 3.92a	2.70 ± 2.02a	105.0 ± 1.34a	1.61 ± 0.81a	6.41 ± 1.46 ab
Max. limits*	70	nc	nc	20	nc	1	150

BDL: below detection limit; nc: not considered. Means followed by the same letters in the column are not significantly different according to Fisher's LSD test ($p < 0.05$); mean values ± standard error of the mean ($n = 3$). * maximum limits presented in Brasil [70].

increase in available Cu at the 15 % biochar rate is consistent with the higher Cu concentrations in both biochars (115 and 168 mg kg⁻¹ for BC300 and BC500, respectively) compared with FW (24 mg kg⁻¹), as shown in Table 1. Lastly, the 0%BC co-compost showed higher Ba concentrations than the other treatments ($p < 0.05$), except when compared with the 5%BC500 treatment.

Overall, all co-composts showed contaminant levels below the maximum limits allowed by Brazilian national regulations, confirming the safety of these materials for agricultural use. Specifically, the levels of total Ni, As, and Pb stayed within legal limits. Although Hg

Table 6

Concentration of available heavy metals in the final co-composts made from food waste mixed with sewage sludge biochar produced at 300 °C (BC300) or 500 °C (BC500), applied at various proportions (0, 5, 10, 15, and 20 % w/w).

Treatments	Ni	Cu	Cr	As	Ba	Hg	Pb
0%BC	BDL	1.88 ± 0.53bc	BDL	0.01 ± 0.03a	0.11 ± 0.02a	BDL	BDL
5%BC300	BDL	1.60 ± 0.06c	BDL	0.02 ± 0.01a	0.06 ± 0.002bc	BDL	BDL
10%BC300	BDL	2.82 ± 0.34abc	BDL	BDL	0.03 ± 0.004cd	BDL	BDL
15%BC300	BDL	4.68 ± 0.45a	BDL	BDL	0.02 ± 0.003cd	BDL	BDL
20%BC300	BDL	3.75 ± 0.20 ab	BDL	BDL	0.03 ± 0.002cd	BDL	0.85 ± 0.05a
5%BC500	BDL	2.91 ± 0.32abc	BDL	0.03 ± 0.004a	0.08 ± 0.02 ab	BDL	BDL
10%BC500	BDL	2.86 ± 0.30 ab	BDL	0.01 ± 0.01a	0.01 ± 0.001d	BDL	BDL
15%BC500	BDL	4.84 ± 0.87a	BDL	0.01 ± 0.01a	0.02 ± 0.001cd	BDL	0.68 ± 0.09a
20%BC500	BDL	3.55 ± 0.20abc	BDL	0.003 ± 0.01a	0.01 ± 0.002cd	BDL	0.53 ± 0.05a

BDL: below detection limit; nc: not considered. Means followed by the same letters in the column are not significantly different according to Fisher's LSD test ($p < 0.05$); mean values ± standard error of the mean ($n = 3$).

concentrations exceeded the limit, it is important to note that these values refer to the total concentrations, not available concentrations. Studies in the literature indicate that adding biochar can immobilize Hg or reduce its toxicity [71–74]. This is further supported by the available Hg levels, which fall BDL (Table 6). On the other hand, biochar derived from sludge may contain some heavy metals, and, in some cases, composts containing biochar showed slightly higher total HMs contents compared to 0%BC. However, these metal levels remain extremely low and well below the maximum limits set by environmental laws or organic residue standards from Brazil [70], the European Union [75], China [76], and the International Biochar Initiative (IBI) [77] guidelines (Table 54). These results indicate that HM concentrations are lower than established standards, demonstrating that our composting products meet these criteria and can be safely used in agricultural fields without contamination risk.

3.7. Effects of co-compost made from biochar and food waste on maize growth

The relative chlorophyll content (SPAD index value) and the dry matter yield of the aboveground parts of maize plants are presented in Fig. 4. For the SPAD index, the highest values were observed in the treatments with composts, especially with the application of co-composts in higher proportions of biochar (10 % and 20 % of BC300 or BC500), which showed superior performance ($p < 0.05$) compared to the non-fertilized control (Fig. 4A). Overall, the highest aboveground maize dry matter was observed with the application of compost (0%BC) and co-composts, being higher than both the non-fertilized and fertilized controls ($p < 0.05$) (Fig. 4B). The fertilized control, despite receiving chemical fertilization, produced less dry matter than composted treatments, highlighting the importance of adding organic matter and nutrients with gradual release for crop development. On the other hand, the lowest dry matter production results occurred in the unfertilized soil. These data suggest that co-composts not only increase biomass production but also improve photosynthesis and plant health, possibly by providing a continuous supply of essential nutrients, as evidenced by the higher SPAD index values observed in these treatments.

Similar positive effects of biochar-enriched co-composts have been observed across crops and conditions. Rauf et al. [78] found that sunflower showed a 115–132 % increase in key agronomic traits and significant improvements in chlorophyll levels, water use efficiency, and antioxidant responses when amended with biochar-containing co-composts. This treatment also notably reduced Cd accumulation in grains (up to 94 %). Likewise, Naveed et al. [79] reported that *Brassica napus* experienced up to 151 % higher photosynthetic rates and 158 % greater root dry weight, along with improved physiological efficiency. Additionally, Mikajlo et al. [80] confirmed that these co-composts enhance soil fertility and microbial activity, resulting in nearly six times more lettuce biomass than the control, compared with only threefold increases with a mix of biochar and compost. Overall, these findings

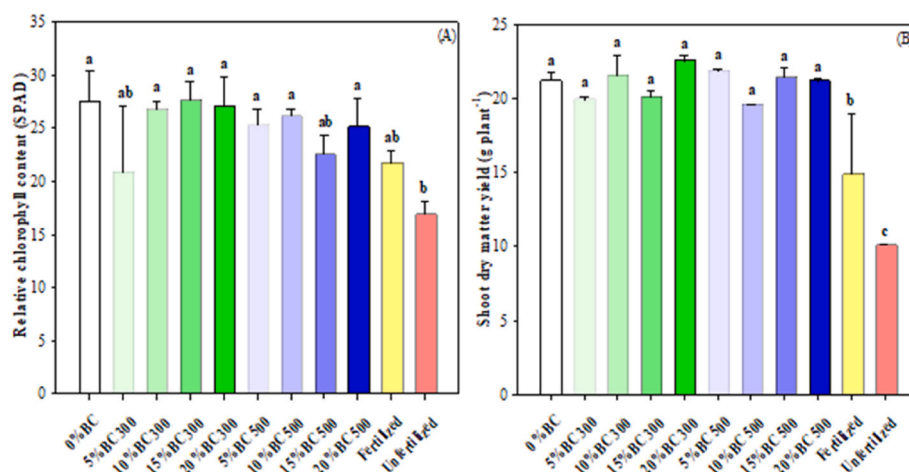


Fig. 4. Maize relative chlorophyll content (A) and shoot dry matter yield (B) in response to different co-composts made from food waste mixed with sewage sludge biochar produced at 300 °C (BC300) or 500 °C (BC500), applied at various proportions (0, 5, 10, 15, and 20 % w/w). Values are presented as mean \pm standard error. Different letters above the bars indicate significant differences among the co-composts (Fisher's LSD test, $p < 0.05$).

consistently show that biochar-enriched co-composts promote plant growth, enhance photosynthesis, and improve soil health across various species and environmental conditions.

The biochar co-compost mixtures significantly increased the SPAD value, likely due to higher soil N availability and increased N in the leaves. This probably contributed slightly to the increased growth. Specifically, co-composts containing 10 % or 20 % BC300 or BC500 increased maize chlorophyll levels by 49 %–60 % compared with the unfertilized control. The lack of difference in dry matter production between the co-composts and the 0%BC compost can be attributed to the use of a chemical nutrient solution in all compost treatments, which probably limited the effect of the co-composts. This indicates that the combined application of co-composts and mineral fertilization produced complementary effects on nutrient availability and plant growth compared with mineral fertilization alone. Although the co-compost had a higher P content than 0%BC (Fig. 3), no significant differences were observed. Additionally, the short crop cycle until harvest may have limited the expression of the fertilizing power of the co-composts. In this regard, longer-term field studies have proven more suitable for evaluating the residual effects and gradual nutrient release from composts and biochar in the soil [81–83]. In contrast, our findings show that shoot dry matter yield was significantly improved by the co-application of both co-composts and mineral fertilization, compared with the fertilized or unfertilized controls. This improvement is likely attributed to improved nutrition and the bio-stimulatory effects of the compost. A study examining the effects of applying 2 % co-compost (made of animal manures, straw, rock powder, soil, mature compost, and biochar) to sandy loam soil found enhanced plant growth in greenhouse conditions [84], especially at lower nutrient supply levels. Therefore, the observed plant responses primarily reflect a synergy between co-compost and mineral fertilization under greenhouse conditions, rather than the isolated effect of the co-compost.

Although the biochar co-compost mixtures showed promising results, significantly increasing SPAD values and maize shoot dry matter yield when combined with chemical fertilization, their effects in isolation remain unclear. Future studies should explore the impact of these co-composts alone and compare their performance with chemical fertilization, particularly in long-term field trials to fully assess their potential for enhancing plant growth and nutrient release.

4. Conclusions

Co-composting FW with SSB improved stability, nutrient retention, and reduced heavy metal bioavailability in the final product. The

addition of biochar, especially that produced at 500 °C and applied at higher rates (15–20 %), increased levels of P, Ca, S, and Zn, while maintaining contaminant levels below regulatory limits, confirming the environmental safety of the co-composts. Although biochar-enriched co-composts enhanced chemical quality and nutrient content, these improvements did not lead to higher maize biomass yields under greenhouse conditions compared to 0%BC. This is probably due to the short cultivation period and the use of nutrient solutions containing chemical nutrients across treatments. However, both shoot dry matter yield and SPAD index (particularly at higher proportions of 10 % and 20 % BC300 or BC500) increased with the combined use of co-composts and mineral fertilization compared to both fertilized and unfertilized controls, indicating improved nutrient uptake and photosynthetic activity. These findings suggest that co-composting FW with SSB, particularly BC500, produces more stable, nutrient-rich materials that have potential for long-term soil improvement. Future field studies are recommended to evaluate nutrient release dynamics, residual fertility, and crop productivity throughout full growing cycles.

CRediT authorship contribution statement

Jane Ribeiro dos Santos: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **José Ferreira Lustosa Filho:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Camila Rodrigues Costa:** Methodology, Formal analysis. **Marcela Granato Barbosa dos Santos:** Methodology, Formal analysis. **Alessandra Monteiro de Paula:** Writing – original draft, Methodology. **Jader Galba Busato:** Writing – original draft, Methodology, Formal analysis. **Cícero Célio de Figueiredo:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.biombioe.2026.109037>.

Data availability

Data will be made available on request.

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