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Production, characterization, and application of biochar derived from *Eucalyptus pellita* bark waste for soil quality improvement

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ABSTRACT

Biochar production, a widely used biomass waste-management approach, involves pyrolysis and can serve as a soil amendment. In this study, *Eucalyptus pellita* bark waste obtained from a pulp and paper industry in Muara Enim, South Sumatra, Indonesia, was utilized as the feedstock. Biochar was produced by pyrolysis at 300, 400, and 500 °C for residence times of 60, 90, and 120 minutes to determine its physicochemical properties. The produced biochar was subsequently applied to loamy sand soil at rates of 2.5%, 5%, and 10% to evaluate its effects on soil physicochemical properties.The results showed that increasing pyrolysis temperature and residence time decreased biochar yield, organic carbon (OC), and organic matter (OM), while increasing macronutrient (Ca, P, K, and Mg) and micronutrient concentrations, as well as pH, particularly at 500 °C for a 120-minute residence time. Biochar application at higher rates, especially 10%, significantly increased soil OC, N, P, K, Ca, and Mg, while reducing bulk density and increasing porosity. The highest concentrations of P, K, Ca, and Mg were observed in soil amended with biochar produced at 500 °C for 120 minutes and applied at the 10% rate, reflecting the higher inorganic nutrient content of high-temperature biochar. Soil nitrogen content also increased with increasing biochar application rate and pyrolysis temperature, primarily due to enhanced nitrogen retention in the soil–biochar system.

Keywords: biochar, pyrolysis, bark, *Eucalyptus pellita*, loamy sand, biochar dosage, physical properties, chemical properties.

INTRODUCTION

Biochar is a carbon-rich solid material produced through thermal processes under limited oxygen conditions (Singh and Singh, 2020). The environmental and soil-related benefits of biochar use include the removal of contaminants from water and soil, improvement of soil quality, and carbon sequestration (Ramola et al., 2022). Storing carbon in soil is one method to reduce CO_2 emissions into the atmosphere. Since CO_2 is a significant greenhouse gas contributing to global warming, the utilization of biochar as a Carbon Capture and Storage (CCS) medium offers a promising solution to mitigate climate change by sequestering carbon in the soil. Additionally, the use of biochar for soil carbon storage improves soil quality, thereby enhancing plant growth and productivity (Guo et al., 2020).

The effectiveness of biochar depends significantly on its characteristics, which are influenced by both the biochar production process and the type of biomass used (Ippolito et al., 2020). Biomass for biochar production may be derived from organic waste, livestock manure, agricultural residues, and forestry waste (Pourhashem et al., 2019). Forestry residues, particularly those from the pulp and paper industry, which utilises wood as a raw material, often include unused parts of trees, such as bark. In Indonesia, the pulp and paper industry commonly uses *Eucalyptus pellita* wood, generating *Eucalyptus pellita* bark waste that can be used as feedstock for biochar production. The suitable process for biochar production is pyrolysis.

Pyrolysis can be classified into two main types: fast pyrolysis and slow pyrolysis. Fast pyrolysis primarily produces bio-oil, while slow pyrolysis favors biochar production (Fang et al., 2020). Slow pyrolysis typically operates within a temperature range of 300–800 °C, with a heating rate of 1–100 °C/min, and a residence time of 10-2,000 minutes (Fang et al., 2020; Boateng, 2020). The operating conditions of the pyrolysis process significantly affect the characteristics of the resulting biochar. Previous studies have shown that lower pyrolysis temperatures yield higher biochar yields. For example, Sen et al. (2023), Fernandes et al. (2020), and Vamvuka et al. (2023) used *Quercus cerris* phloem bark, *Eucalyptus* residues, and forestry waste as feedstocks at temperatures of 400 °C, 450 °C, and 350 °C, respectively, producing biochar yields of 42%, 42.76%, and approximately 35%. Conversely, higher pyrolysis temperatures increase the carbon content of biochar, as reported by Domingues et al. (2020) and Saletnik et al. (2022), who used *Eucalyptus* sawdust and oak bark at 750 °C and 500 °C, respectively, yielding carbon contents of 91% and 60.99%, respectively.

Other parameters, such as residence time and heating rate, also affect biochar yield. A slower heating rate tends to produce a higher yield, as observed by Shagali et al. (2021) and Li et al. (2021), who used walnut shell and lignin feedstocks at heating rates of 10 °C/min and 5 °C/min, resulting in yields of approximately 39% and 55.5%, respectively. Conversely, shorter residence times result in higher yields, as demonstrated by Sen et al. (2023) and Wang et al. (2020), who used *Quercus cerris* phloem bark and rape straw, respectively, with residence times of 30 and 60 minutes, producing biochar yields of approximately 33% and 70.4%, respectively. Pyrolysis conditions also influence other characteristics such as volatile matter, total ash, total hydrogen, total nitrogen, surface area, C:H ratio, C:O ratio, and macronutrient content. These properties also depend on the type of feedstock used. For instance, Saletnik et al. (2022) found that total hydrogen in biochar derived from oak bark decreased from 3.48% to 3.05% between 400 and 450 °C but slightly increased to 3.07% at 500 °C, while Vercruysse et al. (2021) reported a steady decrease from 2.84% to 1.69% for ivy leaf biochar between 400 and 700 °C.

Biochar reduces soil bulk density and compaction while enhancing porosity, water retention capacity, hydraulic conductivity, and aggregate stability; however, its effectiveness depends on the soil type, biochar quality, and dosage (Mendes, 2022). However, biochar performance depends on its physicochemical properties (e.g., particle size, porosity, surface area, and functional groups) and on the characteristics of the target soil (e.g., texture, pH, and carbon content) (Blanco and Lal, 2023). The primary advantage of biochar lies in its ability to enhance the availability of essential nutrients, particularly nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) (Yadav and Khare, 2020). Its high adsorption capacity allows biochar to retain nutrients in the root zone, reduce leaching and surface runoff losses, and provide a slow release of nutrients to plants (Datta and Meena, 2021).

The study by Torgbenu et al. (2025) utilised biochar derived from coconut husk and sugarcane bagasse produced at 510 °C and 210 °C, respectively, for 1 hour, with an application rate of 5 kg per plot. The results demonstrated that the addition of biochar to soil increased organic carbon, available N, P, K, and Ca, pH, cation exchange capacity, electrical conductivity, and soil porosity compared with the control soil without biochar. Biochar application rates can influence soil characteristics, as shown in a study by Chen et al. (2024), which applied corn straw biochar produced at 350 °C for 30 minutes to sandy loam soil at 1%, 2.5%, 5%, and 10%. The findings indicated that higher biochar doses resulted in increased soil water content, soil organic carbon, and total N, P, and K in the amended soil.

This study offers novelty in the use of *Eucalyptus pellita* bark as a raw material for biochar production under varied operational conditions, followed by its application to soil. Previous studies generally investigated either the effect of operational variations during pyrolysis or the application of biochar produced under a single operating condition. In contrast, this study integrates both approaches by employing multiple combinations of pyrolysis temperatures and residence times for biochar production and subsequently applying the resulting biochar to soil at different application rates.

The objective of this research is to utilize solid waste in the form of *Eucalyptus pellita* bark obtained from the pulp and paper industry in Muara Enim, South Sumatra, Indonesia, by varying operating conditions during biochar production and applying different application rates to loamy sand soil. These efforts aim to evaluate the influence of pyrolysis conditions on the characteristics of the resulting biochar and to assess how different biochar doses affect the properties of soil-biochar mixtures.

MATERIALS AND METHODS

The experimental stages of biochar production and its application to soil are illustrated in Figure 1.

Preparation of raw materials

The raw material used in this study was *Eucalyptus pellita* bark waste obtained from a pulp and paper mill located in Muara Enim Regency, South Sumatra, Indonesia. The bark waste was received predominantly in fibrous form due to prior industrial processing. In the laboratory, the material

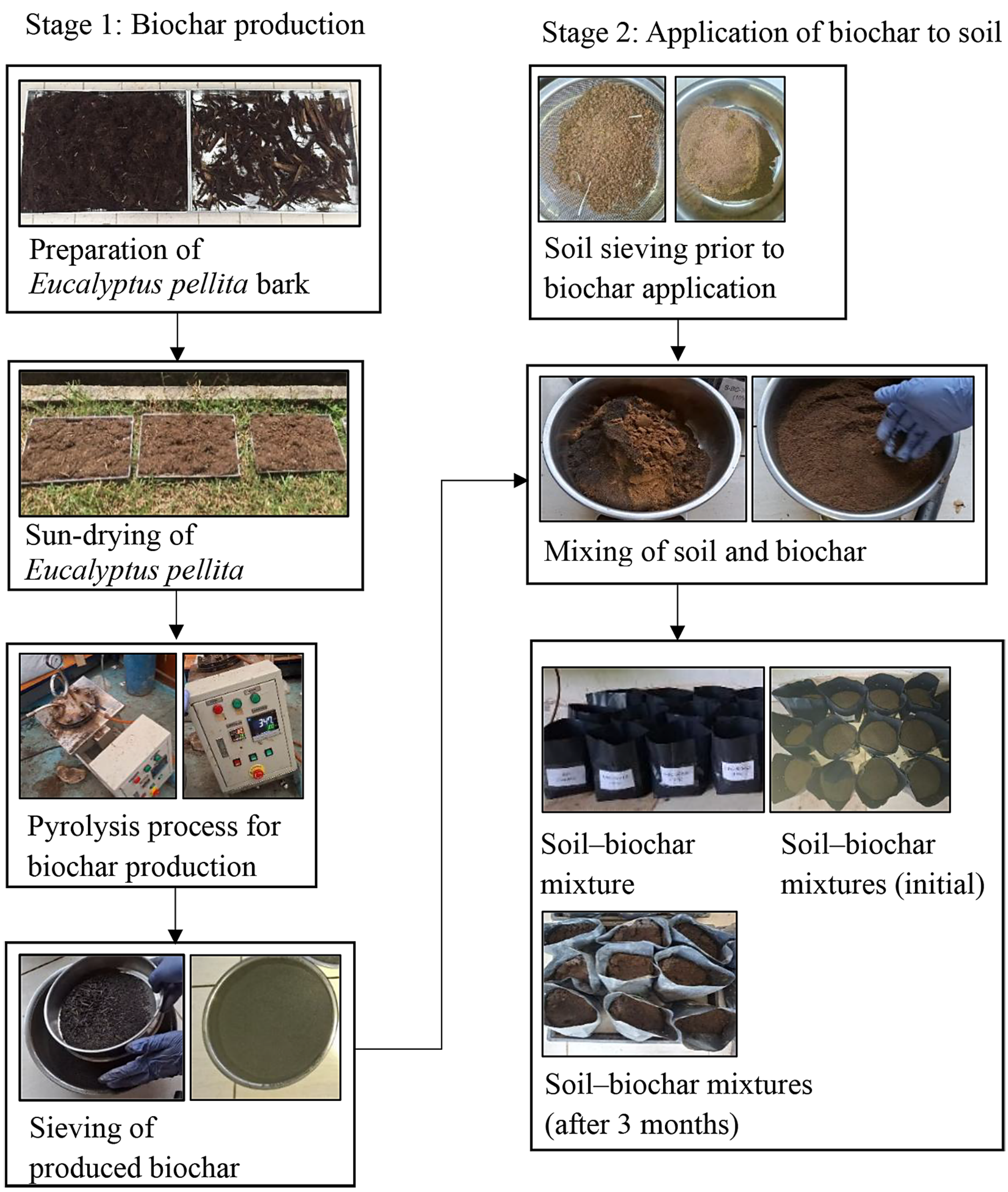

Figure 1. Experimental stages of biochar production and application to soil, including feedstock preparation, biochar production, and soil-biochar mixing and incubation

was manually separated into fibrous and coarse fractions to ensure feedstock uniformity. Subsequently, the fibrous fraction of *Eucalyptus pellita* bark was dried for 5 days to reduce its moisture content before pyrolysis.

Biochar production

Biochar was produced in a laboratory-scale batch pyrolysis reactor, as illustrated in the schematic diagram (Figure 2) and the actual experimental setup (Figure 3). After drying, 300 g of the dried fibrous fraction of *Eucalyptus pellita* bark, used as received from the pulp and paper industry, was directly loaded into the batch pyrolysis reactor (R) for each experimental run. The pyrolysis temperature was set at 300, 400, and 500 °C, and the residence time was varied to 60, 90, and 120 min, yielding nine biochar products. Nitrogen gas from the nitrogen gas cylinder (T-1) was continuously supplied to the batch pyrolysis reactor (R) during the pyrolysis process to maintain an inert atmosphere. Cooling water (T-3) was used as the cooling medium supplied to the condenser (CD). During pyrolysis, volatile vapors generated in the reactor were directed through a condenser (CD). Condensable vapors were cooled and collected as smoke liquid in the condensate collector (T-2), while non-condensable gases exited the system through the gas outlet. After completion of the pyrolysis process and subsequent cooling, the solid product (biochar) was obtained directly from the batch pyrolysis reactor (R). The yields of pyrolysis products reported in Table 2 were determined by collecting and measuring the mass of each fraction (smoke liquid and biochar) from the experimental setup, while the mass of non-condensable gases was calculated using Equation 1. The biochar yield was calculated using Equation 2, the smoke liquid yield was calculated using Equation 3, and the gas yield was subsequently calculated using Equation 4.

$$m_{\text{gas}}\,(g) = m_{\text{feedstock}} - m_{\text{biochar}} - m_{\text{smoke liquid}} \quad (1)$$

$$Y_{\text{biochar}}\,(\%) = \frac{m_{\text{biochar}}}{m_{\text{feedstock}}}\, x\, 100 \quad (2)$$

$$Y_{\text{smoke liquid}}\,(\%) = \frac{m_{\text{smoke liquid}}}{m_{\text{feedstock}}}\, x\, 100 \quad (3)$$

$$Y_{\text{gas}}\,(\%) = 100 - Y_{\text{biochar}} - Y_{\text{smoke liquid}} \quad (4)$$

where: $m_{feedstock}$ – mass of feedstock (g),
$m_{biochar}$ – mass of biochar (g),
$m_{smoke\ lqiuid}$ – mass of smoke liquid (g),
$Y_{biochar}$ – yield of biochar (%),
$Y_{smoke\ lqiuid}$ – yield of smoke liquid (%),
Y_{gas} – yield of gas (%).

Separation of biochar products

After cooling, the produced biochar was ground and sieved using a 30-mesh sieve. The fraction passing through the sieve was used as the biochar product for soil application.

Selection of biochar for soil application

The selection of biochar for soil application was based on yield analysis and the chemical and physical characteristics of the produced biochars. To enable a clear comparison of temperature effects, biochars produced at 300, 400, and 500 °C with a 120-minute residence time were selected.

Soil preparation

The soil used in this study was collected from Ogan Komering Ulu Timur Regency, South

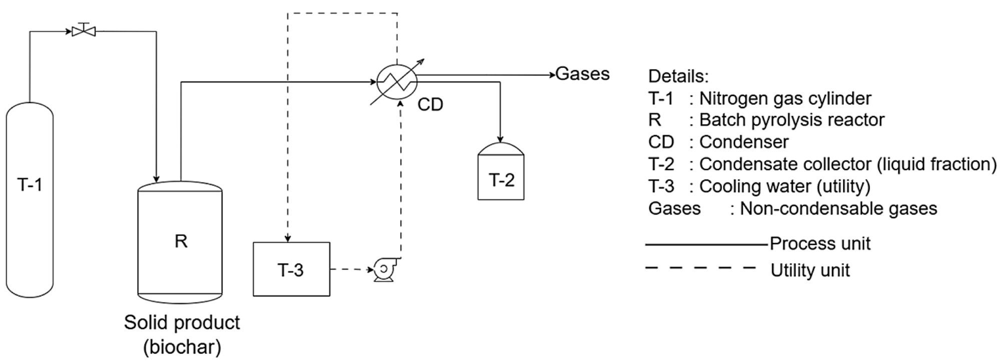

Figure 2. Schematic process flow diagram of the laboratory-scale batch pyrolysis system for biochar production

Figure 3. Photographs of the laboratory-scale batch pyrolysis experimental setup

Sumatra, Indonesia. Based on particle-size analysis, the soil was classified as loamy sand, consisting of 80.82% sand, 9.59% silt, and 9.59% clay. Before biochar application, the soil sample was sieved to remove coarse materials such as stones and roots.

Application of biochar to soil

The biochar used for soil application was produced at pyrolysis temperatures of 300, 400, and 500 °C with a residence time of 120 min. Biochar was applied to the soil at rates of 0% (control), 2.5%, 5%, and 10% (w/w) in polybags, with a total soil–biochar mixture mass of 1.500 g. The mixtures were incubated for three months. During the incubation period, the soil–biochar mixtures were watered based on the weight loss observed over time to maintain moisture content, following the method described by Domingues et al. (2020).

Biochar and soil-biochar mixture characterization

Physicochemical properties of biochar and soil samples were determined using standardized analytical methods recommended by the Ministry of Agriculture of the Republic of Indonesia (2023), as summarized in Table 1.

RESULTS AND DISCUSSION

Analysis of pyrolysis product yields

Eucalyptus pellita bark was used as feedstock in a pyrolysis process under varying operating conditions, specifically at 300, 400, and 500 °C and residence times of 60, 90, and 120 minutes. The pyrolysis process produced three main products: biochar, liquid smoke (condensable tar/oil), and non-condensable gases that exited through the condenser. The average yields of the pyrolysis products, consisting of biochar, liquid smoke (condensable tar), and non-condensable gases, are presented in Table 2. The table shows that increasing the pyrolysis temperature decreased biochar yield, and a longer residence time likewise reduced it. The highest biochar yield was obtained at 300 °C for 60 minutes (63.27%), while the lowest yield occurred at 500 °C for 120 minutes (44.40%). In contrast, liquid smoke yield exhibited an opposite trend, increasing with higher pyrolysis temperatures and longer residence times

Therefore, the reduction in biochar weight and yield with increasing temperature and residence time indicates that more volatile matter contained in the *Eucalyptus pellita* bark was released, forming pyrolysis gases that exited through the condenser. These gaseous products were divided into two fractions: non-condensable gases and condensable gases. The condensable gases accumulated in the Erlenmeyer flask as liquid smoke, thereby increasing its weight and yield, while the biochar weight and yield decreased with rising temperature and longer pyrolysis duration.

The pyrolysis process occurs in two stages: primary pyrolysis, during which volatile compounds are released at lower temperatures, followed by secondary pyrolysis, which involves further cracking of volatile compounds and the formation of char (Abioye et al., 2025). In fast

Table 1. Physicochemical properties and analytical methods of biochar and soil samples

Parameters	Sample	Method/Instruments	References
Organic carbon (OC) and organic matter (OM)	Biochar	Gravimetric method	(Ministry of Agriculture of the Republic of Indonesia, 2023)
Organic Carbon (OC)	Soil	Walkley and Black method	
Total nitrogen (N)	Soil & Biochar	Kjeldahl-titrimetry method	
Total phosphorus (P)	Soil & Biochar	Spectrophotometric method	
Total potassium (K)	Soil & Biochar	Flame photometry method	
Calcium (Ca) and magnesium (Mg)	Soil & Biochar	Atomic absorption spectroscopy (AAS)	
Sulfur (S)	Biochar	Gravimetric method	
Boron (B)	Biochar	Spectrophotometric method	
Fe, Cu, Zn, Mn	Biochar	Atomic absorption spectroscopy (AAS)	
pH	Soil & Biochar	Electrometric method	
Bulk density	Soil & Biochar	Gravimetric method	
Particle density	Soil & Biochar	Pycnometer (flask method)	
Porosity	Soil & Biochar	Calculation	

pyrolysis, the formed vapors must be rapidly removed to maximize bio-oil yield; however, in slow pyrolysis, vapor removal is slower, allowing the vapor-phase components to continue reacting with each other, leading to a higher proportion of solid char relative to bio-oil, particularly at lower temperatures (< 500 °C) (Uzun et al., 2016). Biochar is generally assumed to form through solid-phase reactions in which devolatilized biomass leaves a carbonaceous residue (primary char). In contrast, in reality, it is also produced by the dehydration of primary pyrolysis products (secondary char) (Brown, 2015). The main pyrolysis products consist of gases (a mixture of CO, CO_2, H_2, and CH_4), H_2O, liquid bio-oil, and solid char (Liu et al., 2023).

$$\text{Biomass} \rightarrow \text{Gas}_{(1)} + \text{Tar}_{(1)} + \text{Char}_{(1)} \quad (1)$$

$$\text{Gas}_{(1)} + \text{Tar}_{(1)} + \text{Char}_{(1)} \rightarrow \text{Gas}_{(2)} + \text{Tar}_{(2)} + \text{Char}_{(2)} \quad (2)$$

Reactions during pyrolysis include both primary and secondary reactions, as shown in Reactions (1) and (2) (Song, 2016). During pyrolysis, biomass is heated to a specific temperature, causing the compounds within it to vaporize and release gases and vapors, while leaving behind char, which represents the primary reaction. In slow pyrolysis, the gases and vapors remain in the reactor for a longer time, allowing prolonged contact among the gas, vapor, and char, which subsequently undergo secondary reactions, forming the final products (gas, vapor, and char) with yields different from those produced in the primary stage.

Thus, increasing the temperature from 300 °C to 500 °C results in a lower biochar yield, as the additional formation of secondary char at higher temperatures is counterbalanced by further devolatilization of primary char (Ronsse et al., 2015). Similarly, longer residence times (60–120 minutes) enhance interactions among the formed gaseous and vapor-phase compounds and the biochar, thereby promoting the release of additional volatiles from the solid phase, which consequently decreases biochar yield but increases liquid smoke yield by generating more condensable and non-condensable gases. Although higher temperatures reduce biochar yield and increase liquid smoke yield, the biochar yield remains dominant, ranging from 44.40% to 63.27%, compared to the lower liquid smoke yield of 14.09% to 24.40%.

These findings are consistent with other studies reporting a decrease in biochar yield with increasing pyrolysis temperature. For instance, Sen et al. (2023) observed biochar yields ranging from 29–42% from phloem bark (*Quercus cerris*) pyrolyzed between 400–500 °C; Wang et al. (2020) reported yields of 21.4–41.3% from corn stalks pyrolyzed for 2 hours at 300–700 °C; and Fernandes et al. (2020) obtained yields of 32.44–42.76% from *Eucalyptus urophylla* and *Eucalyptus grandis* wood pyrolyzed for 1 hour at 450–950 °C.

Similarly, studies focusing on residence time also support the observed trend of decreasing biochar yield with prolonged pyrolysis duration. For example, Wang et al. (2020) found biochar yields ranging from 23.7–28.4% for corn stalks pyrolyzed at 500 °C for 1–4 hours, while Sen et al. (2023)

Table 2. Mass and yields of products obtained from the pyrolysis process

No.	Temperature (°C)	Residence time (minutes)	$m_{biochar}$ (g)	$m_{liquid\ smoke}$ (g)	m_{gas} (g)	$Y_{biochar}$ (%)	$Y_{liquid\ smoke}$ (%)	Y_{gas} (%)
1	300	60	189.80±9.58	42.27±6.26	67.93	63.27±3.19	14.09±2.09	22.64
2	400	60	156.20±3.27	53.20±5.09	90.60	52.07±1.09	17.73±1.70	30.20
3	500	60	146.80±2.95	54.04±5.02	99.16	48.93±0.98	18.01±1.67	33.05
4	300	90	176.00±6.00	47.06±6.84	76.94	58.67±2.00	15.69±2.28	25.65
5	400	90	152.31±1.79	54.68±5.96	93.00	50.77±0.60	18.23±1.99	31.00
6	500	90	143.80±5.54	58.60±8.53	97.60	47.93±1.85	19.53±2.84	32.53
7	300	120	175.00±4.12	51.64±7.80	73.36	58.33±1.37	17.21±2.60	24.45
8	400	120	143.80±2.77	55.19±8.01	101.01	47.93±0.92	18.40±2.67	33.67
9	500	120	133.20±2.77	73.20±9.57	93.60	44.40±0.92	24.40±3.19	31.20

Note: Results are expressed as mean ± standard deviation (n = 5). The initial feedstock mass ($m_{feedstock}$) was fixed at 300 g for all runs. m_{gas} and Y_{gas} were calculated by difference.

reported yields of 28–33% for *Quercus cerris* bark pyrolyzed at 500 °C for 30–150 minutes.

Hemicellulose decomposes first, beginning at around 220 °C and nearly completing at 315 °C; cellulose begins to decompose at approximately 315 °C and is almost entirely converted into non-condensable gases and condensable vapors by 400 °C; whereas lignin starts to decompose at 160 °C but proceeds slowly and gradually up to 900 °C (Brown, 2015). Above 450 °C, lignin decomposition becomes the predominant reaction (Uzun et al., 2016), which accounts for the increased liquid smoke yield observed at 500 °C and 120 minutes.

Analysis of biochar characteristics

Chemical characterization of biochar

The organic carbon (OC) value was obtained by converting the organic matter (OM) content; therefore, OC is closely related to the OM content in biochar. Table 3 shows that increasing the pyrolysis temperature and residence time decreases the OC content of biochar. Biomass contains volatile matter, including small, labile organic compounds (Ronsse et al., 2015). The pyrolysis process releases volatile matter, reducing both OM and OC. This decrease is also attributed to increased formation of aromatic ring structures in biochar at higher pyrolysis temperatures (Mutolib et al., 2023) and to a reduction in aliphatic C groups (Peng et al., 2011). Pyrolysis volatilizes aliphatic groups, and the high degree of aromatization increases biochar's resistance to microbial decomposition (Jindo and Sonoki, 2019). Consequently, lower pyrolysis temperatures produce higher OC values because aliphatic carbon remains relatively abundant, whereas at higher temperatures aromatic carbon structures become more dominant.

This trend is consistent with the findings of Lu et al. (2021), who reported that total carbon in biochar derived from *S. superba* decreased with increasing pyrolysis temperature from 350–750 °C, with total C declining from 606.4 g/kg to 562.4 g/kg. Similarly, the study by Khanmohammadi et al. (2015) using sewage sludge as a feedstock showed a decrease in TOC with increasing pyrolysis temperature from 300 to 700 °C over 2 hours, with TOC decreasing from 34 g/100 g at 300 °C to 25.1 g/100 g at 700 °C. Research by Kujawska et al. (2024) also demonstrated a similar trend for sewage sludge biochar, where TOC decreased from 32.33% at 400 °C to 17.89% at 800 °C.

Macronutrients consist of N, P, K, Ca, Mg, and S. As shown in Table 3, the biochar products exhibited higher contents of N, K, and Ca, while S, P, and Mg contents were lower. Table 3 shows that increasing the pyrolysis temperature (from 300 to 500 °C) and residence time (from 60 to 120 minutes) generally increases the concentrations of Ca, K, and P in biochar, but tends to decrease the concentrations of N and S.

The highest Ca, Mg, and P contents were obtained at 500 °C and 120 minutes, 1,488.91, 199.33, and 66.55 mg/100 g, respectively, while the highest K content, 811.76 mg/100 g, was observed at 500 °C and 60 minutes. Conversely, the highest N and S contents were recorded at 300 °C and 90 minutes, amounting to 603.47 and 113.63 mg/100 g, respectively.

These findings are consistent with studies by Saletnik et al. (2022), who used *Quercus petraea* bark at 450–950 °C for 1 hour, and Wang et al.

Table 3. Organic carbon, organic matter, and macronutrient contents of biochar and *Eucalyptus pellita* Bark

No.	Temperature (°C)	Residence time (minutes)	Organic carbon (%)	Organic Matter (%)	N (mg/100 g)	P (mg/100 g)	K (mg/ 100 g)	Ca (mg/100 g)	Mg (mg/100 g)	S (mg/100 g)
1	*Eucalyptus pellita* bark (Raw material)		35.94	64.17	582.69	46.65	366.83	1,044.61	106.69	32.58
2	300	60	31.07	55.48	573.96	54.92	431.23	903.23	100.36	96.55
3	400	60	34.03	60.76	536.26	57.28	550.12	1,234.89	135.64	80.55
4	500	60	28.82	51.47	470.14	64.42	811.76	1,300.91	145.33	72.44
5	300	90	32.86	58.69	603.47	57.43	590.21	1,142.65	127.38	113.63
6	400	90	28.09	50.16	514.35	61.98	655.17	1,278.89	153.04	7.77
7	500	90	28.72	51.29	474.18	65.15	613,53	1,326.27	145.26	59.95
8	300	120	30.59	54.62	579.66	54.33	409.62	995.25	110.36	7.83
9	400	120	31.71	56.63	512.92	61.60	618.82	1,178.13	131.56	91.12
10	500	120	28.81	51.45	515.55	66.50	674.13	1,488.91	199.33	84.36

(2020), who used corn stalks at 300–700 °C for 1–4 hours. Both studies demonstrated that the contents of Ca, Mg, P, and K increased with temperature. The enrichment of these inorganic elements with increasing temperature and residence time is attributed to the enrichment of inorganic compounds during pyrolysis (Xiao et al., 2018). Enrichment refers to the relative increase in the concentration of elements or compounds in biochar due to the reduction of total organic mass during pyrolysis. In contrast, the decrease in N content with increasing temperature can be attributed to the volatilization of nitrogen-containing compounds produced during amino acid decomposition (Xiao et al., 2018).

Therefore, it can be concluded that pyrolysis temperature exerts a greater influence on the enhancement of macronutrient content, as the highest levels of K, Ca, Mg, and P were obtained at 500 °C. Pyrolysis duration also plays a role, particularly in increasing the concentrations of P, Ca, and Mg, with the highest values observed at 120 minutes.

The analysed micronutrients included B, Fe, Cu, Zn, and Mn. As shown in Table 4, Fe and Mn exhibited the highest concentrations among the micronutrients, while B, Zn, and Cu showed lower concentrations. The table indicates that increasing the pyrolysis temperature from 300 to 500 °C generally increased micronutrient contents in biochar. Similarly, extending the residence time from 60 to 90 minutes increased micronutrient concentrations, but a decline was observed at 120 minutes, with the highest levels of Fe, Mn, B, Zn, and Cu at 500 °C. Prolonging the pyrolysis time also increased micronutrient contents up to 90 minutes; however, at 120 minutes, a decline was observed.

Table 4 shows that pyrolysis increased the pH of biochar. The raw *Eucalyptus pellita* bark exhibited an acidic pH of 6.15, while the pH of the resulting biochars ranged from 7.15 to 8.28. An increase in temperature from 300 to 400 °C raised biochar pH, particularly at 60 and 90 minutes; however, a slight decrease was observed at 500 °C. Extending the residence time from 60 to 120 minutes generally increased the pH, especially at 500 °C, although different trends were observed at 300 °C and 400 °C. At 300 °C, the pH increased from 60 to 90 minutes but decreased at 120 minutes. In contrast, at 400 °C, the pH continuously decreased from 60 to 120 minutes. The highest pH (8.28) was obtained at 500 °C and 120 minutes, while the lowest pH was observed at 300 °C and 60 minutes.

Thus, increasing the temperature from 300 to 400 °C and extending the time from 60 to 90 minutes generally raised biochar pH, while longer durations (120 minutes) caused a decline, except at high temperatures (500 °C), where both longer time and high temperature produced the highest pH. This finding is consistent with the study by Wang et al. (2020), who observed an increase in pH with rising temperature and time (300–700 °C, 1–4 hours) during corn stalk pyrolysis, followed by a decline at longer durations (4 hours).

The increase in temperature enhances the ash (inorganic) content of biochar, contributing to higher pH values at elevated temperatures (Ronsse et al., 2015). As discussed in the previous paragraph, the enrichment of macronutrients in biochar further contributes to the rise in pH, reflecting the accumulation of inorganic compounds as pyrolysis temperature and residence time increase. The rise in alkaline

Table 4. Micronutrient contents and pH of Biochar and *Eucalyptus pellita* bark

No.	Temperature (°C)	Residence time (minutes)	B (ppm)	Fe (ppm)	Cu (ppm)	Zn (ppm)	Mn (ppm)	pH
1	*Eucalyptus pellita* bark (Raw material)		21.98	11,597.41	7.81	17.03	507.59	6,15
2	300	60	26.45	14,119.44	6.12	21.80	571.49	7.15
3	400	60	25.45	16,883.51	7.41	23.26	620.85	8.45
4	500	60	30.45	18,670.51	8.20	26.63	619.56	8.08
5	300	90	26.42	12,499.38	6.43	22.90	593.88	7.53
6	400	90	29.47	17,977.84	8.78	21.04	638.40	8.27
7	500	90	30.12	19,032.52	8.67	23.18	731.92	8.21
8	300	120	27.21	13,656.32	5.95	22.60	538.59	7.37
9	400	120	29.79	12,843.82	7.98	22.67	609.34	8.19
10	500	120	27.43	15,690.09	7.98	25.06	663.56	8.28

constituents, particularly Ca, Mg, and K, plays a key role in elevating biochar pH (Houben et al., 2013). Consistent with this, Table 3 shows that the concentrations of Ca, Mg, and K increase with higher temperatures and longer residence times during pyrolysis.

Physical characterization of biochar

The biochar used in this study was sieved using a 30-mesh sieve, producing finer biochar with a particle size of 595 µm. Table 5 shows that the pyrolysis process increases bulk density while decreasing porosity. Therefore, the findings of this study indicate that pyrolysis alters the physical structure of the biomass, specifically *Eucalyptus pellita* bark, which initially has a lower bulk density, into a biochar product with higher bulk density, while reducing the porosity of the original biomass, which is initially higher than that of the resulting biochar.

This result is consistent with the findings of González-Prieto et al. (2024), who reported that biochar had a higher bulk density than the raw biomass. Their study, conducted at 400–500 °C for 280 minutes using *P. pinaster*, showed an increase in bulk density from 115.5 kg/m^3 (biomass) to 147.0 kg/m^3 (biochar). Likewise, for *E. globulus*, bulk density increased from 91.3 kg/m^3 to 104.5 kg/m^3 after pyrolysis.

A study conducted by Bera et al. (2014) using mustard stem as feedstock at pyrolysis temperatures of 400–600 °C also demonstrated that increasing temperature raised both bulk density and particle density, with values ranging from 0.135–0.152 g/cc and 0.40–0.65 g/cc, respectively. Similarly, research by Khanmohammadi et al. (2015) using sewage sludge at pyrolysis temperatures of 300–700 °C for 2 hours reported an increase in particle density with increasing temperature, ranging from 1.81–2.16 Mg/m^3, while bulk density increased between 300–500 °C with values ranging from 0.62–0.64 Mg/m^3. The dissociation and/or volatilization of organic components at higher pyrolysis temperatures increases the proportion of mineral matter, thereby raising particle density (Khanmohammadi et al., 2015).

With increasing pyrolysis temperature, most volatiles are released from the biomass, leading to deformation of particle surfaces; however, no significant morphological changes occur except the formation of cracks and new pores. The lignocellulosic structure of biomass generally remains intact during pyrolysis (Uzun et al., 2016), indicating that pyrolysis affects the resulting biochar's physical characteristics. However, different biomass types may undergo distinct physical transformations. During pyrolysis, the biochar surface morphology becomes rougher and displays larger pore openings as organic components decompose, with the resulting gas molecules expanding the biochar's pore structure (Jamilatun et al., 2022).

Table 5 shows that increasing the pyrolysis temperature from 300 to 500 °C and extending the residence time from 60 to 120 minutes increases both bulk density and particle density while reducing porosity. The 30-mesh sieve used in this study produced biochar particles smaller than 595 µm. Higher pyrolysis temperatures and longer residence times also yield biochar that is more easily ground, as volatile matter is more readily devolatilized during pyrolysis (Zhang et al., 2020).

Higher pyrolysis temperatures and longer residence times produce finer biochar particles, which pack more densely and fill interparticle pores, thereby increasing bulk density and reducing porosity. Mensah et al. (2024) reported that fine biochar (100–200 µm) derived from waste wood exhibits a density of 1.9 g/cm³, while coarse biochar (1.5–3.5 mm) exhibits a density of 1.58 g/cm³.

Analysis of soil-biochar mixtures

Chemical characterization of soil-biochar mixtures

Table 8 shows that increasing the biochar application rate from 2.5% to 5% and then to 10% increased the soil OC content. According to the technical guidelines for chemical analysis of soil, plant, water, and Fertilizer issued by the Ministry of Agriculture of the Republic of Indonesia (2023), in Table 6, the control loamy sand soil (without biochar) is categorized as having a "Low" C (carbon) content. The addition of biochar increased the soil's C level to the "Moderate" or "High" category. A 2.5% biochar application elevated the soil to the "Moderate" category for all biochar produced at 300, 400, and 500 °C. At the 10% biochar dose, all biochar (300, 400, and 500 °C) raised the soil to the "High" C category.

The highest OC value in the soil was observed in the treatment amended with 10% biochar produced at 300 °C with a residence time of 120 minutes. As previously explained in the section Chemical Characterization of Biochar, the OC content of biochar is influenced by pyrolysis temperature, with higher temperatures promoting the formation of aromatic C and reducing aliphatic C (Peng et al., 2011). Therefore, biochar produced at lower temperatures contains a higher proportion of aliphatic C and consequently exhibits higher OC content.

Nevertheless, the application of biochar produced at 500 °C at a 10% dose also increased soil OC compared with the 2.5% and 5% doses. The increase in OC at the 2.5% biochar dose ranged from 22.21% to 34.34%, whereas at the 10% dose, the increase was substantially higher, ranging from 153.64% to 84.61% compared with the control soil without biochar.

The observed trend demonstrates that the biochar application rate strongly influences soil OC, as the dose determines the magnitude of carbon input to the soil. Meanwhile, the OC content of the biochar itself is determined by the pyrolysis temperature. Biochar produced at lower temperatures has a higher OC content than that produced at higher temperatures, because aromatic structures form during pyrolysis.

This finding is consistent with the study by Chen et al. (2024), who used corn straw biochar produced at 350 °C and applied at rates of 0%, 1%, 2.5%, 5%, and 10%. Their results showed that higher biochar application rates led to greater increases in soil organic carbon, with the highest OC observed at the 10% dose. Similarly, Torgbenu et al. (2025) reported that applying 5 kg/plot (3 × 1 m) of coconut husk and sugarcane bagasse biochars (produced at 500 °C and 210 °C, respectively) increased soil OC by approximately 166.7%–216.7%.

Table 8 shows that increasing the biochar application rate from 2.5% to 5% to 10% resulted in higher soil pH values. According to the Technical Guidelines for Chemical Analysis of Soil, Plant, Water, and Fertilizer issued by the Ministry of

Table 5. Bulk density, particle density, and porosity of *Eucalyptus pellita* bark feedstock and biochar products

No.	Temperature (°C)	Residence time (minutes)	Bulk density (g/cm³)	Particle density (g/cm³)	Porosity (%)
1	*Eucalyptus pellita* bark (Raw material)		0.27	1.82	85.16%
2	300	60	0.27	1.65	83.64%
3	400	60	0.30	1.75	82.86%
4	500	60	0.32	1.83	82.51%
5	300	90	0.28	1.75	84.00%
6	400	90	0.30	1.85	83.78%
7	500	90	0.33	1.87	82.35%
8	300	120	0.30	1.61	81.37%
9	400	120	0.29	1.79	83.80%
10	500	120	0.33	1.79	81.56%

Table 6. Evaluation criteria for soil parameters (C, N, P, and K)

No.	Soil parameter	Category				
		Very Low	Low	Moderate	High	Very high
1	C (%)	<1	1–2	2–3	3–5	>5
2	N (%)	<0.1	0.1–0.2	0.21–0.5	0.51–0.75	>0.75
3	P_2O_5 HCl 25% (mg/100 g)	<15	15–20	21–40	41–60	>60
4	K_2O HCl 25% (mg/100 g)	<10	10–20	21–40	41–60	>60

Note: Ministry of Agriculture of the Republic of Indonesia (2023), Technical Guidelines for Chemical Analysis of Soil, Plant, Water, and Fertilizer.

Table 7. Evaluation criteria for Soil pH

No.	Soil parameter	Category					
		Very acidic	Acidic	Slightly acidic	Neutral	Slightly alkaline	Alkaline
1	pH	<4.5	4.5–5.5	5.5–6.5	6.6–7.5	7.6–8.5	>8.5

Note: Ministry of Agriculture of the Republic of Indonesia (2023), Technical Guidelines for Chemical Analysis of Soil, Plant, Water, and Fertilizer.

Table 8. OC and pH of soil, biochar, and soil-biochar mixtures, with evaluation criteria based on the technical guidelines for chemical analysis of soil, plant, water, and fertilizer (Ministry of Agriculture of the Republic of Indonesia, 2023)

No.	Type of biochar*	Biochar dosage (%)	OC (%)	OC evaluation category in soil	pH	pH evaluation category in soil
1	BC-300-120	-	30.59	-	7.37	-
2	BC-400-120	-	31.71	-	8.19	-
3	BC-500-120	-	28.81	-	8.28	-
4	S (Control)	0	1.82	Low	4.17	Very acidic
5	S-BC-300-120	2.5%	2.44	Moderate	4.99	Acidic
6	S-BC-400-120	2.5%	2.22	Moderate	5.07	Acidic
7	S-BC-500-120	2.5%	2.33	Moderate	4.69	Acidic
8	S-BC-300-120	5%	3.28	High	5.14	Acidic
9	S-BC-400-120	5%	1.94	Low	5.12	Acidic
10	S-BC-500-120	5%	2.36	Moderate	5.51	Slightly acidic
11	S-BC-300-120	10%	4.61	High	5.75	Slightly acidic
12	S-BC-400-120	10%	3.17	High	5.78	Slightly acidic
13	S-BC-500-120	10%	3.35	High	5.25	Slightly acidic

Note: *on sample codes under the "Type of Biochar" column: For biochar samples: BC–Pyrolysis Temperature–Residence Time. For soil–biochar mixture samples: S–BC–Pyrolysis Temperature–Residence Time. The pyrolysis temperature is expressed in degrees Celsius (°C). The residence time is expressed in minutes (min).

Agriculture of the Republic of Indonesia (2023), in Table 7, the control soil (without biochar) was categorized as "Very Acidic" with a pH. The addition of biochar improved soil pH, shifting it to the "Acidic" and "Slightly Acidic" categories.

A 2.5% biochar application produced "Acidic" soil across all biochar types (300, 400, and 500 °C). At the 5% application rate, the resulting pH ranged from "Acidic" to "Slightly Acidic": biochars produced at 300 °C and 400 °C yielded "Acidic" soils, and biochar produced at 500 °C yielded "Slightly Acidic" soil. Meanwhile, applying 10% biochar produced "Slightly Acidic" soils across all pyrolysis temperatures (300, 400, and 500 °C).

The increase in soil pH following biochar addition can be attributed to the alkaline nature of the biochars, which had pH values of 7.37, 8.19, and 8.28 for biochars produced at 300 °C, 400 °C, and 500 °C, respectively. In contrast, the control soil exhibited a very acidic pH of 4.17. Therefore, increasing biochar application rates from 2.5% to 10%, regardless of temperature (300–500 °C), effectively raised the soil pH, with the highest pH observed at the 10% application rate representing an increase of approximately 25.90–38.61% compared to the control loamy sand soil.

The increase in pH is caused by the rise in alkaline cations such as Ca, Mg, and K during the pyrolysis process (Domingues et al., 2020), which become increasingly concentrated within the ash fraction of the biochar (Houben et al., 2013), ultimately enabling biochar to exhibit a liming effect when incorporated into soil.

These results are consistent with those of Domingues et al. (2020), who studied biochars derived from chicken manure and coffee husks, produced at 350, 450, and 750 °C, and applied at rates of 0%, 5%, 10%, 15%, and 20%. Their results showed that increasing biochar application rates enhanced soil pH, with the highest pH values (9.2 and 10.0 for chicken manure and coffee husk biochars, respectively) obtained at 20% biochar applied at 750 °C, compared to the control soil with a pH of 4.6. Similarly, Liu et al. (2024) reported that applying rice husk biochar produced at 450 °C for 4 hours at rates of 0%, 10%, and 20% increased soil pH proportionally with dosage, achieving a 4.84% increase at the 20% rate.

Table 9 and Table 10 show that increasing the biochar application rate from 2.5% to 5% and then to 10% increased the soil contents of N, P, K, Ca, and Mg. According to the Technical Guidelines for Chemical Analysis of Soil, Plant, Water, and Fertilizer (Ministry of Agriculture of the Republic of Indonesia, 2023), the control loamy sand soil (without biochar) is classified as having "Very Low" Nitrogen (N) and Potassium (K) contents, "Low" Calcium (Ca) and Magnesium (Mg) contents, and "Moderate" Phosphorus (P) content.

The addition of biochar at 2.5%, 5%, and 10% improved soil nutrient status, with Ca, P, and K reaching the "Very High" category and N and Mg reaching the "Moderate" category at the 10% rate. The highest Ca, P, K, and Mg contents were obtained from biochar produced at 500 °C with a residence time of 120 minutes, as described in Section Chemical Characterization of Biochar. Increasing pyrolysis temperature enriches the inorganic fraction of biochar, particularly P, K, Ca, and Mg, because more mineral constituents remain after thermal decomposition. Consequently, high-dose biochar application (e.g., 10%) substantially enhanced

Table 9. N, P, and K contents of soil, biochar, and soil–biochar mixtures, with evaluation criteria based on the technical guidelines for chemical analysis of soil, plant, water, and fertilizer (Ministry of Agriculture of the Republic of Indonesia, 2023)

No.	Type of biochar*	Biochar dosage (%)	N (mg/100g)	N Evaluation category in soil	P (mg/100 g)	P Evaluation category in soil	K (mg/100 g)	K Evaluation category in soil
1	BC-300-120	-	579.66	-	54.33	-	409.62	-
2	BC-400-120	-	512.92	-	61.60	-	618.82	-
3	BC-500-120	-	515.55	-	66.50	-	674.13	-
4	S (Control)	0	71.54	Very low	40.88	Moderate	6.59	Very low
5	S-BC-300-120	2.5%	173.73	Low	39.43	Moderate	11.54	Low
6	S-BC-400-120	2.5%	179.70	Low	45.80	High	11.99	Low
7	S-BC-500-120	2.5%	176.73	Low	47.83	High	11.66	Low
8	S-BC-300-120	5%	166.18	Low	40.39	Moderate	13.14	Low
9	S-BC-400-120	5%	191.75	Low	43.20	High	29.05	Moderate
10	S-BC-500-120	5%	180.41	Low	47.07	High	32.91	Moderate
11	S-BC-300-120	10%	203.24	Low	48.69	High	49.91	High
12	S-BC-400-120	10%	178.15	Low	47.69	High	74.11	Very high
13	S-BC-500-120	10%	241.06	Moderate	77.12	Very high	99.95	Very high

Note: *on sample codes under the "Type of Biochar" column: For biochar samples: BC–Pyrolysis Temperature–Residence Time. For soil–biochar mixture samples: S–BC–Pyrolysis Temperature–Residence Time. The pyrolysis temperature is expressed in degrees Celsius (°C). The residence time is expressed in minutes (min).

Table 10. Ca and Mg contents of soil, biochar, and soil–biochar mixtures, with evaluation criteria based on the technical guidelines for chemical analysis of soil, plant, water, and fertilizer (Ministry of Agriculture of the Republic of Indonesia, 2023)

No.	Type of biochar*	Biochar dosage (%)	Ca (mg/100 g)	Ca evaluation category in soil	Mg (mg/100 g)	Mg evaluation category in soil
1	BC-300-120	-	995.25	-	110.36	-
2	BC-400-120	-	1,178.13	-	131.56	-
3	BC-500-120	-	1,488.91	-	199.33	-
4	S (Control)	0	13.34	Low	14.04	Low
5	S-BC-300-120	2.5%	45.40	High	14.01	Low
6	S-BC-400-120	2.5%	57.62	High	18.31	Low
7	S-BC-500-120	2.5%	55.43	High	16.67	Low
8	S-BC-300-120	5%	74.59	Very high	16.67	Low
9	S-BC-400-120	5%	89.73	Very high	19.61	Low
10	S-BC-500-120	5%	97.86	Very high	20.60	Low
11	S-BC-300-120	10%	149.28	Very high	25.15	Moderate
12	S-BC-400-120	10%	196.03	Very high	29.28	Moderate
13	S-BC-500-120	10%	206.22	Very high	36.47	Moderate

Note: *on sample codes under the "Type of Biochar" column: For biochar samples: BC–Pyrolysis Temperature–Residence Time. For soil–biochar mixture samples: S–BC–Pyrolysis Temperature–Residence Time. The pyrolysis temperature is expressed in degrees Celsius (°C). The residence time is expressed in minutes (min).

soil macronutrient levels, especially in soils with initially very low nutrient status.

The highest soil nitrogen content was observed in soil amended with biochar produced at 500 °C and applied at 10%. These results suggest that increasing the biochar application rate and pyrolysis temperature enhanced soil nitrogen content by combining nitrogen input from biochar with improved retention of native soil nitrogen. The capacity of biochar to adsorb ammonium and nitrate and to regulate nitrogen mineralization processes has been reported to reduce nitrogen losses and enhance nitrogen retention in soil systems (Jin et al., 2016).

These findings are consistent with those of Chen et al. (2024), who reported that increasing the application rate of corn straw biochar (0–10%) produced at 350 °C significantly enhanced total N, P, and K, with the highest values observed at the 10% rate. Similarly, Mielke et al. (2022) demonstrated that the application of sugarcane straw biochar produced at 350–750 °C increased soil P, K, Ca, and Mg contents, with the 10% dose resulting in the greatest increases compared with the control soil.

Physical characterization of soil–biochar mixtures

Table 11 shows that increasing the biochar application rate from 2.5% to 5% and then to 10% reduces soil bulk density while increasing soil porosity. The bulk density of the control loamy sand soil (without biochar) was higher at 1.50 g/cm³, compared to the soil–biochar mixtures, which exhibited lower bulk densities ranging from 0.94–1.22 g/cm³. Conversely, the control soil had lower porosity (38.95%) than the biochar-amended soils, which had higher porosity values ranging from 52.97 to 71.16%.

This decrease in bulk density and increase in porosity of biochar-amended soils can be attributed to the much lower bulk density (0.29–0.33 g/cm³) and substantially higher porosity (81.37–83.80%) of biochar compared to the control loamy sand soil (bulk density 1.50 g/cm³, porosity 38.95%).

Based on Table 11, increasing the biochar dosage from 2.5% to 10% consistently decreased bulk density and increased porosity. The highest bulk density and lowest porosity were observed in soil amended with 2.5% biochar, while the lowest bulk density and highest porosity were found in soil amended with 10% biochar. The lowest bulk density (0.94 g/cm³) was recorded in soil mixed with biochar produced at 400 °C for 120 minutes and applied at a 10% rate. This outcome is consistent with the bulk density of the biochar itself, which was lowest at 0.29 g/cm³ for biochar produced at 400 °C and 120 minutes, compared to 0.30 g/cm³

Table 11. Bulk density and porosity of soil, biochar, and soil-biochar mixtures

No.	Type of biochar*	Biochar dosage (%)	Bulk density (g/cm³)	Porosity (%)
1	BC-300-120	-	0.30	81.37
2	BC-400-120	-	0.29	83.80
3	BC-500-120	-	0.33	81.56
4	S (Control)	0	1.50	38.95
5	S-BC-300-120	2.5%	1.15	52.97
6	S-BC-400-120	2.5%	1.17	54.96
7	S-BC-500-120	2.5%	1.22	54.70
8	S-BC-300-120	5%	1.00	60.93
9	S-BC-400-120	5%	1.07	57.42
10	S-BC-500-120	5%	0.96	62.67
11	S-BC-300-120	10%	1.07	55.26
12	S-BC-400-120	10%	0.94	61.16
13	S-BC-500-120	10%	1.14	57.25

Note: *on sample codes under the "Type of Biochar" column: For biochar samples: BC–Pyrolysis Temperature–Residence Time. For soil–biochar mixture samples: S–BC–Pyrolysis Temperature–Residence Time. The pyrolysis temperature is expressed in degrees Celsius (°C). The residence time is expressed in minutes (min).

and 0.33 g/cm³ for biochars produced at 300 °C and 500 °C, respectively. The reduction in bulk density ranged from 18.60% to 22.79% at the 2.5% biochar rate and from 23.57% to 28.36% at the 10% rate, compared with the control soil. Meanwhiwle, the increase in porosity ranged from 35.98% to 41.09% at 2.5% and from 41.86% to 46.96% at 10%.

These results align with the findings of Morim et al. (2024), who studied Acacia longifolia wood biochar produced at 450 and 550 °C and applied at rates of 0%, 3%, 6%, and 10%. They observed a decrease in bulk density by 8–51% at 6% and 10% biochar rates, with reductions proportional to the increase in biochar dosage. Similarly, Sadowska et al. (2023) reported that sunflower husk biochar (produced at 440–480 °C) applied at rates of 0, 40, 60, and 80 t/ha reduced soil bulk density, with bulk density values of 1.523 Mg/dm³ (control) and 1.226 Mg/dm³ (at 80 t/ha). Furthermore, biochar with smaller particle sizes can more effectively reduce soil bulk density, as finer particles fill soil pores more efficiently than coarser biochar particles (Torgbenu et al., 2025). Lower bulk density and higher porosity indicate a greater number of pore spaces within the material. Thus, incorporating biochar into the soil increases the number of pores, resulting in reduced bulk density and enhanced porosity in the soil–biochar mixture compared to the control soil.

CONCLUSIONS

Biochar produced from *Eucalyptus pellita* bark showed decreasing yields, organic carbon (OC), and organic matter (OM) contents as pyrolysis temperature increased from 300 to 500 °C and residence time increased from 60 to 120 minutes. Higher temperatures and longer residence times increased ash-derived macronutrients and micronutrients, elevated pH, and resulted in higher bulk density and lower porosity. When applied to loamy sand soil, increasing biochar doses from 2.5% to 10% enhanced soil OC, with the highest carbon input obtained at the 10% dose using biochar produced at 300 °C. Soil N, P, K, Ca, and Mg concentrations also increased, with the most significant values observed in loamy sand soil amended with biochar produced at 500 °C at the 10% dose. Increasing the biochar dose reduced the bulk density of the loamy sand soil and increased its porosity, with the lowest bulk density observed at a 10% biochar application produced at 400 °C.

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