Research Article
doi: 10.1590/01047760202632013665
vol(32), 2026

CERNE

How does pyrolysis temperature influence the physicochemical properties of biochar from *Coffea canephora* husk?

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TECHNOLOGY OF FOREST PRODUCTS

ABSTRACT

Background: Coffee cultivation is one of the most important agricultural activities in Brazil and generates large amounts of waste during fruit processing. Approximately 93% of the coffee fruit volume is discarded, with the husk being one of the main by-products. Inadequate disposal may cause environmental impacts, whereas its valorization through pyrolysis can provide a sustainable and value-added alternative. This study evaluated the effect of pyrolysis temperature (400, 600, and 800 °C) on the physicochemical properties of biochar produced from coffee husk, aiming at its use as a soil conditioner.

Results: The biomass was subjected to controlled pyrolysis in a muffle furnace at a heating rate of 5 $°C.min^{-1}$ and a residence time of one hour after reaching the final temperature. The resulting biochar was characterized for co-product yield, bulk density, chemical composition (ash, volatiles, and fixed carbon), and pH. Increasing the pyrolysis temperature reduced biochar yield and density, while increasing fixed carbon content. Fixed carbon increased from 67% at 400 °C to 77% at 800 °C, whereas volatile content decreased from 25% to 10%. The pH decreased up to 600 °C and increased at 800 °C.

Conclusions: Pyrolysis temperature strongly influences biochar properties, requiring a balance between yield and quality according to the intended application. Although all evaluated temperatures were technically feasible, biochar produced at 800 °C showed the greatest potential for long-term application in tropical acidic soils.

Keywords: *Agro-industrial waste; Biomass; Sustainability; Coffee husks.*

HIGHLIGHTS

Pyrolysis temperature alters *Coffea canephora* husk biochar yield and quality.
Biochar at 800 °C has higher fixed carbon, favoring long-term soil use.
Biochar at 400 °C has higher density and volatiles for faster nutrient release.
Coffee husk biochar supports circular economy and reduces environmental impacts.

PIMENTEL, L. M.; DELATORRE, F. M.; CUPERTINO, G. F. M.; MANJATE, M. J.; SILVA, Á. M.; OLIVEIRA, T. R.; CRUZ, B. S.; PROTÁSIO, T. P.; DIAS JÚNIOR, A. F. How does pyrolysis temperature influence the physicochemical properties of biochar from *Coffea canephora* husk? CERNE, v. 32, e103665, 2026. DOI: 10.1590/01047760202632013665.

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Scientific Editor: Amelia Guimaraes Carvalho

Received: November 03 2025
Accepted: April 21 2026

CERNE
ISSN 0104-7760

INTRODUCTION

Coffee is one of the most relevant agricultural commodities in the world, driving extensive economic and social chains. In the 2024/2025 harvest, global production was estimated at approximately 174 million 60kg bags, with Brazil responsible for around 70 million, accounting for nearly 37% of global production (Boschiero, 2023; USDA, 2024). This significant representation establishes the country as the world's leading producer and exporter, supporting a strongly structured industry that encompasses both small and large producers. However, the robustness of this production chain contrasts with the high generation of waste. It is estimated that approximately 93% of the total weight of the coffee fruit consists of by-products such as husk, pulp, and mucilage (Herrera, 2021; Hoseini *et al*., 2021). Coffee processing methods, including dry and wet routes, generate different types and proportions of residues. In wet processing, husk and pulp represent 43.2 wt% of the whole fruit, followed by mucilage and soluble sugars (11.8 wt%, without fermentation) and parchment (6.1 wt%) (Esquivel; Jiménez, 2012). Among these residues, coffee husk stands out as the most abundant fraction. It is estimated that around 10 million tons of coffee husk are generated worldwide annually, much of which is discarded without proper treatment (Tamilselvan *et al*., 2024). Such practices can lead to significant environmental impacts, including soil and water contamination, as well as greenhouse gas emissions.

Paradoxically, the chemical composition of coffee husk, rich in lignin, cellulose, and hemicellulose, highlights its potential as a raw material for technological valorization processes (Hoseini *et al*., 2021). This compositional profile has encouraged the development of pathways capable of converting this waste into higher value-added products, contributing to the mitigation of environmental impacts and the strengthening of more sustainable production chains (Afessa *et al*., 2024; Nguyen *et al*., 2023). Thus, what was once considered an environmental liability is now recognized as a strategic opportunity within the principles of the circular economy. The utilization of coffee production waste can promote industrial symbiosis models, in which the waste of one sector is converted into raw material for another, favoring resource efficiency and waste reduction (Tayibi *et al*., 2021). In this context, the valorization of coffee husk represents a promising path for the integration of environmental sustainability, technological innovation, and the generation of economic value. Among the available routes, pyrolysis has emerged as one of the most efficient alternatives. It is a thermochemical process that promotes the decomposition of biomass under controlled conditions and with limited oxygen presence, resulting in three main products: gases, bio-oil, and biochar (Cupertino *et al*., 2024; Silva *et al*., 2023).

Among the products obtained through pyrolysis, biochar has gained prominence in the scientific community. As the solid fraction of the process, it is a carbonaceous material with a porous structure and high chemical stability, whose properties depend on the nature of the biomass and the pyrolysis parameters employed (Mahmood *et al*., 2025). When incorporated into the soil, it acts as a multifunctional conditioner, promoting greater water retention, pH correction, and increased nutrient availability (Bolan *et al*., 2024; Ighalo *et al*., 2025; Torres *et al*., 2023). In tropical soils, often degraded and of low fertility, these effects contribute to the rehabilitation and enhancement of agricultural productivity (Basak *et al*., 2022). Furthermore, the stable carbon present in its structure gives biochar a significant role in mitigating climate change, as it remains in the soil for long periods (Shoudho *et al*., 2024). This combination of properties makes biochar a promising technological solution, capable of transforming agroindustrial waste into valuable resources and supporting the transition from a linear production model to a low-carbon circular economy.

To fully achieve these benefits, it is essential to understand how production conditions, especially the pyrolysis temperature, modulate the physicochemical properties of biochar and, consequently, its performance in different applications. Lower temperatures tend to preserve organic compounds and mineral nutrients, favoring immediate effects on soil fertility, while higher temperatures promote the removal of volatile compounds and enrichment in fixed carbon, resulting in a more stable material with a larger surface area, suitable for carbon sequestration and long-term applications (Bednik *et al*., 2022; Tomczyk *et al*., 2020). This direct relationship between thermal conditions and functionality gives biochar remarkable versatility, allowing it to be tailored for various agricultural, environmental, and industrial purposes. Thus, the conversion of coffee husk into biochar emerges as an integrated solution for the sustainable management of agricultural waste, combining environmental, energy, and economic benefits. Understanding the influence of pyrolysis conditions, especially temperature, on biochar properties is essential to optimize its performance and maximize its agronomic and environmental benefits. In this context, the present study aimed to produce biochar from coffee husk at different pyrolysis temperatures, evaluating the changes in its physicochemical properties and discussing its implications for soil use and the strengthening of sustainable production systems.

MATERIAL AND METHODS

Collection, characterization of lignocellulosic biomass, and biochar production

The coffee husks of the *Coffea canephora* species used in this research were collected at Sítio Café com Leite, in the rural area of the Oriente region, in the municipality of Jerônimo Monteiro, Espírito Santo, Brazil (coordinates: 20°43'23.6"S 41°23'00.2"W). After collection, the husks were subjected to preparation and characterization processes for analysis of their physical and chemical properties. The moisture content (dry basis) was determined according to the standard D1762-84 (ASTM, 2021). The structural chemical composition of the biomasses, including extractives, lignin, and holocellulose content, was determined using the

TAPPI T-204 cm-17 (TAPPI, 2017) and TAPPI T-222 om-21 (TAPPI, 2021) standards. The bulk density was obtained as described in the standard D5057-17 (ASTM, 2017). The contents of volatile materials, ash, and fixed carbon were analyzed following the procedures specified in the standard D1762-84 (ASTM, 2021).

For biochar production, the coffee husk was dried in an oven at 102 ± 3°C for 24 hours to remove moisture and prevent any influence on the pyrolysis process. Pyrolysis was carried out in a fixed-bed reactor. For each trial, 400g of dried coffee husk were placed in a closed metallic reactor, positioned inside a muffle furnace. The process occurred in an inert atmosphere, with no gas entry, at final temperatures of 400, 600, and 800°C, an initial temperature of 30°C, a heating rate of 5°C.min^{-1}, and a residence time of one hour maintained at the final temperature. The gravimetric yields of biochar, pyrolysis liquid, and non-condensable gases were quantified using Equations 1, 2, and 3.

$$BY = \left(\frac{M_{bio}}{m_n}\right) \times 100 \quad (1)$$

$$PLY = \left(\frac{M_{lp}}{m}\right) \times 100 \quad (2)$$

$$NGY = 100 - (BY + PLY) \quad (3)$$

Where: *BY*= biochar yield (%); M_{bio} = biochar mass (g); m_m = dry mass of husk (g); *PLY* = pyroligneous liquid yield (%); M_{ip} = pyroligneous liquid mass (g); *NGY* = yield of non-condensable gases (%).

Biochar Characterization

After production, the biochar was analyzed for bulk density, as described in standard D5057-17 (ASTM, 2017). In addition, the moisture content, volatile materials, ash, and fixed carbon contents were quantified according to the procedures described in standard D1762-84 (ASTM, 2007). The pH was determined using a 2:20 (biochar: distilled water) ratio. The sample was agitated for 15 minutes at 500 rpm, followed by a 30-minute resting period. The pH measurement was performed using an electrode system, with prior calibration using pH 4.0 and 7.0 buffer solutions.

Visual analysis of biochar microstructures (SEM)

The samples were previously ground and homogenized, then passed through a 60 mesh sieve (0.250 mm). The retained fragments were mounted on metal supports using carbon tape and coated with a thin layer of gold in a Balzers Union SCD 030 system. Images were obtained by scanning electron microscopy (SEM) using a JSM-IT200 equipment (Tokyo, Japan), operated at 10 kV, with a magnification of 500x. The proprietary JEOL software was used both for image capture and for the identification of pores in the samples.

Statistical Analysis

The data were subjected to normality tests (Shapiro-Wilk) and homoscedasticity tests (Bartlett). Analysis of variance was conducted following a completely randomized design, with three response variables related to pyrolysis temperature (400, 600, and 800°C). After detecting significant differences, the regression model that best predicted the data behavior was adjusted. All analyses were performed at a 95% probability level. Standard error measures were provided for a better understanding of the confidence interval obtained for each studied variable. The R Core Team software were used for all statistical analyses.

RESULTS

The physicochemical properties of *Coffea canephora* biomass are presented in Table 1. The average values, accompanied by standard deviations, reflect the variation between experimental repetitions. The characterization highlights relevant attributes for biochar production intended for soil use. Low moisture content favors the pyrolysis process, while low bulk density indicates a lightweight material (Safarian, 2023). However, this characteristic can be disadvantageous, as it reduces mass loading in the reactor and may hinder transport and storage efficiency. Lignin and holocellulose influence the thermal degradation behavior of the biomass, with lignin contributing to higher fixed carbon yield and structural stability of the resulting biochar, while holocellulose is more readily decomposed into volatile compounds (Grottola et al., 2022). The extractive content can affect yield and the interaction of biochar with the soil (Idbella et al., 2024). The ash fraction contributes to mineralization and nutrient supply, while volatile materials reflect the ease of thermal decomposition and the generation of porosity (Gross et al., 2024). Fixed carbon provides stability to biochar and influences its persistence in the soil, being relevant for carbon retention and long-term fertility (Gross et al., 2024).

The yields of biochar, pyrolysis liquid, and non-condensable gases as a function of temperature are presented in Figure 1. The biochar yield decreased as the temperature increased, reducing from approximately 43% at 400°C to around 32% at 800°C, fitting precisely to a non-linear regression model. The non-condensable gases showed a continuous increase with rising temperature,

Table 1: Physicochemical properties of *Coffea canephora* biomass.

Property	*Coffea canephora*
Moisture content (%)	7.73 ± 0,02
Bulk density (kg.m^{-3})	156.06 ± 8.93
Lignin (%)	28.56 ± 2.43
Holocellulose (%)	43.85 ± 2.56
Extractives (%)	28.26 ± 1.73
Ash (%)	7.14 ± 0.10
Volatile materials (%)	67.80 ± 1.04
Fixed Carbon (%)	25.09 ± 1.03

Values expressed as mean ± standard deviation.

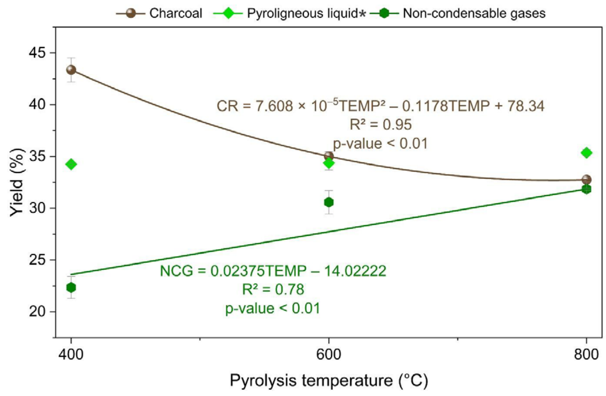

Figure 1: Yields of pyrolysis products from *Coffea canephora* husk. (*) no statistically significant difference was observed).

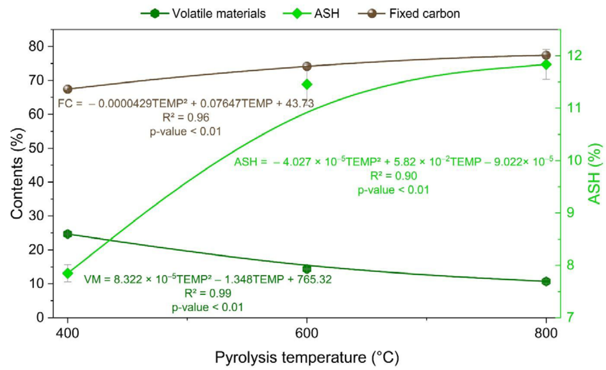

Figure 3: Proximate composition of biochar derived from *Coffea canephora* husk at different pyrolysis temperatures.

starting at 22% at 400°C and reaching about 32% at 800°C. The pyrolysis liquid yield initially was 34% at 400°C, decreased to 30.5% at 600°C, and then increased again to 35% at 800°C, indicating a redistribution of volatile matter during pyrolysis.

Figure 2 presents the moisture content (A) and bulk density (B) of biochar as a function of pyrolysis temperature. The moisture content increased from 3.64% at 400°C to approximately 6.3% at 600°C, then decreased to 5.5% at 800°C. This pattern is well described by a quadratic regression (R^2 = 0.99). The bulk density decreased linearly with the increase in temperature, from 293 kg.m^{-3} at 400°C to 249 kg.m^{-3} at 800°C ($p < 0.01$; R^2 = 0.85), reflecting greater development of the structural porosity of the biochar.

The proximate composition of biochar obtained at different temperatures is presented in Figure 3.

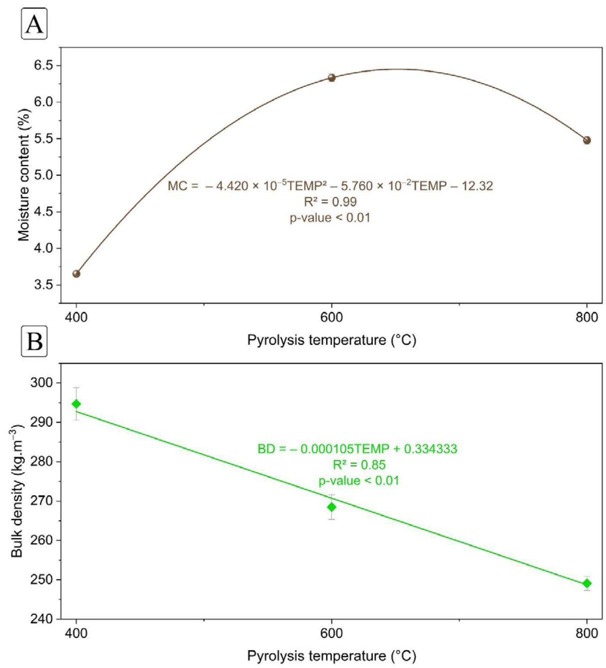

Figure 2: Physical properties of *Coffea canephora* husk biochar.

With the increase in temperature, a reduction in volatile materials and an increase in fixed carbon were observed, highlighting the consolidation of the carbonaceous fraction. The ash content increased slightly, indicating the concentration of remaining minerals. These characteristics are essential for the chemical stability and nutrient retention of biochar in the soil. Although the trend appears approximately linear, a non-linear model provided a better fit to the data. The model was statistically significant ($p < 0.01$), with a determination coefficient of R^2 = 0.85. The pH of the biochar (Figure 4) decreased from 10.2 at 400°C to 9.75 at 600°C, followed by an increase to 10.8 at 800°C.

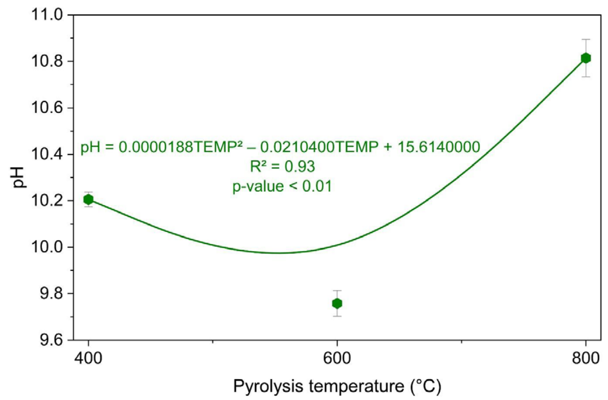

Figure 4: pH analysis of biochar derived from *Coffea canephora* bark under different pyrolysis temperatures.

The Pearson correlation matrix (Figure 5) was used to quantify and visualize the relationship between pyrolysis temperatur and the main physicochemical properties and yields of biochar.

Temperature was strongly and positively correlated with fixed carbon content (R^2 = 0.97) and positively with ash content (R^2 = 0.85). In contrast, temperature was strongly and negatively correlated with biochar yield (R^2 = -0.95). No statistically significant correlation was observed between temperature and biochar pH. The microstructure of the raw biomass and the biochars produced at 400, 600, and 800°C is illustrated in Figure 6.

The original biomass exhibits a compact and heterogeneous surface, with irregular pores and a fibrous

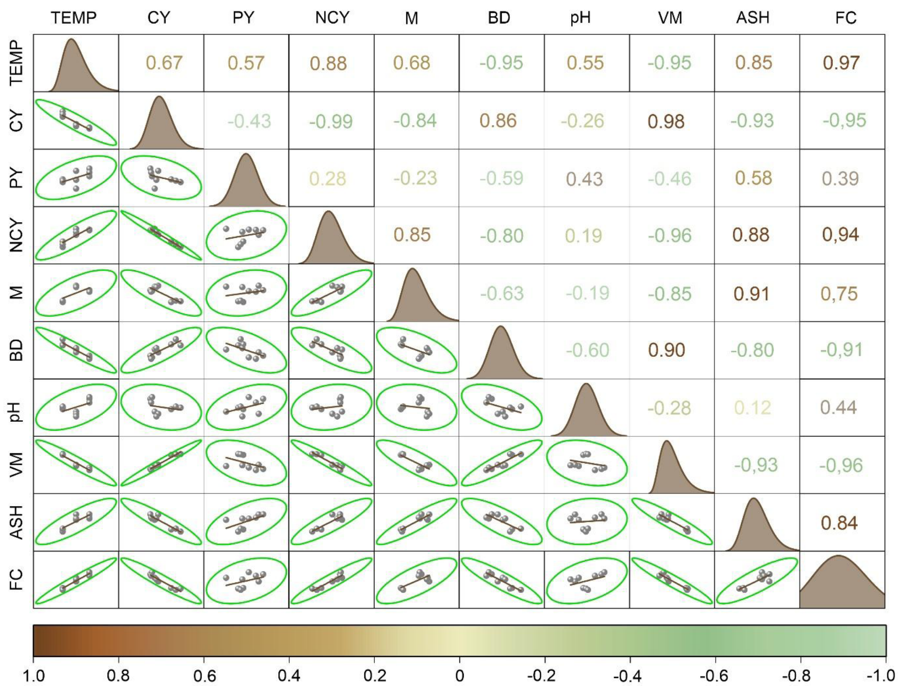

Figure 5: Correlation matrix between pyrolysis temperatures and biochar properties. Where: TEMP = temperature; CY = biochar yield; PY = pyrolysis liquid yield; NCY = non-condensable gas yield; M = moisture; BD = bulk density; pH = pH; VM = volatile materials; ASH = ash; FC = fixed carbon.

structure characteristic of lignocellulosic material (Figure 6). At 400°C, partial disintegration of the structure is observed, with the beginning of lamellae and filament formation. At 600 and 800°C (Figure 6), the biochar exhibits well-defined porosity, thick cell walls, and predominantly polygonal pores, indicating progressive removal of volatile matter and consolidation of a stable structure. This structural evolution results in biochars with high water and nutrient retention capacity, fundamental properties for improving soil fertility and carbon sequestration.

DISCUSSION

Physicochemical properties of coffee husks and impacts on biochar production

The residual biomass of *Coffea canephora* exhibits characteristics favorable to biochar production for soil use. Its low moisture content (Table 01) reduces the energy demand and the time required for pyrolysis, making the process more efficient and economically viable (Awasthi *et al.*, 2023; Mohamed *et al.*, 2024; Tripathi *et al.*, 2016). The bulk density of 156.06 kg.m^{-3} (Table 1), considered relatively low, indicates a lightweight material that can facilitate handling due to reduced weight per unit volume and easier feeding into the reactor. In addition, lower bulk density can enhance heat transfer during pyrolysis by increasing void spaces and improving gas circulation, promoting more uniform thermal processing, although it may reduce transport and storage efficiency in large-scale applications (Carneiro *et al.*, 2025). The structural chemical composition of coffee husk (Table 1), comprising 28.56% lignin, 43.85% holocellulose, and 28.26% extractives, is comparable to lignocellulosic materials widely used for biochar production, such as walnut shell (45.74% lignin, 37.92% cellulose, 13.32% hemicellulose), wheat straw (6.71%, 47.47%, 31.74%), cotton stalks (21.89%, 55.20%, 16.07%), and rice husk (17.57%, 38.51%, 25.38%) (Chen *et al.*, 2015; Ding *et al.*, 2023). The moderate lignin content contributes to the structural stability of the biochar due to its aromatic structure and greater thermal resistance, which promote the formation of a more condensed and stable carbon matrix during pyrolysis, while the high extractive content, characteristic of the husks, influences both the yield and the surface properties of the material.

During pyrolysis, the volatilization of extractives and the decomposition of holocellulose contribute to the formation of micropores and functional groups on the biochar surface, increasing its surface area (Zou *et al.*, 2024). This microporous structure favors water retention, nutrient adsorption in the soil, and performance in rapid adsorption processes of heavy metals (Lin *et al.*, 2025), Highlighting the environmental and agricultural potential of the material. In pyrolyses conducted at low temperatures, the degradation products of cellulose play a predominant role in defining the characteristics of biochar, due to the higher presence of oxygenated functional groups compared to biochars derived from lignin (Lin *et al.*, 2025; Sharma *et al.*, 2024). This structural configuration provides advantages, as cellulose-rich biochars tend to exhibit improved adsorption performance due to their well-developed mesoporous structure, which facilitates mass transfer, and the abundance of oxygenated functional groups (e.g., carboxyl and hydroxyl) capable of interacting with contaminants (Feng *et al.*, 2022).

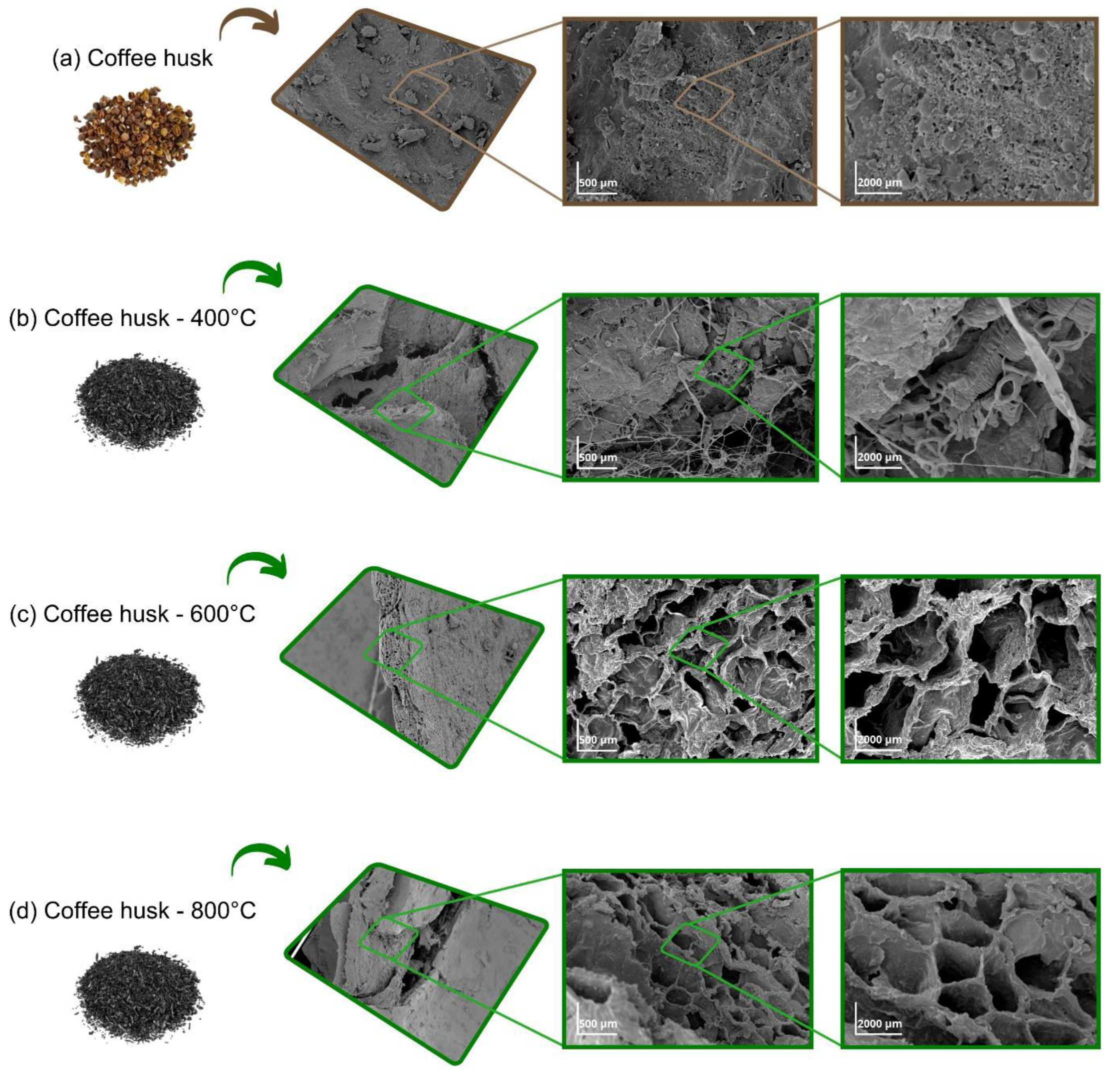

Figure 6: Scanning electron microstructure images (SEM) of *Coffea canephora* husk biochar produced at different pyrolysis temperatures.

The presence of ash in the coffee husk biomass (Table 01) indicates the existence of inorganic minerals capable of enriching the biochar with macro and micronutrients and adjusting the pH, significantly contributing to soil fertility. As it is a waste material, the obtained value is comparable to other husk biomasses commonly used in biochar production as cotton stalk and corn stalks (Gao *et al.*, 2021; Zou *et al.*, 2024). These ashes are rich in silicates (SiO_2), alkali metals (K, Na), and alkaline earth metals (Ca, Mg), which transform into metal oxides during pyrolysis, giving the biochar alkaline properties, with a pH ranging from 8 to 12 (Luan *et al.*, 2023). This inherent alkalinity makes biochar a useful tool for correcting acidic soils and immobilizing pollutants, while the gradual release of phosphorus (P) and potassium (K) from the mineral fraction increases the cation exchange capacity (CEC) and electrical conductivity (EC) of the soil, promoting greater nutrient availability and improving fertility (Lin *et al.*, 2025; Luan *et al.*, 2023). The fixed carbon content (Table 1) increased with pyrolysis temperature, reflecting the progressive devolatilization of the biomass and the enrichment of the solid fraction in carbon. Higher temperatures promote the breakdown of labile components and the formation of more condensed aromatic structures, resulting in biochars with greater fixed carbon content (Đukanović *et al.*, 2025). This characteristic is directly associated with enhanced stability and recalcitrance, which are key factors for long-term persistence in soil. Consequently, biochars produced at higher temperatures tend to contribute more effectively to carbon sequestration and to improvements in soil quality, due to their longer residence time and greater resistance to microbial degradation (Hernandez-Soriano *et al.*, 2016).

Effect of temperature on the yield of pyrolysis products from coffee husk (*Coffea canephora*)

The statistical analysis revealed no significance for the yield of pyrolysis liquid, while the non-condensable gases showed a proportional increase with the rise in final pyrolysis temperature, with the greatest increase observed between 400°C and 600°C (8.11%) (Figure 1). This behavior may be attributed to intensified thermal degradation of labile components between 400 and 600 °C and to secondary cracking reactions and lignin decomposition at higher temperatures, increasing gas formation (Chen *et al*., 2022). The final pyrolysis temperature has a direct influence on biochar yield, with values close to 32% at higher temperatures and around 43% at lower temperatures (Figure 1). This trend is associated with the intensity of thermal decomposition of the biomass: at higher temperatures, the degradation of cellulose and hemicellulose is intensified, promoting greater release of volatile compounds and, consequently, reducing the remaining solid fraction (Hu *et al*., 2022). From an operational and economic standpoint, high biochar yields are desirable, as they indicate better utilization of biomass and greater material availability for agricultural and environmental applications. However, increasing pyrolysis temperature, although reducing gravimetric yield, promotes structural and chemical transformations that enhance biochar quality, increasing carbon content and reduces H/C and O/C ratios, which are associated with greater stability and are valued in carbon credit methodologies (Adhikari *et al*., 2024). In contrast, materials produced at lower temperatures tend to exhibit a higher density of oxygenated functional groups and greater surface reactivity, favoring nutrient adsorption and interaction with the soil matrix (Fazi *et al*, 2026).

In contrast, higher temperatures result in biochars with higher fixed carbon content, a more condensed and aromatic structure, and superior chemical stability, characteristics that make them more suitable for carbon sequestration and long-term applications (Protásio *et al*., 2021; Shoudho *et al*., 2024). Thus, pyrolysis temperature is a determining parameter, as it influences not only yield but also the physicochemical properties and functional performance of biochar. In the case of coffee husk, establishing an optimal point between yield and quality is essential to enable the production of stable, sustainable biochar with high potential for improving fertility and mitigating environmental impacts in agricultural soils.

Influence of pyrolysis temperature on biochar properties and its potential implications in soil

The biochar produced from coffee husk showed moisture content of 3.64%, 6.33%, and 5.47% for pyrolysis temperatures of 400, 600, and 800°C, respectively (Figure 2A). Although lower pyrolysis temperatures generally preserve more oxygenated functional groups (e.g., hydroxyls), which can enhance water retention, the lower moisture observed at 400 °C may be attributed to experimental conditions such as ambient relative humidity during storage and handling, as well as differences in pore structure affecting water adsorption (Zhang *et al*., 2015). The variation in moisture reflects changes in the internal structure of the biochar, affecting its water retention capacity in the soil. Biochars with higher moisture can absorb and store water, contributing to moisture maintenance in sandy soils or those with low water retention capacity, favoring root growth and plant survival during periods of water deficit (Razzaghi *et al*., 2020). Figure 2B shows that the bulk density of the biochar decreased with the increase in pyrolysis temperature, reflecting the loss of volatile compounds and the structural contraction of the material (Dias Júnior *et al*., 2020). Lower density biochars tend to be more porous, which increases the available area for water storage and provides shelter for beneficial microorganisms, stimulating soil biological activity (Bolan, S. *et al*., 2023a). However, this greater porosity also makes the biochar more susceptible to surface erosion and wind removal, and carbon credit methodologies typically require its incorporation into the soil to enhance permanence and reduce losses, thereby improving its long-term effectiveness as a soil conditioner. (Li *et al*., 2025).

The volatile compound content decreased from approximately 25% to 10% with the increase in pyrolysis temperature (Figure 3), due to the sequential decomposition of the biomass constituents (Li *et al*., 2025; Shaaban *et al*., 2014). Biochars produced at low temperatures, with higher volatile content, provide easily assimilable carbon for the soil microbiota, promoting microbial activity and rapid mineralization, which results in greater nutrient availability for plants (Maaz *et al*, 2021; Zhou *et al*., 2024). High-temperature biochars, with lower volatile content, exhibit greater chemical stability and are suitable for long-term carbon sequestration, contributing to climate change mitigation and soil structural stability (Afshar; Mofatteh, 2024). The ash content increased up to 600°C and stabilized at 800°C, ranging from 8% to just over 12% (Figure 3). The ashes contribute essential inorganic nutrients such as calcium, potassium, and magnesium, aiding in soil fertility and promoting microbial activity (Wang *et al*., 2020). In addition, these mineral fractions influence the pH of the biochar, potentially correcting the acidity of acidic and weathered soils, increasing cation exchange capacity and the efficiency of applied fertilizers (Bolan, N. *et al*., 2023b).

Fixed carbon increased from 67% at 400°C to 77% at 800°C (Figure 3), reflecting greater polymerization of the carbonized biomass and higher resistance to degradation. Biochars rich in fixed carbon promote the formation of macroaggregates in the soil, increasing structural stability and water retention in sandy soils (KELLY *et al*., 2017). This increase in chemical stability also reduces the decomposition of the biochar, ensuring the permanence of carbon in the soil and contributing to long-term carbon sequestration (Idbella *et al*., 2024). The pH of the biochar showed a slight decrease from 400°C to 600°C (Figure 4), followed by an increase up to 800°C (Ding *et al*., 2014; Yu *et al*., 2014; Zhao; Ta; Wang, 2017). The increase in pH at high temperatures results from the release of alkaline salts from the carbonized matrix and the modification of oxygenated functional groups (Fakhar *et al*., 2025). Alkaline biochars are capable of correcting the acidity of degraded soils, increasing cation exchange capacity, and improving the availability of essential nutrients, promoting higher crop productivity and enhancing soil quality in the long term (Sama *et al*., 2025).

In light of these results, it becomes evident that pyrolysis temperature should be chosen according to the agronomic or environmental objective. Figure 5 presents the correlation matrix between biochar properties and pyrolysis temperature, highlighting how thermal variations influence its characteristics and, consequently, its performance in soil. Strict temperature control shows a very strong inverse correlation with volatile compounds (R = -0.95) and an almost perfect direct correlation with fixed carbon (R = 0.97), explaining the chemical stability of biochar, a critical factor for its role in long-term carbon sequestration. Additionally, the increase in pyrolysis temperature is associated with improvements in desirable agronomic characteristics, such as higher ash content (R = 0.85), which contributes to soil acidity correction and mineral nutrient supply, and the increase in pyrolysis temperature itself (R = 0.55), reinforcing process control. Therefore, the functionality of biochar in soil goes beyond simple elemental composition. The strong inverse correlation between pyrolysis temperature and apparent density (R = -0.95) indicates a profound physical restructuring of the material, reflecting increased porosity and changes in the internal structure.

Impact of pyrolysis temperature on biochar morphology

The images obtained by Scanning Electron Microscopy (SEM) of the biochar clearly show the structural modulation as a function of pyrolysis temperature (Figure 6). The progressive restructuring of the coffee husk is observed from the compact biomass (Figure 6a) to Biochar-400°C (Figure 6b), when the devolatilization process begins. The maximum development of porosity occurs from 600°C onward (Figure 6c), at which point the degradation and polycondensation of carbon preserve the original cell architecture, converting it into an intricate network of interconnected macropores with a characteristic "honeycomb" morphology. Biochar at Biochar 800 °C (Figure 6d), this structure is maintained, but the carbonized walls appear more compact and well-defined, reflecting the near-complete elimination of volatile compounds and the increase in fixed carbon. (Hernandez-Soriano *et al.*, 2016; Shoudho *et al.*, 2024).

Functionally, this high porosity is crucial for the biochar's performance in the soil, contributing to water retention and expanding the reactive surface area, factors that govern the mechanisms of nutrient and pollutant adsorption (Torres *et al.*, 2023). Furthermore, the preservation of the cell architecture ensures structural stability, favoring the durability of the biochar and its role as a conditioner and carbon sequester in the soil (Shoudho *et al.*, 2024). Thus, the morphological analysis complements and validates the physicochemical results, highlighting that pyrolysis temperature is the key parameter for engineering the porosity of biochar and, consequently, for its effective application in the soil system.

Impacts and future perspectives of biochar use

The results presented reinforce that pyrolysis temperature plays a central role in determining the physicochemical and morphological properties of biochar, directly impacting its performance in the soil. Higher temperatures promote an increase in fixed carbon and chemical stability, favoring long-term carbon sequestration and acidity correction in degraded soils (Kim *et al.*, 2017). On the other hand, biochars produced at lower temperatures retain a higher amount of volatile compounds and density, which may stimulate microbial activity and increase the rapid availability of nutrients, although this effect depends on the magnitude of the differences observed between the evaluated temperatures (e.g., 400 and 800 °C). These findings indicate that the thermal engineering of biochar allows its characteristics to be adjusted according to specific agricultural or environmental management objectives. Future research should focus on exploring the relationship between pyrolysis temperature, microstructure, and interactions with soil microbiota, as well as evaluating biochar performance in different soil types and agricultural systems, including combined effects with fertilizers and organic additives. Additionally, application prospects in the remediation of contaminated soils, water retention in semi-arid regions, and greenhouse gas mitigation position biochar as a strategic tool for sustainable agriculture and ecosystem services. as a strategic tool for sustainable agriculture and ecosystem services.

CONCLUSION

The results demonstrate that the final pyrolysis temperature influenced the physicochemical properties of *Coffea canephora* husk biochar. As the temperature increased, a reduction in gravimetric yield and bulk density was observed, accompanied by an increase in fixed carbon content and changes in pH. The biochar produced at 400°C exhibited higher density and higher volatile material content, parameters that may favor water retention and the rapid release of nutrients, making it recommended for sandy or low-fertility soils that require immediate improvement in productive capacity. The material obtained at 600°C showed a balance between ash content, fixed carbon, and pH, which can provide mineral nutrients and moderate stability, suitable for soils with medium texture, where both nutrition and moisture retention need to be balanced. On the other hand, the biochar produced at 800°C showed higher fixed carbon content and a more alkaline pH, making it ideal for acidic or heavily weathered soils, acting on acidity correction, increasing CEC, and long-term carbon sequestration. Coffee husk is an abundant and nutritious waste, with great potential for biochar production and agricultural use. Although all temperatures are feasible, pyrolysis at 800°C is the most recommended for use in tropical acidic soils and long-term applications.

ACKNOWLEDGMENTS

Acknowledgements this study was funded by the Coordination for the Improvement of Higher Education Personnel (CAPES – Finance Code 001), the National Council for Scientific and Technological Development (CNPq - Universal Call No. 18/2021, Call for Productivity Grants in Technological Development and Innovative Extension No.

08/2022, Support for International Scientific, Technological and Innovation Research Projects No. 14/2023, Knowledge Brazil – Collaboration Network No. 22/2024, Support for International Scientific, Technological and Innovation Research Projects No. 16/2024), the Espírito Santo Research and Innovation Support Foundation (FAPES – Universal Call No. 13/2025, FAPES Technological Extension No. 09/2024), Thiago Protásio would like to thank the Research Support Foundation of the State of Minas Gerais (FAPEMIG) for funding the project APQ-05431-24 (Grant Agreement FAPEMIG/DPE No. 103658065/2024). We also thank the Grupo de Pesquisa em Bioenergia e Bioprodutos de Base Florestal and the Laboratório de Energia de Biomassa (LEB/UFES), for their invaluable assistance in carrying out the various analyses required for this study.

AUTHORSHIP CONTRIBUTION

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Data processing: FMD; GFMC; MJM; AMS; BSC; TRO; TPP; AFDJ
Data analysis: LMP; FMD; GFMC; MJM; AMS; BSC; TRO; AFDJ
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Data availability:

The datasets supporting the conclusions are included in the article.

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