

Biochar from pruned *Ficus benjamina* branches: Carbonization temperature effects on properties and applicability as solid biofuel and soil amendment applications

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ABSTRACT

The pruned branches of *Ficus benjamina* represent an underutilized lignocellulosic biomass with high thermochemical conversion potential. This study investigated the effect of the carbonization temperature (400, 500, and 600 °C, residence time of 2 h) on the physicochemical, energetic and structural properties of the biochar produced and determined its potential as a solid biofuel and soil amendment. Proximate and elemental analysis, BET surface area, carbon stability assessment, higher heating value (HHV) determination, and polycyclic aromatic hydrocarbons (PAHs) quantification using UHPLC-FLD were performed. Increasing the carbonization temperature resulted in a significant reduction in energy yield, volatile content, and hydrogen content. However, the ash content (10.49 to 13.41 wt.%), carbon (66.71 to 68.93 wt.%), electrical conductivity (1.48 to 3.21 dS m⁻¹), and BET area (3.49 to 26.04 m² g⁻¹) increased. PAHs concentrations remained within safe limits (23.40 to 160.17 µg kg⁻¹). The HHV ranged from 24.23 to 26.07 MJ kg⁻¹, comparable to sub-bituminous coal and charcoal. Increasing the temperature significantly improved the stability of the biochar. The mean residence times ranged from 1627 to 1734 years, indicating a high carbon sequestration potential. The biochars produced meet international standards (IBI and EBC). Biochar produced to 500 °C showed an optimal balance between energetic, structural, and chemical stability properties. The results show that carbonization of the pruned branches of *Ficus benjamina* is presented as a viable technology for the production of value-added biochar, as a solid biofuel, and as a soil amendment with carbon sequestration capacity.

Keywords: *Ficus benjamina*, pyrolysis, biochar properties, PAHs, biofuel, soil amendment.

INTRODUCTION

Urban expansion and the transition to circular economies have highlighted the need to implement sustainable approaches to the treatment of urban solid waste. Among the sources of urban solid waste, pruning waste generated in urban green spaces and recreational areas generates serious

urban planning problems when not properly utilized [Pedroza et al., 2021]. Commonly, most of this waste is discarded in landfills or incinerated, and a small fraction is used in compost preparation [Ashani et al., 2020; Ayilara et al., 2020]. Despite its potential to generate environmental benefits, its use is still limited due to the lack of quantitative data on its production and quantity, the difficulties

in classifying it, and transportation and storage challenges [Meira et al., 2024]. In response to this problem, the pyrolysis process represents a viable alternative for the efficient processing of municipal lignocellulosic wastes, which is characterized by their environmentally sustainable nature and its diverse products [Ayiania et al., 2019]. The valorization of these wastes through pyrolysis is considered an opportunity with great environmental and energy potential, although it often presents economic and implementation limitations [Maccarini et al., 2020].

Ficus benjamina is a perennial shrub commonly used for ornamental purposes. It belongs to the *Ficus* genus (*Moraceae*) and comprises more than 800 species around the world [Adhikari et al., 2023]. It is one of the most relevant urban tree species, and its prevalence is highlighting in multiple cities. It is characterized by its rapid growth, generating around 16 kg of pruning per individual [Pérez-Arévalo & Velázquez-Martí, 2018], so frequent pruning is necessary to regulate its expansion and leafiness. These residues could be used to produce biochar through the pyrolysis, which represents a viable option to reduce waste disposal problems and develop a circular economy in urban environments [Walikhani et al., 2022].

Biochar, is a carbon-rich product obtained from the pyrolysis of lignocellulosic biomass under limited oxygen conditions [Pérez et al., 2025], and temperature, the operating variable of pyrolysis, influences the physicochemical properties of biochar [Handiso et al., 2024], for instance, wood waste derived biochar has been observed to increase with increasing temperature, pH, electrical conductivity, ash content, fixed carbon, and specific surface area, while volatile matter content, hydrogen, and oxygen content decrease [Rabiee Abyaneh et al., 2024]. Furthermore, the textural properties, such as the BET surface area, significantly determine the functionality of biochar as a soil amendment and carbon sequestration agent, establishing a direct correlation between the chemical composition and the cation exchange capacity [Ferraro et al., 2024; Taboada-Ruiz et al., 2024]. However, the safe application of biochar requires considerations of quality and safety. Pyrolytic conversion of various biomasses under different carbonization conditions results in biochars with varying levels of polycyclic aromatic hydrocarbons (PAHs), persistent organic pollutants formed during pyrolysis due to incomplete

combustion of organic matter [De la Rosa et al., 2019; Odinga et al., 2021].

Despite growing interest in the valorization of urban pruning waste through pyrolysis, there is a significant gap in specific content on the physicochemical characteristics and PAHs content of biochars derived from *Ficus benjamina*, limiting the optimization of processing parameters and the evaluation of their safe application potential in environmental systems. Therefore, this study aimed to evaluate the effect of carbonization temperature on the physicochemical, energetic, and textural properties of biochar produced from pruned *Ficus benjamina* branches, including the determination of yield, higher calorific value, structural stability, BET surface area and PAHs concentrations, in order to assess its potential as a solid biofuel and safe soil amendment.

MATERIALS AND METHODS

Materials

The pruned branches of *Ficus benjamina* trees were collected from urban parks in Chiclayo city, Peru. After collection, the material was manually sorted, separating the leaves from the branches. Only branches with diameters between 12 ± 3 mm were selected, which were cut into sections of approximately 10 cm in length to facilitate handling and processing. Subsequently, the branches were dried in a forced convection oven (Binder brand, model FD 115) at 105 ± 5 °C for 24 h, to eliminate the remaining moisture. A fraction of these branches was initially crushed using a domestic mill (Corona model L12104), followed by fine grinding in an analytical knife mill (IKA M20 universal mill) until a homogeneous powder was obtained. The pulverized material was sieved using a vibrating screen, selecting particles ranging in size from 0.075 to 0.3 mm (Fig. 1). The whole and ground samples were stored in airtight bags and kept in a desiccator to prevent moisture re-absorption prior to characterization or subsequent thermal carbonization.

Biochar preparation

The dried *Ficus benjamina* branches were cut into 1 to 2 cm long segments and subsequently subdivided longitudinally to optimize surface exposure during the carbonization process. For



Figure 1. Sample preparation for characterization and carbonization

pyrolysis, a carbonization system was used in a limited oxygen atmosphere using 100 ml porcelain crucibles. The carbonization protocol consisted of placing 30 ml of previously washed sea sand as a base layer in the crucible (1), followed by 20 g of the sample (2), and then completely covering the crucible with sand up to the rim (3). The sea sand acted as a deoxygenating agent to create a reducing atmosphere. The crucible was covered with aluminum foil over its mouth and, subsequently, the corresponding lid was placed (4) to minimize gas exchange with the outside environment (Fig. 2).

Carbonization was carried out in an electric muffle furnace (Thermolyne, Eurotherm 2116 model) at temperatures of 400, 500, and 600 °C in triplicate for each temperature (5). Once the target temperature was reached, the samples were held for 2 h to ensure complete thermochemical conversion. The samples were subsequently cooled inside the muffle furnace for

24 h until they reached room temperature. The biochar obtained (6) was separated from the sea sand by sieving with a mesh stainless steel strainer (7), weighed, and labeled BR400, BR500, and BR600 depending on the process temperature. For subsequent physicochemical analyzes, the biochar was washed with distilled water to remove sea sand residue, oven dried at 80 °C for 24 h, manually crushed in a porcelain mortar and sieved with a Tyler 100 mesh. The final samples were stored in airtight plastic bags inside a desiccator until analysis. The mass yield (Y), energy yield (EY) and fuel ratio of biochars were determined using Eq. 1, 2 and 3.

$$Y(\%) = \frac{\text{Biochar weight (g)}}{\text{Biomass weight (g)}} \cdot 100 \quad (1)$$

$$EY(\%) = \frac{HHV_{\text{biochar}}}{HHV_{\text{biomass}}} \cdot Y \quad (2)$$

$$\text{Fuel ratio} = \frac{\text{Fixed carbon content}}{\text{Volatile matter content}} \quad (3)$$

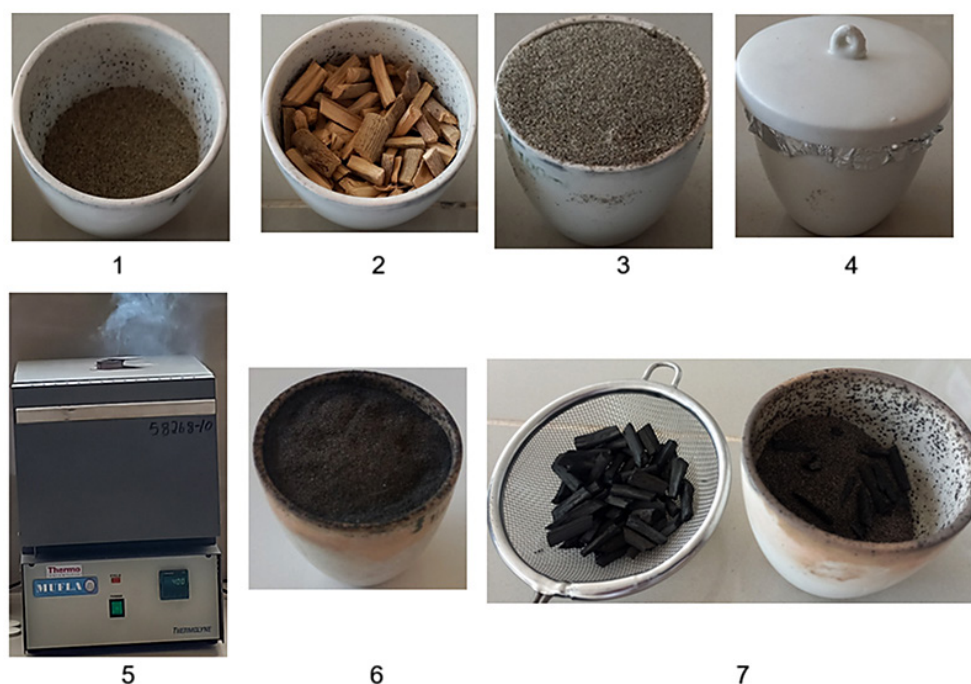


Figure 2. Preparation of biochar from *Ficus benjamina* branches

Proximate and elemental analysis

The quantification of the ash and volatile matter content of the pruned branches of *Ficus benjamina* and the biochar produced was carried out according to the procedures of ASTM D3175 and ASTM D3174, respectively, in triplicate. Results were expressed as weight percentages on a dry basis. The fixed carbon content was determined by difference, according to Eq. 4 [Tu et al., 2022].

$$\begin{aligned} \text{Fixed carbon (\%)} &= 100 - \\ &- (\% \text{ of volatile matter} + \% \text{ of ash}) \end{aligned} \quad (4)$$

The C, H, and N contents of the pruned *Ficus benjamina* branches and the biochar produced were determined using the elemental analyzer of the CKIC model 5E-CHN2200, according to the ASTM D5373 procedure, while the S content was determined using the 5E-IRSII module of the CKIC model, according to the ASTM D4239 procedure. For the analysis of C, H, N, and S, approximately 0.3 g of sample was used and the samples were carried out in triplicate. Values were expressed as percentages by weight and on a dry basis. The oxygen (O) content was determined by difference, according to Eq. 5 [Tu et al., 2022].

$$\begin{aligned} O (\%) &= 100 - \\ &- (\% C + \% H + \% N + \% S + \% \text{ of ash}) \end{aligned} \quad (5)$$

Analysis of higher calorific values

The higher calorific value (HHV) of the pruned branches of *Ficus benjamina* and the resulting biochars were determined according to ASTM D5865-07. A LECO Isoperibol AC600 calorimeter was used. Approximately 0.2 g of dry sample was placed in the bomb calorimeter, which was pressurized with oxygen to 3 MPa. The results were expressed in MJ kg⁻¹, on a dry basis, and each test was performed in triplicate.

pH and electrical conductivity analysis

The pH of the biochars produced was determined by preparing a suspension of 1 g of biochar in 20 ml of distilled water. Samples were shaken on a Multi Bio RS-24 rotary shaker at 100 rpm for 24 h and then left to stand for 30 min. After this time, the reading was taken with a pH meter (HANNA, model HI2300), which was previously calibrated with buffer solutions of 4, 7, and 10.

The pH reading was considered stable when it did not vary more than 0.1 units for 30 s. Electrical conductivity was determined using the same solution used in pH measurement using an EC/TDS/NaCl/°C meter (HANNA, model HI2300). Both analyses were performed in triplicate.

Stability of biochars

The stability of biochars was evaluated by calculating the recalcitrance potential (R_{50}), the mean residence time (MRT), the aromaticity factor (f_a) and the stable carbon mass fraction (SCF) from the proximate and elemental analyses, using Eq. 6 to 9 [Sette et al., 2020].

$$R_{50} = \frac{0.17 \cdot (0.474VM + 0.963FC + 0.067ash)}{(100 - ash) + 0.00479} \quad (6)$$

$$MRT = 4501 \cdot e^{-1.3VM \cdot FC - 0.8} \quad (7)$$

$$f_a = \frac{0.967 \cdot FC}{C} \quad (8)$$

$$SCF = 0.921 - 0.422 VM/FC \quad (9)$$

where: FC , C and VM correspond to the fixed carbon, volatile matter and carbon content of the biochars, in wt. %.

Analysis of BET surface area and total pore volume

The surface area and total pore volume analysis of the *Ficus benjamina* branches and biochars was performed on a Micromeritics Autochem II 2920 V5.02 analyzer by the single-point method at a relative pressure of 0.3 using nitrogen adsorption at −180 °C, according to the ISO 9277 procedure. Samples were degassed at 100 °C for 30 min prior to BET surface area analysis. The total pore volume was determined from the volume of nitrogen adsorbed at a relative pressure of 0.97.

Analysis of polycyclic aromatic hydrocarbon

Fifteen of the 16 PAHs identified by the United States Environmental Protection Agency (US EPA) were analyzed. Analytical standards were purchased from Accustandard (New Haven, CT, USA). PAHs were extracted by weighing 5 g of biochar sample in 50 ml Falcon tubes, followed by the addition of 5 ml of ultrapure water and 10 ml of acetonitrile. The mixture was vortexed for 10 min, then subjected to ultrasonic extraction for 10 min, and finally centrifuged at 4500 rpm and 4 °C

for 5 min. One ml of the supernatant was taken for analysis using an ultra-high performance liquid chromatography-fluorescence detector (UHPLC-FLD) using an Agilent 1290 Infinity II system (Agilent Technologies, USA) with OpenLAB CD ChemStation Rev. C. 01.10 software. Chromatographic separation was performed on an Agilent Zorbax Eclipse PAH column (4.6 mm id x 100 mm, 1.8 μ m) with a flow rate of 1.8 ml/min, mobile phase of type I water and acetonitrile, column temperature of 25 °C and injection volume of 10 μ L.

Statistical analysis

Data were analyzed using one-way ANOVA with Duncan's post hoc test ($p < 0.05$). When the assumptions of normality and homogeneity of variance were not met with the Shapiro-Wilk and Levene tests, respectively, the nonparametric Kruskal-Wallis test with Holm's post hoc test was used. The analyzes were performed using the RStudio 2024.04.1 software.

RESULTS AND DISCUSSION

Physicochemical characterization of biochars

The physicochemical characterization of the produced biochars is summarized in Table 1.

Proximal composition

The proximate composition of the biochars obtained from the pruned branches of *Ficus benjamina* showed significant compositional changes

related to the carbonization temperature ($p < 0.05$). The volatile matter content progressively decreased with increasing temperature (Table 1) as a result of the degradation and vaporization of the lignocellulosic components, specifically hemicellulose and cellulose. This behavior is consistent with previous studies on biochars derived from various herbaceous and woody plants [Tu et al., 2022]. In turn, the ash content increased significantly, evidencing the progressive concentration of mineral components after volatilization of the organic fraction [Li Lee et al., 2017] and the presence of higher inorganic components [Tu et al., 2022], a trend consistent with studies on biochars derived from black pine, willow, and poplar wood [Ferraro et al., 2024]. Consistent with these changes, fixed carbon, a fundamental parameter of the structural stability of biochar in soils [Yu et al., 2022], showed a significant increase due to the progressive transformation of biomass through dehydration, depolymerization, and formation of stable aromatic structures [Lijie et al., 2020]. These compositional changes show, on the one hand, that the increase in ash can limit energy applications due to a reduction in calorific value and the formation of slags during combustion [Kukuruzović et al., 2023], and, on the other hand, its rich profile in essential nutrients favors its use as a mineral amendment in agricultural soils [Zajac et al., 2018].

Elemental composition

Elemental analysis of biochars derived from pruned branches of *Ficus benjamina* revealed significant compositional changes as carbonization temperatures increased (Table 1). The carbon

Table 1. Physicochemical properties of biochars from pruned branches of *Ficus benjamina*

Properties	Branches*	BR400	BR500	BR600
Volatile matter (wt.% dry basis)	83.99 $\pm$ 0.26	26.58 $\pm$ 0.21 ^a	21.47 $\pm$ 0.20 ^b	17.04 $\pm$ 0.32 ^c
Ash (wt.% dry basis)	3.39 $\pm$ 0.03	10.49 $\pm$ 0.07 ^c	11.34 $\pm$ 0.035 ^b	13.41 $\pm$ 0.033 ^a
Fixed carbon (wt.% dry basis)	12.62 $\pm$ 0.2	62.93 $\pm$ 0.27 ^c	67.19 $\pm$ 0.23 ^b	69.55 $\pm$ 0.34 ^a
C (wt.% dry basis)	42.36 $\pm$ 0.02	66.71 $\pm$ 0.55 ^b	68.93 $\pm$ 0.061 ^a	67.45 $\pm$ 0.18 ^{ab}
H (wt.% dry basis)	6.15 $\pm$ 0.2	2.71 $\pm$ 0.32 ^a	2.25 $\pm$ 0.076 ^b	1.76 $\pm$ 0.046 ^c
N (wt.% dry basis)	0.64 $\pm$ 0.02	0.72 $\pm$ 0.034 ^a	0.74 $\pm$ 0.040 ^a	0.76 $\pm$ 0.06 ^a
S (wt.% dry basis)	0.045 $\pm$ 0.004	0.11 $\pm$ 0.00 ^b	1.40 $\pm$ 0.070 ^a	1.49 $\pm$ 0.017 ^a
O (wt.% dry basis)	47.42 $\pm$ 0.2	19.27 $\pm$ 0.34	15.33 $\pm$ 0.16	15.14 $\pm$ 0.22
H/C	1.74	0.49 $\pm$ 0.061	0.39 $\pm$ 0.001	0.31 $\pm$ 0.0081
O/C	0.84	0.22 $\pm$ 0.0054	0.17 $\pm$ 0.0019	0.17 $\pm$ 0.0029
pH	--	8.64 $\pm$ 0.015	9.54 $\pm$ 0.042	10.49 $\pm$ 0.022
Electrical conductivity (dS m ⁻¹)	--	1.48 $\pm$ 0.020	2.02 $\pm$ 0.037	3.21 $\pm$ 0.032

Note: Equal letters in the same row means there is no statistically significant difference. * [Llanos et al., 2023].

content progressively increased from 400 °C to 500 °C, attributed to enhanced devolatilization of hydrogen and oxygen in water vapor, as well as elimination of oxygenated functional groups (carboxyl and hydroxyl), which selectively concentrate carbon in the carbon matrix [Chaves Fernandes et al., 2020]. However, a decrease in carbon content was observed at 600 °C. This effect could be explained by secondary gasification processes, where solid carbon is transformed into gaseous compounds (CO and CO₂), favored by the porous structure of biochar and the presence of inorganic elements with catalytic activity [L. Wang et al., 2023]. This behavior has been reported in lignocellulosic biomasses under intense thermal conditions [Chaves Fernandes et al., 2020; Oginni & Singh, 2020].

At the same time, the hydrogen content decreased significantly ($p < 0.05$) with increasing carbonization temperature from 400 °C to 600 °C, a trend consistent with studies on carbonized black pine, poplar, and willow biochars between 400 °C and 650 °C [Ferraro et al., 2024], associated with aromatic condensation and increased thermal stability [Chaves Fernandes et al., 2020]. Similarly, the oxygen content decreased significantly due to the loss of oxygenated functional groups, such as carboxyls, carbonyls and hydroxyls, through dehydration, decarboxylation, and decarbonylation reactions, processes that intensify aromatic condensation and increase the hydrophobicity and structural stability of biochar [Oginni & Singh, 2020]. A similar behavior was reported in eucalyptus biochars, where the oxygen content decreased from 19.41 wt.% to 10.57 wt.% when carbonized between 450 °C and 950 °C [Chaves Fernandes et al., 2020].

In contrast, the nitrogen content did not show significant variations while maintaining values of 0.76 ± 0.06 wt.%, indicating retention in thermostable structures, such as nitrogenous heterocyclic compounds resistant to pyrolytic volatilization [Usman et al., 2015]. Similar behavior has been observed in biochars derived from *Miscanthus x giganteus* and *Kanlow* switchgrass, where the nitrogen content increased from 1.08 wt.% to 1.55 wt.% and from 0.64 wt.% to 1.20 wt.%, respectively, when carbonized between 500 °C and 900 °C [Oginni & Singh, 2020], in addition in eucalyptus biochars carbonized between 750 °C and 950 °C with an increase from 1.06 wt.% to 1.34 wt.% nitrogen [Chaves Fernandes et al., 2020].

Finally, the sulfur content showed a significant increase from 0.045 ± 0.004 wt.% in the initial biomass to 1.40 ± 0.070 wt.% at 500 °C, stabilizing at 600 °C (1.49 ± 0.017 wt.%), evidencing retention in less volatile structures or thermal saturation of the process, variable behavior depending on the chemical nature of sulfur in the original biomass. This behavior has been reported in other studies when carbonizing *Kanlow* switchgrass from 500 °C to 900 °C, whose sulfur content increased from 0.11 wt.% to 0.21 wt.% [Oginni & Singh, 2020]. These results indicate that there is an optimal thermal threshold between 400 °C and 500 °C to maximize the carbon content, while low nitrogen levels (< 0.98 wt.%) favor energy applications with reduced environmental impact by minimizing the risk of NO_x formation during combustion [Ahmad et al., 2017].

H/C and O/C ratio

The H/C and O/C ratios, obtained from the data in Table 1, showed a progressive decrease with increasing carbonization temperature. The decrease in the H/C ratio is due to a significant loss of hydrogen in the carbon matrix, attributed to dehydration, dehydrogenation, and C–H bond cleavage reactions, which favors the formation of more stable aromatic structures [Shakya et al., 2022; Venkatesh et al., 2022]. Similarly, the O/C ratio progressively decreased from 0.84 (branches) to 0.17 ± 0.0029 (600 °C), due to decarboxylation and dehydration reactions that eliminate oxygen in the form of CO and CO₂, promoting carbon aromatization [Venkatesh et al., 2022]. Previous studies agree with this trend, showing that biochars derived from woody biomass tend to present lower H/C and O/C ratios as the carbonization temperature increases, which is associated with greater structural stability [Chaves Fernandes et al., 2020; Tu et al., 2022].

The H/C ratios < 0.7 and O/C < 0.4 in biochars are considered suitable for agricultural applications and as soil carbon sequestration agents, according to the guidelines established by the International Biochar Initiative (IBI) and the European Biochar Certificate (EBC) [Ibi, 2015; The European Biochar Certificate, 2023]. Biochars produced from *Ficus benjamina* branches meet the IBI and EBC guidelines, suggesting their potential to amend carbon-deficient soils and promote long-term carbon storage. Previous studies have shown that the O/C ratio is a critical indicator of biochar stability in soil, an O/C

ratio < 0.2 is associated with a half-life greater than 1000 years, while ratios between 0.2 and 0.6 correspond to a half-life between 100 and 1 000 years and values greater than 0.6 are associated with stability less than 100 years [Tu et al., 2022].

According to these criteria, biochar obtained at 400 °C could have an estimated half-life between 100 and 1 000 years, while biochars obtained at 500 °C and 600 °C would show a persistence greater than 1000 years. This high structural stability is essential not only to ensure long-term carbon sequestration in agricultural soils, but also to prolong their functionality as an organic amendment without rapid degradation. Furthermore, low H/C and O/C ratios correlate with lower CO₂, soot and water vapor emissions during combustion, resulting in greater energy efficiency [Hadey et al., 2022]. In this context, the generated biochars are technically viable as alternative solid fuels. Taken together, the results support the idea that the biochars obtained in this study meet essential technical criteria for energy, environmental, and agronomic applications, representing a sustainable option for the management of urban lignocellulosic waste.

pH and electrical conductivity

The pH and electrical conductivities of the biochars derived from the pruned branches of *Ficus benjamina* are summarized in Table 1. The pH of the biochars ranged from 8.64 ± 0.015 to 10.49 ± 0.022 with increasing carbonization temperature from 400 °C to 600 °C. This behavior confirms the alkaline nature of biochar, widely reported in the literature [Shakya et al., 2022; S.-X. Zhao et al., 2017]. The progressive increase in pH can be attributed to several thermochemical mechanisms. The decomposition of acidic functional groups, such as carbonyls (–COOH), reduces surface acidity, while the relative concentration of mineral components, especially alkaline salts and carbonates, such as CaCO₃ and MgCO₃, contributes to the increase in alkalinity through the thermal transformation of organic fractions and the accumulation of ash [Shakya et al., 2022; Tu et al., 2022]. This alkaline mineralization intensifies with increasing temperature, increasing the buffering capacity of the material. From an agronomic perspective, the high pH values of biochars produced at 400, 500, and 600 °C give them the potential to correct soil acidity, improve nutrient availability, and optimize cation exchange

capacity, which can generate more favorable conditions for crop development in degraded or acid soils [Ortiz et al., 2020]. Similarly, its application can help mitigate greenhouse gas emissions from the soil by reducing denitrification processes and stabilizing organic compounds.

Unlike pH, which measures hydrogen ion activity, electrical conductivity (EC) is a critical parameter for evaluating the agronomic performance of soil-applied amendments because it provides a direct estimate of salinity and significantly influences plant growth [Abbas et al., 2018]. In this study, the biochars obtained showed a significant increase in EC with increasing carbonization temperature, from 1.48 ± 0.020 dS m⁻¹ at 400 °C to 3.21 ± 0.032 dS m⁻¹ at 600 °C (Table 1). This variation is related to the increase in the content of ash and the accumulation of inorganic mineral salts released during pyrolysis, such as Na, K, Ca, and Mg [Oginni & Singh, 2020]. Previous studies have reported biochars derived from agricultural, herbaceous and industrial biomasses with higher EC than those obtained in this study, indicating the moderately saline nature of the biochars analyzed [Abbas et al., 2018; Oginni & Singh, 2020]. According to the recommended EC ranges for soil amendments, biochars produced at 400 °C and 500 °C would be classified as non-saline (0 to 2 dS m⁻¹) and are appropriate for application in non-saline or very low salinity soils. On the contrary, biochar obtained at 600 °C, which has an EC of 3.21 dS m⁻¹, would be classified within the moderate salinity range and can be used in soils with some salt accumulation, without posing a risk of ionic toxicity [Smith & Doran, 2015; Venkatesh et al., 2022].

Overall, the results indicate that these biochars prepared between 400 °C and 600 °C have physicochemical properties compatible with sustainable agronomic applications. The accumulation of an alkaline pH, a moderate ash content, and EC values within appropriate ranges reinforces their viability as an amendment for acid soils or low- salinity soils.

BET area and total pore volume

The *Ficus benjamina* branches presented a BET surface area of 0.18 m² g⁻¹ and a total pore volume of 0.0001 cm³ g⁻¹, while the biochars showed significant increases from 3.49 m² g⁻¹ to 26.04 m² g⁻¹ (BET surface area) and from 0.0018 cm³ g⁻¹ to 0.013 cm³ g⁻¹ (total pore volume) with

increasing temperature from 400 °C to 500 °C (Fig. 3). This increase is attributed to the release of volatile matter and the formation of pores during the thermal decomposition of the lignocellulosic structure of the branches [Elnour et al., 2019]. Furthermore, this behavior induces the formation of vascular channels, microfractures, and amorphous carbonaceous structures [S.-X. Zhao et al., 2017], increasing the porosity of the charred material. However, increasing the temperature from 500 °C to 600 °C (18.69 m² g⁻¹ and 0.0094 cm³ g⁻¹) showed a decrease in both parameters. This reduction may be associated with the deposition of polycondensed aromatic structures on the surface of the coal and the partial collapse of the carbon matrix, leading to pore clogging or fine particles formation [Ortiz et al., 2020].

The low surface area observed in this study could be explained by the high ash content, whose inorganic components block the entry of nitrogen gas during adsorption at 77 K [Kim et al., 2020; Song & Guo, 2012]. Similar results have been reported for biochars derived from other lignocellulosic residues, such as palm fibers [Selvarajoo & Oochit, 2020] and black pine wood [Ferraro et al., 2024], where the textural behavior depends on the carbonization conditions and the mineral content of the source biomass. In this context, biochar produced at 500 °C for 2 h shows a larger surface area BET and an optimal ash content, suggesting its suitability as a multifunctional amendment with potential

applications in both the energy and environmental management sectors.

Stability of the produced biochars

Biochars derived from pruned branches of *Ficus benjamina* showed a progressive increase in the recalcitrance potential (R_{50}) as the carbonization temperature increased from 400 °C to 600 °C, reaching values of 0.140 ± 0.0002 to 0.149 ± 0.0003 , respectively (Table 2). This increase reflects a higher relative aromatic carbon content compared to other less condensed forms [Oginni & Singh, 2020]. The results are in agreement with previous studies on *Miscanthus x giganteus* and *Kanlow* switchgrass biochars, obtained by carbonization between 500 °C and 700 °C for 30 min [Oginni & Singh, 2020] and on biochars derived from fruit waste used in the wine and cider industries, obtained by pyrolysis and gasification [Sette et al., 2020]. The R_{50} values were lower than 0.5, placing them below highly recalcitrant materials such as soot or graphite, the observed behavior suggests moderate resistance to degradation and adequate potential for carbon sequestration in soils [Harvey et al., 2012].

The aromaticity factor (fa) and the stable carbon mass fraction (SCF) also increased significantly with increasing carbonization temperature (Table 2). These results are consistent with studies reported for biochars produced from apple pomace and grape residues [Sette et al., 2020] and for biochars produced from *Miscanthus x giganteus*, which showed fa ranging from 0.928 to 0.975 and

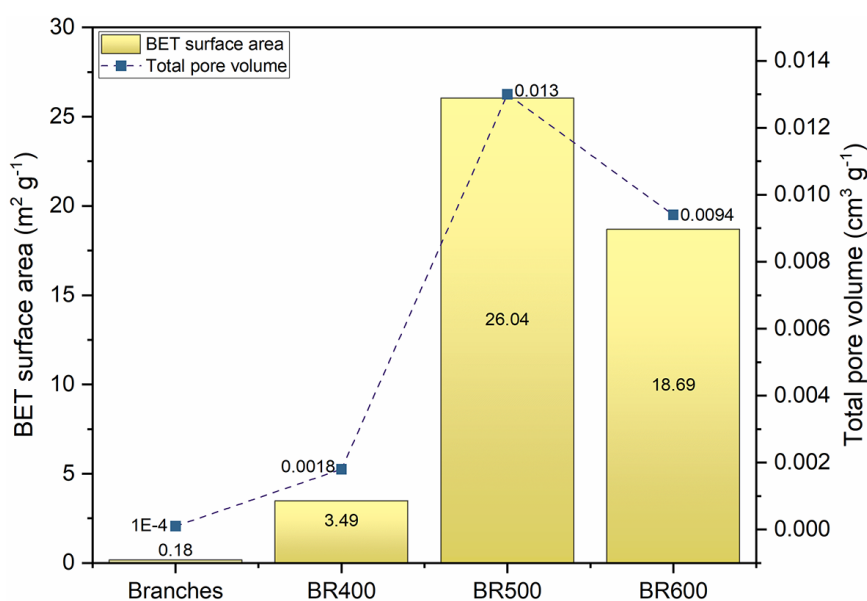


Figure 3. BET area and pore volume of *Ficus benjamina*

Table 2. Recalcitrance potential, aromaticity factor, stable C mass fraction and mean residence time of biochars produced at 400, 500, 600 °C

Parameters	BR400	BR500	BR600
Recalcitrance potential (R_{50})	0.140 ± 0.0002	0.145 ± 0.0002	0.149 ± 0.0003
Aromaticity factor (fa)	0.912 ± 0.0047	0.942 ± 0.0039	0.997 ± 0.0030
Stable C mass fraction (SCF)	0.743 ± 0.0021	0.786 ± 0.0017	0.818 ± 0.0025
Mean residence time (years)	1627.146 ± 1.27	1676.570 ± 1.85	1733.665 ± 3.75

SCF ranging from 0.827 to 0.872 [Oginni & Singh, 2020]. However, the fa (0.463 to 0.670) and SCF (0.695 to 0.852) reported in biochars derived from carbonized walnut and almond shells at 400, 500, and 600 °C with a residence time of 2 h [Ortiz et al., 2020] were lower values than those reported in this study. This behavior would be related to the fact that *Ficus benjamina* biochars contain a higher fixed carbon content and a lower proportion of volatile compounds [Ortiz et al., 2020]. These results show that the lignocellulosic content of the source biomass, together with the thermal conditions, influence the formation of stable aromatic structures. Therefore, biochars obtained at 600 °C showed SCF values greater than 80 %, indicating a higher proportion of structurally recalcitrant carbon [Venkatesh et al., 2022].

Regarding the mean resistance time (MRT), the biochars evaluated reached values between $1\,627.146 \pm 1.27$ and $1\,733.665 \pm 3.75$ years (Table 2), with a significant increase as the carbonization temperature increased. These values are consistent with reported studies on biochars derived from fruit residues used in the wine and cider industry, whose MRT ranged between 1 253 and 1 701 years [Sette et al., 2020], and also with biochars derived from the pigeon pea (*Cajanus cajan*), which ranged between 903.6 and 1 553.58 years [Venkatesh et al., 2022]. This high persistence suggests that biochars derived from branches of *Ficus benjamina* can act as long-lasting carbon sinks and contribute to restoration strategies for degraded soils.

Overall, the results of this study indicate that biochars derived from branches of *Ficus benjamina* possess desirable agronomic and environmental characteristics. Their high aromaticity, high recalcitrance potential, significant stable carbon content, and half-life of more than 1000 years reinforce their applicability in sustainable soil management practices.

Yield and energetic properties of biochars

Mass and energy yield

The mass yield progressively decreased with increasing carbonization temperature (Fig. 4). This behavior is attributed to the release of volatile compounds and non-condensable gases such as CO₂, CO, H₂, and CH₄, generated by the thermal decomposition of the lignocellulosic structure, which promotes the production of liquid and gaseous fractions [B. Zhao et al., 2018]. Previous studies have reported an inverse correlation between carbonization temperature and mass yield, since higher temperatures improve biochar stability and its adsorption capacity for environmental applications [Llanos et al., 2025; Vijayaraghavan & Balasubramanian, 2021]. In general, optimal biochar mass yields are typically reported in the 400 °C to 500 °C, range, although they vary depending on the characteristics of the biomass used [Altikat et al., 2024]. This behavior was also observed in the pyrolysis of *Ficus religiosa* wood and bark, where the mass yield varied from 38.9 wt.% to 22.6 wt.% between 350 °C and 550 °C [Rao et al., 2022], while in biochars produced from the carbonization of pine wood wastes in the range of 300 °C to 600 °C, the mass yield ranged from 66.4 wt.% to 37.3 wt.% [Vijayaraghavan & Balasubramanian, 2021].

Similarly, the energy yield showed significant differences depending on the carbonization temperature. As it increased from 400 °C to 600 °C, the energy yield decreased from $51.6 \pm 0.15\%$ to $39.36 \pm 0.48\%$. This decrease is explained by the reduction in mass yield and the increase in thermal degradation at elevated temperatures, which induces the formation of non-condensable vapors and gases [Baghel et al., 2022]. Biochar obtained at 400 °C and 500 °C showed higher energy yield, attributed to its higher carbon content and lower ash content, which resulted in an increase in its calorific value (Fig. 4). Similar results have been reported in the carbonization of *Prosopis juliflora*, where the energy yield decreased from 63.33

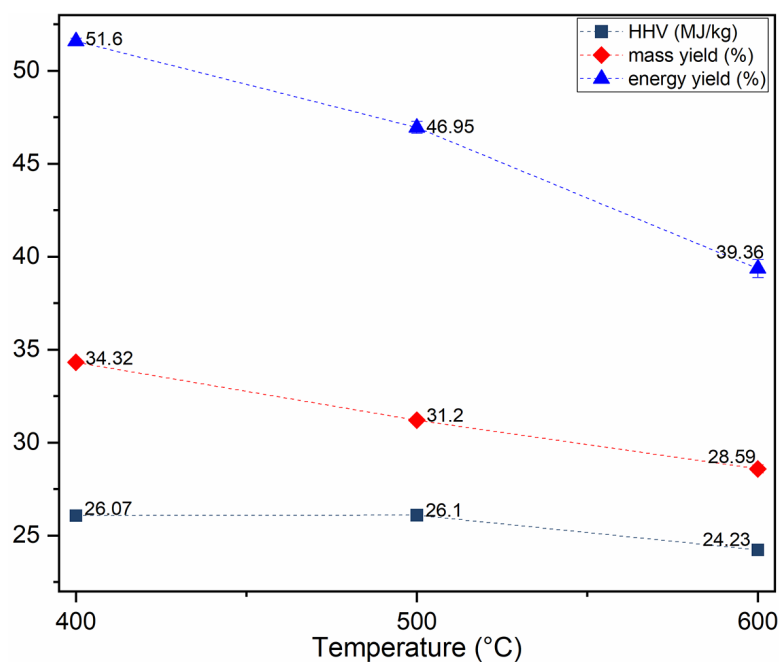


Figure 4. Mass yield, energy yield and HHV of biochars

to 42.90 wt.% with increasing temperature from 300 °C to 600 °C for 1 h [Baghel et al., 2022]. Therefore, biochar production at intermediate temperatures (400 °C to 500 °C) represents a more energy efficient option, optimizing the balance between product quality and recovered mass.

Fuel ratio

The fuel ratio (FR), defined as the ratio of the fixed carbon content to the volatile matter content, is a parameter used to evaluate the combustion properties of a solid fuel [Singh et al., 2020]. In this study, the produced biochars showed a progressive increase in FR with increasing carbonization temperature, from 2.37 ± 0.029 at 400 °C, 3.13 ± 0.040 at 500 °C and 4.08 ± 0.097 at 600 °C. This increase is attributed to the reduction of the volatile fraction and the enrichment of fixed carbon during the increase of carbonization temperature, which is consistent with the literature on the thermal behavior of lignocellulosic materials [Mendoza Martinez et al., 2021]. According to various studies, the recommended values for FR in biochars intended for efficient combustion are in the range of 0.5 to 3 [Singh et al., 2020]. In this context, biochars produced at 400 °C and 500 °C are within the optimal range for their potential use as solid fuel in controlled combustion-based energy conversion processes. In addition to FR, the heating value, another

important parameter, provides a direct measure of the energy density of the biochar.

Higher heating value

The higher heating value (HHV) of the biochars derived from the branches of *Ficus benjamina* showed statistically significant differences ($p < 0.05$) between the carbonized samples at 500 °C and 600 °C (26.10 ± 0.2 MJ kg⁻¹ and 24.23 ± 0.22 MJ kg⁻¹), while the increase observed between 400 °C and 500 °C (26.07 ± 0.075 MJ kg⁻¹ and 26.10 ± 0.2 MJ kg⁻¹) was not significant ($p > 0.05$), as shown in Figure 3. The increase in fixed carbon content from 62.92 to 67.19 wt.% between 400 °C and 500 °C initially favored the increase in HHV; while at 600 °C, the HHV decreased, possibly due to the increase in ash content, from 11.34 wt.% to 13.41 wt.% between 500 °C and 600 °C. This behavior has been reported in other studies, such as the case of palm fiber biochars, whose HHV increased from 23.06 MJ kg⁻¹ to 26.77 MJ kg⁻¹ between 300 °C and 700 °C, and decreased to 25.61 MJ kg⁻¹ when subjected to 900 °C [Selvarajoo & Oochit, 2020]. In general terms, the increase in HHV with carbonization temperature is associated with the enrichment of fixed carbon, the loss of structural oxygen, and the increase in inorganic content can reduce HHV [Oginni & Singh, 2020; Selvarajoo & Oochit, 2020]. However, at

high temperatures, structural degradation and increase in inorganic content can reduce the HHV of biochar.

Biochars produced at 400 °C and 500 °C recorded HHV values between 25 and 30 MJ kg⁻¹, which fall within the optimal range for solid fuels [Ilyushechkin et al., 2014]. The HHV of these biochars significantly exceeded the HHV of Hailar lignite 20.89 MJ kg⁻¹ [An et al., 2017], bituminous coal (25.86 MJ kg⁻¹) [Geng et al., 2016], sub-bituminous coal (24.30 MJ kg⁻¹) [Valdés et al., 2016] and with HHV similar to charcoal (26.07 MJ kg⁻¹) [Motghare et al., 2016]. On the contrary, biochar produced at 600 °C had a HHV of 24.23 MJ kg⁻¹, equivalent to sub-bituminous coal. This behavior is attributed to the excessive volatilization of organic compounds at elevated temperatures, suggesting that temperatures above 500 °C compromise the energy efficiency of biochar. The comparative analysis establishes that optimized biochars (400 °C and 500 °C) constitute viable energy substitutes for conventional coals, exhibiting characteristics superior to bituminous and sub-bituminous coal and comparable to charcoal.

Carbonization temperature emerges as a critical parameter for maximizing energy potential, with an optimal range between 400 °C and 500 °C that balances mass yield and energy efficiency.

PAHs production from the carbonization process

The concentrations of the 15 polycyclic aromatics hydrocarbons (PAHs) in the biochars produced at 400, 500 and 600 °C for 2 h are shown in Table 3. Figure 5a presents the effect of carbonization temperature on individual PAHs concentrations, and Figure 5b shows their distribution by molecular weight. Low molecular weight PAHs (LPAHs) predominated at lower temperatures (400 °C), whereas high molecular weight PAHs (HPAHs) progressively volatilized with increasing temperature (600 °C).

The biochar produced at 400 °C presents the total concentration of PAHs (TPAHs) of 160.17 µg kg⁻¹, with an abundance of low molecular weight PAHs (LPAHs) that represented 79.41% (127.19 µg kg⁻¹) of the total (Figure 5a). The presence of Phe and Nap evidences the thermal stabilization mechanisms reported in the literature, where biomass carbonization increases aromaticity and generates micropores that facilitate the retention of 2- and 3-ring aromatic structures in the carbon matrix [X. Wang & Xing, 2007]. These findings are consistent with studies that identified Nap and Phe as the main contributors to total PAHs concentrations, followed by Ant, Pyr and Flt [De la Rosa et al., 2019]. Furthermore, the literature confirms that low pyrolysis

Table 3. Polycyclic aromatic hydrocarbons (PAHs) contents (µg kg⁻¹) in biochars obtained from *Ficus benjamina* branches

PAHs	Rings number	BR400	BR500	BR600	Limit*, µg kg ⁻¹
Naphthalene (Nap)	2	57.84	20.50	25.23	1750
Acenaphthylene (Acy)	3	0.00	0.00	0.00	34
Fluorene (Flu)	3	2.27	0.00	5.83	71
Phenanthrene (Phe)	3	63.45	0.00	0.00	710
Anthracene (Ant)	3	3.63	0.00	0.00	---
Fluoranthene (Flt)	4	10.90	0.00	0.00	300
Pyrene (Pyr)	4	19.36	0.00	0.00	350
Benzo(a) anthracene (BaA)	4	0.00	0.00	0.00	350
Chrysene (Chr)	4	0.00	0.00	0.00	95
Benzo(b)fluoranthene (BbF)	5	0.00	0.00	0.00	130
Benzo(k)fluoranthene (BkF)	5	0.00	0.00	0.00	100
Benzo(a) pyrene (BaP)	5	0.00	0.00	0.00	190
Dibenzo(a,h) anthracene (DbA)	5	0.00	0.00	0.00	56
Indeno(1,2,3-cd)pyrene (Ipy)	6	0.00	0.46	0.00	150
Benzo(g,h,i)perylene (Bpe)	6	2.72	2.44	0.83	150
Σ 15 PAHs of 16 US-EPA PAHs		160.17	23.40	31.89	

Note: * US-EPA PAHs

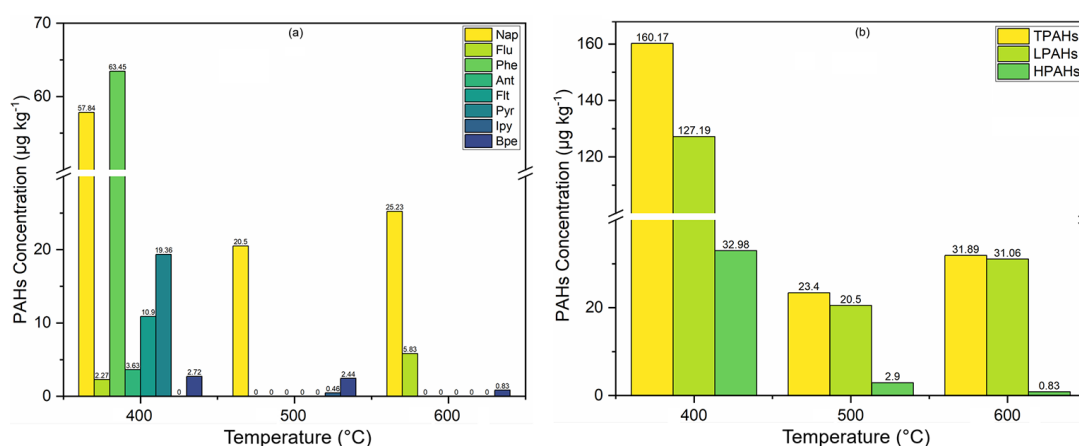


Figure 5. Effect of carbonization temperature; (a) individual PAHs concentrations in biochars; (b) molecular weight distribution in biochars

temperatures (400 °C) favor the formation of 2- and 4-ring PAHs, including Flu, Phe, Ant, Flt, and Pyr [Póltorak et al., 2024].

On the other hand, the biochar produced at 500 °C, the total concentration of PAHs decreased significantly to $23.40 \mu\text{g kg}^{-1}$, with the Nap being the most abundant compound ($20.5 \mu\text{g kg}^{-1}$), followed by Ipy and Bpe, which together represented $2.9 \mu\text{g kg}^{-1}$ of the total. This decrease in total PAHs concentrations relative to 400 °C is attributed to the volatilization of amorphous components, aromatic condensation into non-extractable sheet-like structures, and their preferential adsorption on the carbonaceous matrix of biochar [Keiluweit et al., 2012]. Previous studies have reported active PAHs formation in the range of 400 °C and 500 °C due to polymerization of organic precursors and volatile compounds [Keiluweit et al., 2012]. The results evidence that biochars produced to 500 °C from branches of *Ficus benjamina*, the elimination processes are optimized, establishing this optimal condition to minimize the PAHs content without compromising other properties of the material.

However, the biochar produced at 600 °C, the total concentration of PAHs increased to $31.89 \mu\text{g kg}^{-1}$, with the presence of Nap ($25.23 \mu\text{g kg}^{-1}$), followed by Flu ($5.83 \mu\text{g kg}^{-1}$) and Bpe ($0.83 \mu\text{g kg}^{-1}$). The higher presence of LPAHs at 600 °C is consistent with studies reporting that at temperatures of 500 °C and 600 °C, LPAHs such as Nap and Phe constitute the majority fraction of the biochar obtained, while high molecular weight PAHs (HPAHs) appear in low concentrations, attributed to the fact that high temperatures induce dehydration, decarboxylation and dehydrogenation

reactions that favor the formation and stabilization of light compounds in biochar, while heavier compounds decompose [Devi & Dalai, 2023]. Furthermore, it has been observed that increasing the pyrolysis temperature between 500 °C and 700 °C increases the proportion of derivatives of LPAH in biochars, while HPAHs decrease, evidencing the preferential thermal decomposition of the latter due to their greater structural susceptibility under high temperature conditions [Krzyszczak et al., 2021].

The absence of BaA, Chr, BbF, BkF, Bap, and DbA in all the biochars studied confirms the complete thermal degradation of these PAHs during carbonization [Gondek et al., 2016]. This behavior indicates that these compounds undergo molecular fragmentation at temperatures above 500 °C, where the decomposition products migrate to liquid or gaseous fractions or are completely mineralized during the process [Devi & Dalai, 2023; Keiluweit et al., 2012]. The redistribution profile observed at 600 °C reflects that these elevated temperatures induce a selective chemical rearrangement in which differential thermal stability based on structural complexity determines the final PAHs composition, resulting in a net accumulation of 2- and 3-ring aromatic compounds as the predominant products of thermal cracking reactions.

In this study, high molecular weight PAHs, such as BaA, BaP, Chr, BbF, BkF and DbA, were found in the biochars analyzed. However, these compounds have been reported in biochars derived from date palm residues and other sources of lignocellulosic origin subjected to pyrolysis [Alharbi et al., 2023; Póltorak et al., 2024]. This indicates that the variability in PAHs

concentrations in *Ficus benjamina* biochars is related to the specific composition of biomass and the pyrolysis conditions, which influence the formation and release of these compounds [Keiluweit et al., 2012; Krzyszcak et al., 2021]. Controlling the aforementioned factors is essential to minimize the presence of hazardous compounds in biochar. The results obtained in this study are in agreement with the literature, which shows that Nap and other LPAHs are more abundant at low pyrolysis temperatures (300 °C and 400 °C) due to the condensation of light volatile compounds. However, with increasing pyrolysis temperatures (500 °C and 700 °C), Nap concentration tends to decrease due to its high vapor pressure, which facilitates its volatilization and escape from biochar [De la Rosa et al., 2019; Devi & Dalai, 2023; Hung et al., 2023]. In this study, a decrease in Nap concentration was observed at 500 °C, followed by a slight increase at 600 °C, in agreement with the literature suggesting a secondary decomposition of complex aromatic structures that releases this compound again at higher temperatures.

The biochars used in this study meet the global quality requirements set forth by the European Biochar Certificate (EBC) and the International Biochar Initiative (IBI). PAHs concentrations in these biochars were well below the 6 000 µg kg⁻¹ limit set by the IBI [Ibi, 2015], suggesting that they are safe for use as soil amendments [De la Rosa et al., 2019]. The EBC states that biochars with PAHs concentrations below 4 000 µg kg⁻¹ are suitable for use in agriculture [The European Biochar Certificate, 2023]. All *Ficus benjamina* biochars produced at 400, 500, and 600 °C in this study meet the premium biochar standards, making them safe and effective substitutes for applications involving environmental remediation and the improvement of agricultural soil. Comparative analysis revealed that total PAHs concentrations in this study were much lower than those found in laboratory and commercial biochars produced under different carbonization conditions, which ranged from 608 to 12 347 µg kg⁻¹ [J. Wang et al., 2018]. This comparative advantage over laboratory and commercial biochars, *Ficus benjamina* biochars are positioned as superior quality materials that simultaneously meet the requirements of IBI and EBC.

The results confirm that carbonization temperature selectively determines the distribution of PAHs in *Ficus benjamina* biochars, favoring the formation of LPAHs at moderate temperatures, while HPAHs undergo progressive degradation

with increasing temperature. Compliance with international standards validates their safe applicability in sustainable agriculture and environmental remediation.

CONCLUSIONS

This research demonstrated that the carbonization temperature significantly impacts the physicochemical, energetic, textural, and environmental properties of biochars derived from pruned branches of *Ficus benjamina*. The results showed that biochars produced at 400 °C to 600 °C for 2 h exhibited suitable characteristics for sustainable agronomic applications, highlighting an alkaline pH, a moderate ash content, and electrical conductivity, properties that favor the improvement of acid or low-salinity soils. Biochar produced at 500 °C exhibited the optimal balance with the highest BET surface area (26.04 m² g⁻¹), the lowest ash content (11.34 wt.%), and a low concentration of polycyclic aromatic hydrocarbons (23.40 µg kg⁻¹), attributes that indicate its potential for agricultural and environmental applications. In terms of energetic properties, biochars prepared between 400 °C and 500 °C exhibited higher calorific value values (26.07 to 26.10 MJ kg⁻¹) comparable to charcoal and higher than sub-bituminous coal, establishing their technical viability as a renewable solid biofuel. Stability characterization showed high carbon recalcitrance with elevated aromaticity factors and average residence times exceeding 1 000 years, characteristics that support their potential for long-term carbon sequestration. With respect to the polycyclic aromatic hydrocarbons (PAHs) profile, it was observed that the carbonization temperature regulates their distribution, favoring the formation of low-molecular weight compounds at moderate temperatures, and promoting the progressive degradation of high-molecular weight PAHs as the temperature increases. All levels remained within the limits established by international standards (IBI and EBC), ensuring their safe use in agriculture. These findings confirm that biochars derived from pruned branches of *Ficus benjamina* constitute a viable and environmentally sustainable strategy for the valorization of urban lignocellulosic biomass, with promising applications in the energy, agricultural and environmental sectors.

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