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Using wood anatomical characteristics and physicochemical properties to segregate Amazonian wood wastes for charcoal production

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ABSTRACT

The anatomical characteristics of Amazonian wood wastes significantly influence their suitability for charcoal production, yet this relationship remains underexplored for industrial applications. This study analyzed wood wastes from twelve Amazonian species obtained through reduced-impact logging to identify which anatomical characteristics influence species grouping for improved charcoal production. Tests included anatomical, chemical, basic density (WBD), and carbonization analyses. *Caryocar villosum* exhibited the highest fiber length (1959.18 µm), vessel length (539.82 µm), and cell wall thickness (CWT: 9.17 µm). *Parinari rodolphii* stood out with the greatest total fiber width (25.17 µm). *Dinizia excelsa* had the smallest fiber lumen diameter (FLD: 1.76 µm), the highest wall fraction (WF: 89.14%), and notable CWT (7.22 µm), correlating with high WBD (796 kg m^{-3}) and superior apparent relative density (ARD) of charcoal (620 kg m^{-3}). Four groups of species with similar characteristics were recognized based on the dispersion of the scores in a PCA. FLD, CWT, and WF were the most relevant traits for group formation. *M. elata*, *D. excelsa*, and *Lecythis lurida* were considered the most suitable group for energy purposes due to their high WF and CWT values, resulting in high charcoal ARD (average 591 kg m^{-3}). These findings support the adoption of circular bioeconomy strategies in tropical forestry by promoting the recovery and valorization of wood wastes for renewable energy generation and contributing to more sustainable charcoal supply chains.

KEYWORDS: tropical wood, waste valorization, circular energy, clean energy, biofuel

Utilização de características anatômicas e propriedades físico-químicas da madeira para segregar resíduos de madeira da Amazônia para produção de carvão vegetal

RESUMO

As características anatômicas dos resíduos de madeira amazônica influenciam significativamente sua aptidão para a produção de carvão vegetal, embora essa relação ainda seja pouco explorada em aplicações industriais. Este estudo analisou resíduos de madeira de doze espécies amazônicas obtidas por meio de exploração de impacto reduzido, visando identificar quais características anatômicas influenciam o agrupamento de espécies para produção de carvão vegetal de melhor qualidade. Os testes incluíram análises anatômicas, químicas, de densidade básica (DBM) e de carbonização. *Caryocar villosum* apresentou o maior comprimento de fibra (1959,18 µm), comprimento de vaso (539,82 µm) e espessura da parede celular (EPC: 9,17 µm). *Parinari rodolphii* se destacou com a maior largura total de fibra (25,17 µm). *Dinizia excelsa* apresentou o menor diâmetro do lúmen (DL: 1,76 µm), a maior fração parede (FP: 89,14%) e elevada EPC (7,22 µm), o que se correlacionou com alta DBM (796 kg m^{-3}) e maior densidade relativa aparente (DRA) do carvão vegetal (620 kg m^{-3}). Quatro grupos de espécies com características semelhantes foram reconhecidos com base na dispersão dos escores de uma PCA. DL, EPC e FP foram os atributos mais relevantes para a formação dos grupos. *M. elata*, *D. excelsa* e *Lecythis lurida* formaram o grupo mais adequado para fins energéticos, devido aos elevados valores de FP e EPC, resultando em alta ARD do carvão vegetal (média de 591 kg m^{-3}). Esses achados apoiam a adoção de estratégias de bioeconomia circular na silvicultura tropical, promovendo a recuperação e valorização dos resíduos de madeira para a geração de energia renovável e contribuindo para cadeias de suprimentos de carvão mais sustentáveis.

PALAVRAS-CHAVE: madeira tropical, valorização de resíduos, energia circular, energia limpa, biocombustível

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INTRODUCTION

Sustainable forest management plans (SFMP) in Amazonia are essential for conserving natural resources and maintaining forest health during logging activities (DeArmond *et al.* 2023), especially when implemented under certification systems (Rana and Sills 2024). These plans are regulated by Normative Instruction No. 5, issued on December 11, 2006 (Brazil 2006), by the Brazilian Ministry of the Environment, which provides guidelines for the sustainable harvesting of both timber and non-timber forest products, while ensuring the maintenance of ecosystem functions. Despite these regulatory advances, logging activities still generate significant wood waste. Wood waste in forest management areas was shown to be as high as 2.13 tons per ton of harvested wood (Numazawa *et al.* 2017) or up to 100,000 tons annually (Lima *et al.* 2020*a*). This quantity of waste corresponds to an estimated annual production of 20,000 tons of charcoal, considering a charcoal yield of 20% on a wet basis (Lima *et al.* 2023, Ferreira *et al.* 2024).

One promising solution is the conversion of SFMP wastes into charcoal. By transforming waste materials into valuable bioenergy products, this approach aligns with global sustainability goals by closing resource loops (Corona *et al.* 2019), minimizing waste, and reducing pressure on primary forests (Scrucca *et al.* 2023). Such systems not only recover what would otherwise be low-value biomass but also generate energy alternatives with lower global warming potential (GWP) than fossil fuels, contributing to climate change mitigation efforts in the region (Numazawa *et al.* 2017). Life cycle studies indicate that GHG emissions and air pollutants from biomass and charcoal are considerably lower than those from coal-based energy use (Wang *et al.* 2020, Kikuchi *et al.* 2022). The carbon emissions resulting from the use and production of charcoal are reabsorbed by plants, provided that the wood sources are obtained through techniques that allow proper forest regeneration, such as SFMP. Carbon emissions from the energetic use of wood can even be negative in planted forests, that is, there is more carbon sequestration than emissions (Myint *et al.* 2021). Similar results were found for SFMP (Numazawa *et al.* 2017). Among the advantages of using biomass and derived fuels as energy sources, it is important to highlight their negligible levels of nitrogen (N) and sulfur (S), which are responsible for the release of NOx and SOx during combustion and, consequently, for atmospheric pollution (Lima *et al.* 2020*b*).

In contrast, fossil fuels release carbon that has been stored in the ground for thousands of years, thereby contributing to increasing the global warming potential. It is important to highlight, however, that the climate benefits of biomass depend on the adoption of sustainable practices, including forest regeneration and efficient conversion technologies. Therefore, the global warning potential of biomass relies on achieving a favorable balance between carbon sequestration and emissions over its complete life cycle, encompassing all stages of the biofuel production chain (Liu *et al.* 2017).

In Brazil, the use of logging wastes (e.g., branches, trunk remnants) is legally permitted for charcoal production (Normative Instruction No. 5, dated December 11, 2006) (Brazil 2006), but strategies to optimize their energy efficiency remain underexplored. The use of SFMP waste is hindered by the high heterogeneity of raw materials in terms of dimensions and wood quality, leading to losses in charcoal yield and quality. Segregating wood waste has proven to offer significant benefits, including increased kiln productivity, higher charcoal yield (Lima *et al.* 2023) and improved quality (Barros *et al.* 2023). However, studies exploring the role of wood anatomical characteristics in this context remain scarce in the bioenergy field. This knowledge gap suggests that similar segregation strategies could be beneficial beyond Amazonia, as tropical regions facing similar challenges could enhance their charcoal production efficiency and demonstrate the universal applicability of this approach.

Although the influence of anatomical characteristics on wood basic density is well understood (Baldin *et al.* 2018, Dhaka *et al.* 2020), few studies have explored their potential use as indicators for grouping species and inferring charcoal properties, such as apparent relative density (ARD), an important parameter for applications in the steel industry, as it is associated with compressive strength and friability (Balaguer-Benlliure *et al.* 2023, Barros *et al.* 2023). One of these few studies has shown that fiber lumen density (FLD), a wood anatomical property, was negatively correlated to the apparent relative density of charcoal (Couto *et al.* 2023). The present study seeks to fill this gap by proposing, for the first time, a method for classifying wood residues from SFMP in the Amazonia, based on wood anatomical and physical-chemical characteristics, with the aim of improving charcoal yield and quality. We hypothesize that the anatomical characteristics of wood wastes from managed Amazonian species can serve as reliable indicators for species grouping and for predicting the apparent relative density of charcoal. Thus, we intend to provide valuable information on the potential of anatomical characteristics to classify wood residues from the crown of Amazonian tree species, optimizing the production of quality charcoal and promoting the circular economy through waste recovery and renewable energy generation.

MATERIAL AND METHODS

Collection of wood wastes from a SFMP

The wood wastes come from the Sustainable Forest Management Unit of the Rio Capim farm (between 3° 30' and 3° 45' S and 48° 30' and 48° 45' W longitude), located in Paragominas City (Pará state, Brazil), owned by the Keilla Group in compliance with Brazilian forest legislation. This region exhibits an Am climate (Köppen-Geiger), with an average annual temperature of 26.6ºC and 1805 mm rainfall (Climate-Data.org 2019). Veloso *et al.* (1991) classify the vegetation in the study area as the Submontane Dense Ombrophylous Forest type.

Twelve species from six botanical families (Table 1) were sampled. From each of three trees per species, two wooden discs were collected from the base of the largest branches in the ground, three days after the tree has been felled. Botanical identification was performed using vegetative (leaves) and, when available, reproductive (flowers and fruits) material, sent to the Embrapa Amazônia Oriental Herbarium (IAN, Belém, Pará) for comparison with reference material. Vouchers are accessible via http://brahms.cpatu.embrapa.br/, (registration codes in Table 1). Further details are in Lima *et al.* (2020a).

Obtaining the test specimens and determining the wood basic density

Following the general methodological scheme (Figure 1), two discs of approximately 7 cm were obtained from the base of the largest branch of each sampled tree. One disc was used for total extractives, total lignin and laboratory charcoal production. The second disc was used for Xylotheque samples, wood basic density (WBD) and quantitative anatomical element description via maceration (Figure 1). WBD samples, covering heartwood and sapwood, were sectioned into specimens (2 cm x 1 cm x 5 cm), with the number per disc varying by diameter (Figure 1).

The WBD of the branches was calculated as the arithmetic average of the densities of the specimens per disc. The

Table 1. List of Amazonian species sampled at the Sustainable Forest Management Unit, Rio Capim farm, Paragominas city, Pará state, Brazil, and their voucher registration codes.

Family	Scientific name	Common name	HRC	RCX
Caryocaraceae	*Caryocar villosum* (Aubl.) Pers.	Piquiá	IAN197990	X8717
Chrysobalanaceae	*Licania canescens* Benoist	Casca-Seca	IAN197991	X8713
	Parinari rodolphii Huber	Coco-pau	IAN197997	-
Humiriaceae	*Vantanea parviflora* Lam.	Uxirana	FCUFRA7585	-
Lecythidaceae	*Couratari guianensis* Aubl.	Tauarí-liso	IAN197992	X8724
	Couratari oblongifolia Ducke & Kunth	Tauarí	IAN197996	X8726
	Lecythis lurida (Miers) S.A.Mori	Jarana	IAN197995	X8714
Leguminosae (Mimosoideae)	*Dinizia excelsa* Ducke	Angelim-vermelho	IAN197998	X8718
	Pseudopiptadenia suaveolens (Miq.) J.W.Grimes	Timborana	IAN197989	X8711
Sapotaceae	*Manilkara elata* (Allemão ex Miq.) Monach.	Maçaranduba	IAN197993	X8720
	Pouteria oblanceolata Pires	Abiu	IAN197999	X8722
	Pouteria sp.	Guajará-bolacha	IAN197985	X8719

Herbarium; HRC: Herbarium Registration Code; RCX: Registration Code in the Xyloteque of the Botany Laboratory of Embrapa Eastern Amazon, Belém, Pará, Brazil.

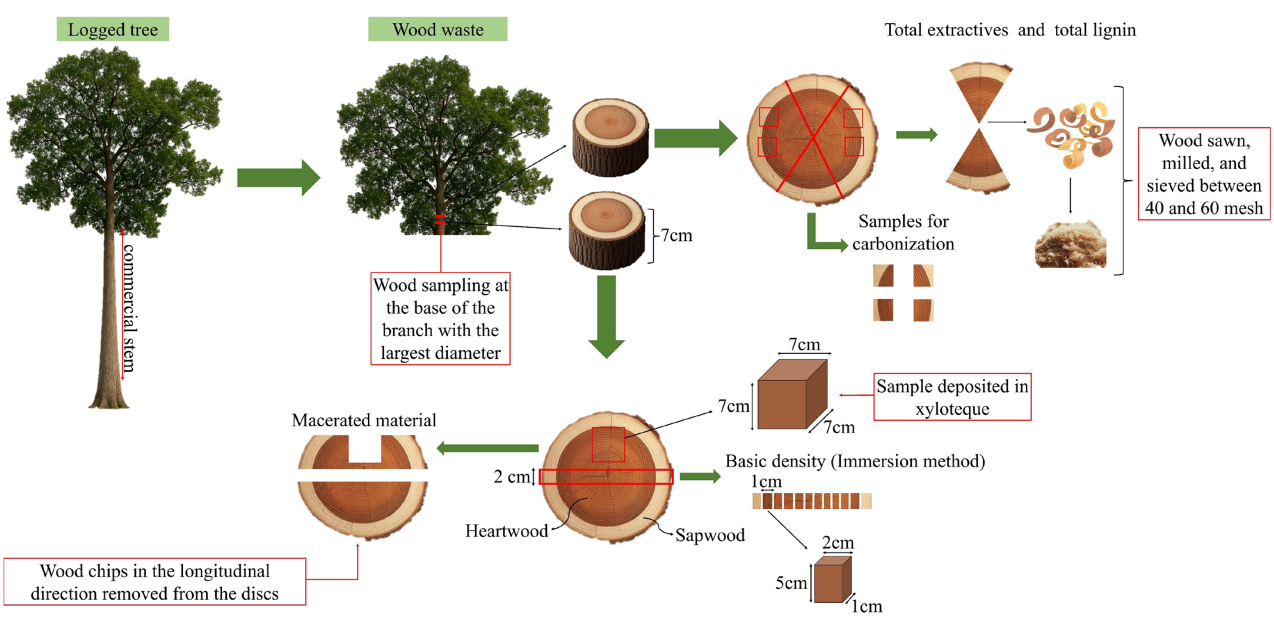

Figure 1. Sampling scheme of discs from wood wastes (branches) and preparation of specimens for analysis of 12 species obtained from a Sustainable Forest Management Unit, Rio Capim farm, Paragominas, Brazil.

WBD was determined based on the NBR 11941 standard (ABNT 2003), in which the volume was obtained by the water immersion method. WBD was classified according to Ruffinatto *et al.* (2015): low (< 400 kg m^{-3}), medium (400–750 kg m^{-3}) and high (> 750–1,000 kg m^{-3}).

Biometrics of fibers and vessel elements

Biometry of anatomical elements followed Franklin (1945). Small fragments of wood were removed from the discs with the aid of a knife. The fragments were placed in flasks containing a solution of glacial acetic acid and hydrogen peroxide (1:1 v/v) and placed in an oven at 60ºC for 24 h. Then, the dissociated material was washed in running water, stained with 1% hydroalcoholic safranin, and set in provisional slides with glycerin.

For the dissociated material (Figure 2), the following quantitative parameters were evaluated: length of vessel elements (LVE), fiber length (FL), total fiber width (TFW), and fiber lumen diameter (FLD). Cell wall thickness (CWT) and wall fraction (WF) were calculated using Equations 1 and 2, respectively (Foelkel and Barrichelo 1975, Paula and Alves 1997).

$$CWT = \left(\frac{TFW - FLD}{2}\right) \quad (1)$$

$$WF\,(\%) = \frac{2 \times CWT}{TFW} \times 100 \quad (2)$$

where: CWT is the cell wall thickness (μm), TFW is the total fiber width (μm), FLD is the fiber lumen diameter (μm), and WF is the wall Fraction (%).

Images of the anatomical elements were obtained using a Motic optical microscope, model BA310Elite. The measurement and quantification procedures followed the recommendations established by the IAWA Committee (IAWA 1989), and fifty measurements were taken for each anatomical element. The variables were measured using Motic Images Plus 3.0 software (Motic, Hong Kong, China).

Determination of total extractives and total lignin content

Total extractives (TE) were measured according to NBR 14853 (ABNT 2010a), using approximately 2 g of wet wood per sample collected. The procedure involved three steps: an extraction with ethanol (2:1 v/v) for 6 h in a Soxhlet extractor; followed by an extraction with pure ethanol for 5 h

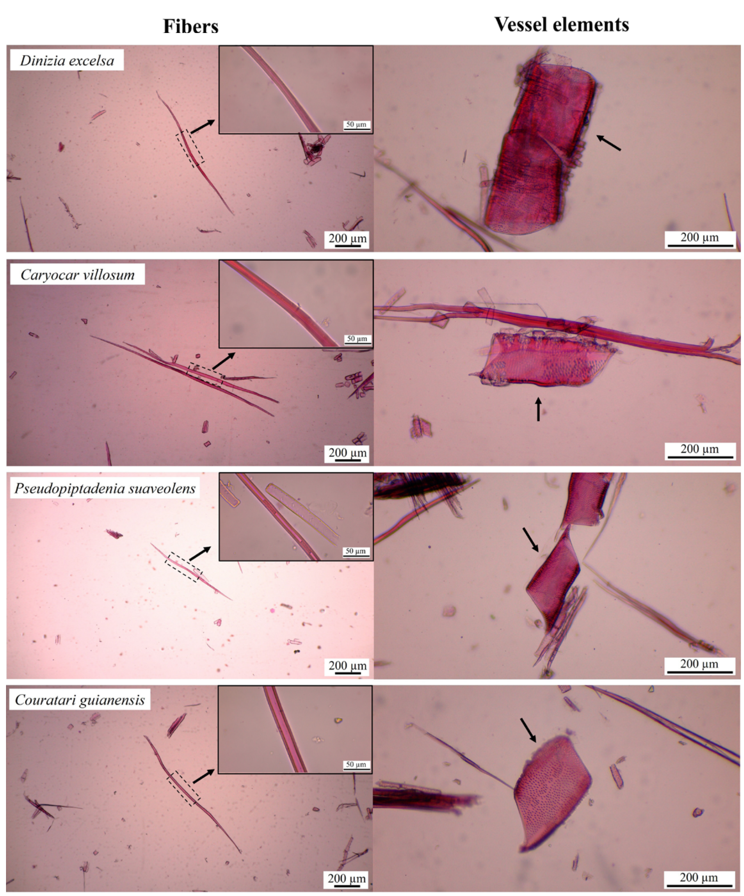

Figure 2. Wood fibers and vessel elements of four Amazonian tree species. Samples from the Sustainable Forest Management Unit, Rio Capim farm, Paragominas, Brazil.

in the same extractor; and, finally, an extraction with boiling distilled water for 2 h. Extractive-free samples were dried in an air circulation oven at 103 ± 2°C to obtain the dry mass.

Insoluble lignin (IL) was determined according to NBR 7989, using the acid hydrolysis method (ABNT 2010b). Soluble lignin (SL) was quantified by UV spectroscopy, as described by Goldschmid (1971). Total lignin (TL) content was calculated by summing up the IL and SL contents. More details can be seen in Lima *et al.* (2020a).

Production and determination of the apparent relative density of charcoal

Carbonizations were carried out in a muffle furnace (model Q318S25T, Quimis brand, São Paulo, Brazil), with a carbonization capsule, water-cooled condenser, and condensable gas collection bottle. Gravimetric yields of charcoal, pyroligneous liquid, and non-condensable gases from the Amazonian wood wastes were analyzed in a previous study (Lima *et al.* 2020*b*).

Around 300 g of initially kiln-dried wood (103 ± 2°C for 24 h) from opposing wedges was carbonized for 4 h and 30 min, reaching a maximum temperature of 450ºC for 30 min. Natural convection cooling lasted 16 h. The heating rate was 1.67ºC/min.

The volume was measured by the hydrostatic method, using four pieces of charcoal from each sampled branch to determine the apparent relative density (ARD). Volume was measured by the water displacement method, immersing the charcoal piece in a 500 cm^3 water-filled beaker placed over a 0.01 g precision balance. Dry mass was obtained after oven-drying samples at 103 ± 2ºC (0.01 g precision). ARD was calculated as the ratio of dry mass to charcoal volume. These procedures are detailed in Lima *et al.* (2020b).

Statistical analyses

Descriptive statistics (mean, median, coefficient of variation, minimum, and maximum values) and boxplots were performed to understand the data variation. Normality and homoscedasticity were assessed using Shapiro-Wilk ($p < 0.05$) and Bartlett ($p < 0.05$) tests, respectively. Pearson's linear correlation ($p < 0.05$) was performed between fiber characteristics, WBD, TE, TL, and charcoal ARD. Linear regression analysis ($p < 0.05$) was used to assess the relationships of WBD with CWT, WF, and FLD, and of ARD with FLD and WF. Hierarchical cluster analysis, utilizing Euclidean distance and the complete linkage method on the first two principal components from PCA, was performed to suggest natural groupings among tropical species. The resulting dendrogram guided the visual delimitation of groups in the PCA score plot, where ellipses were drawn around species that clustered together, providing a clearer interpretation of the multivariate relationships. All analyses were conducted using R software version 4.2.1 (R Core Team 2022).

RESULTS

Biometrics of fibers and vessel elements from waste wood

Among the anatomical characteristics, fiber lumen diameter (FLD) showed the highest variability (CV = 22.26%) among species (Figure 3). The overall order of variability considering all fiber characteristics was: FLD > CWT (CV = 8.65%) > FL (CV = 7.87%) > TFW (CV = 7.44%) > LVE (CV = 7.21%) > WF (CV = 6.90%).

FL ranged from 1017.22 µm (*P. suaveolens*) to 1959.18 µm (*C. villosum*), which also showed the greatest intraspecific variation, along with *P. rodolphii*, *L. lurida*, and *V. parviflora* (Figure 3a). The highest CWT was 9.17 µm in *C. villosum* and the lowest was 4.26 µm in *C. oblongifolia* (Figure 3b). FLD varied from 1.76 µm (*D. excelsa*) to 10.42 µm (*C. oblongifolia*), with more uniform values in several species, including *C. villosum* and *L. lurida* (Figure 3c). *P. rodolphii* showed the highest average LVE (637.8 µm) and *P. suaveolens* the lowest (307.12 µm) (Figure 3d). The highest average TFW was also in *P. rodolphii* (25.17 µm) (Figure 3e). WF was highest in *D. excelsa*, *C. villosum*, and *M. ellata* (>85%) with low intraspecific variation (Figure 3f).

Wood basic density and chemical composition

WBD (CV = 2.66%) exhibited greater homogeneity compared to TE (CV = 24.53%) and TL (CV = 5.82%) (Figure 4). *M. elata* and *D. excelsa* showed the highest average WBD values (913 and 797 kg m^{-3}, respectively), with low variability. *D. excelsa* had the highest average TE (17.9%, dry basis - db), with notable variability (15.9–20.5%, db), whereas *L. canescens* (3.3–4.0%, db), *P. rodolphii* (1.5–2.4%, db), *V. parviflora* (2.1–2.9%, db) and *C. oblongifolia* (3.5–4.2%, db) showed significantly lower and more homogeneous TE values (Figure 4b).

Correlations between anatomical characteristics, wood basic density and apparent relative density of charcoal

Significant correlations ($p < 0.05$) were found between WBD and FLD (r = -0.59), CWT (r = 0.70), WF (r = 0.75) and charcoal ARD (r = 0.79). Other significant correlations were found between ARD and FLD (r = -0.61) and WF (r = 0.65). LT did not correlate with any other variable. There was a negative correlation between FLD (r = -0.63) and TE (Figure 5).

WBD was positively related with CWT and WF, which were able to reasonably predict this wood property, with determination coefficients of 0.49 to 0.55 (Figure 6 a,b). WBD was negatively related with FLD, with a smaller determination coefficient (Figure 6c). The charcoal ARD had an inversely proportional relationship with FLD (Figure 6d), and a positive relationship with WF (Figure 6e). This result suggests that it is possible to classify charcoal from wood waste

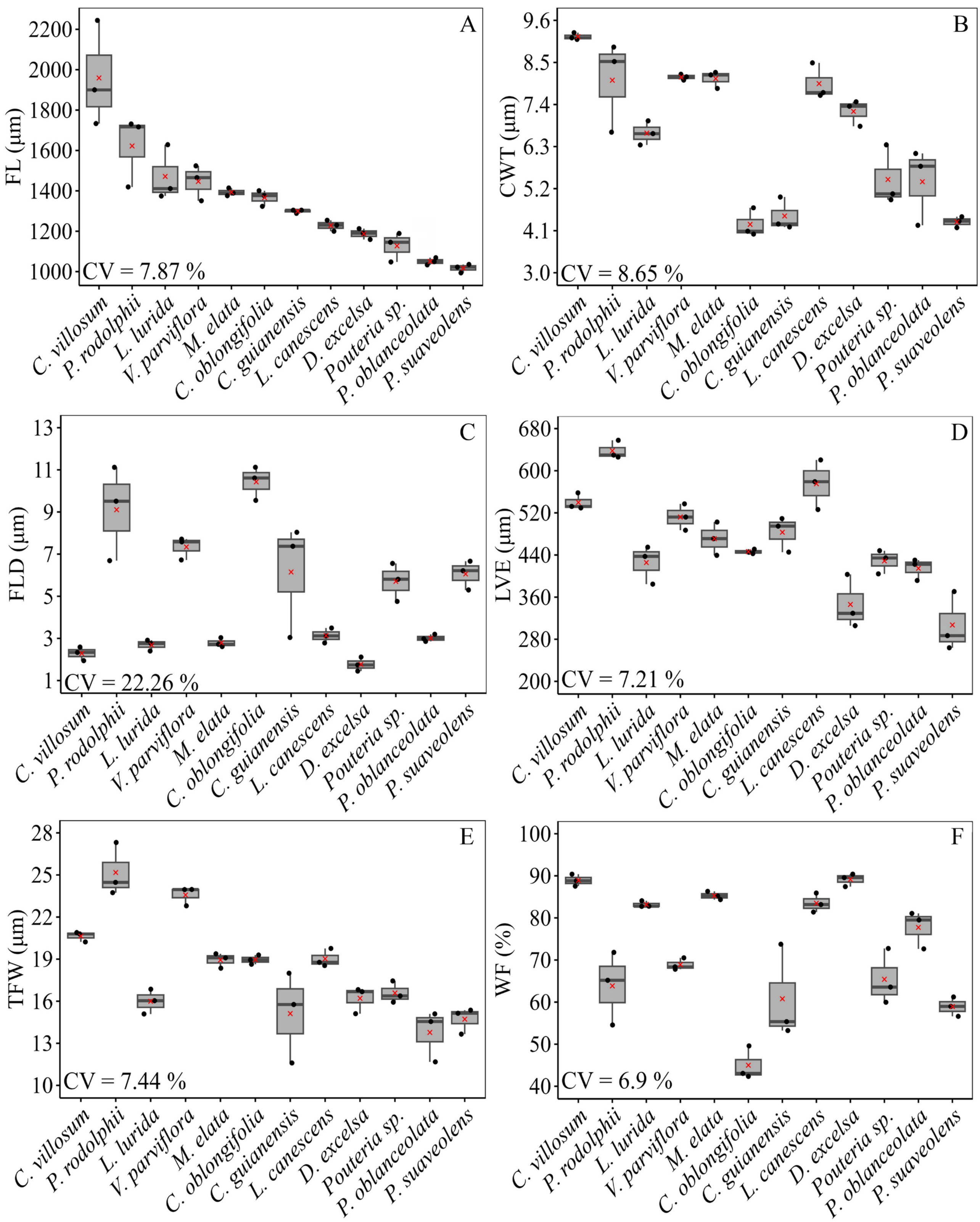

Figure 3. Variation of fiber length - FL (**A**), cell wall thickness - CWT (**B**), fiber lumen diameter - FLD (**C**), length of vessel elements - LVE (**D**), total fiber width - TFW (**E**), and wall fraction - WF (**F**) of wood from 12 species native to Amazonia. The boxplots present the medians (central lines), means (red crosses), and individual values (point clouds).

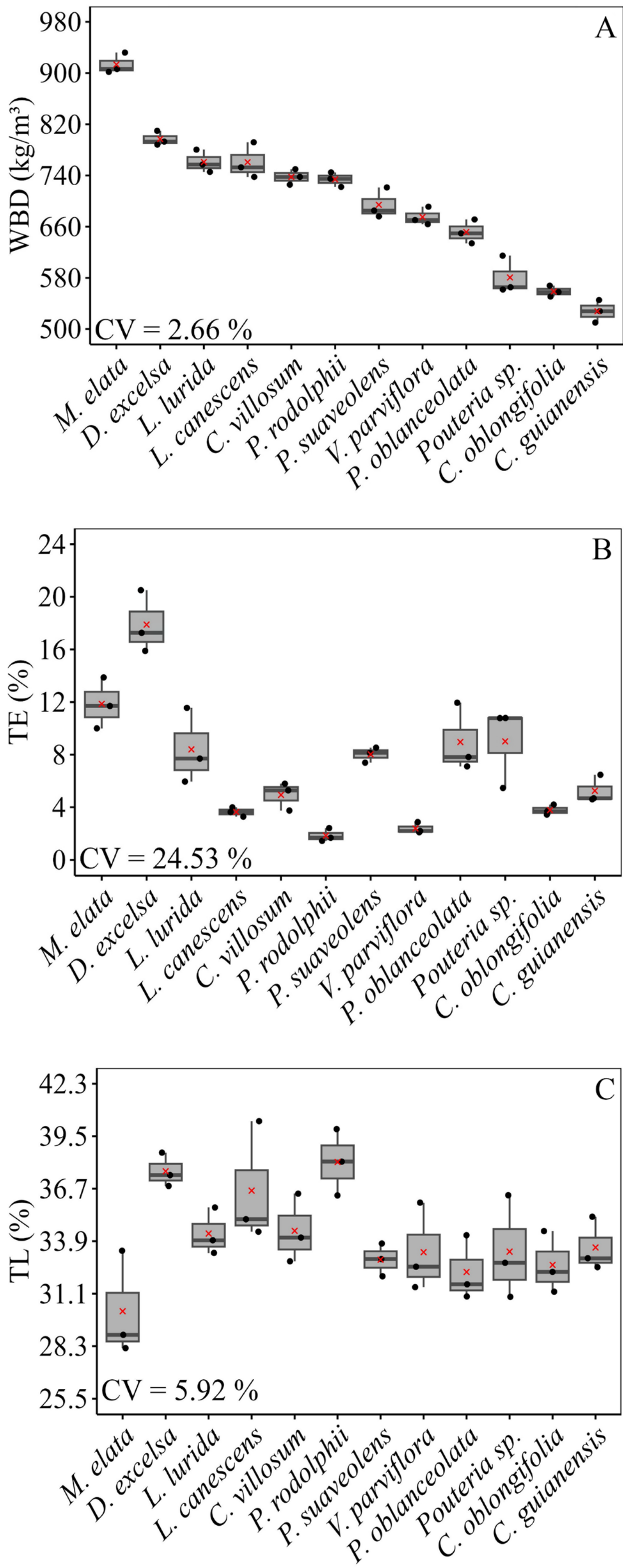

Figure 4. Variation of wood basic density – WBD (**A**), total extractives – TE (**B**), and total lignin – TL (**C**) of wood from 12 species native to the Amazonia. The boxplots present the medians (central lines), means (red crosses), and individual values (point clouds).

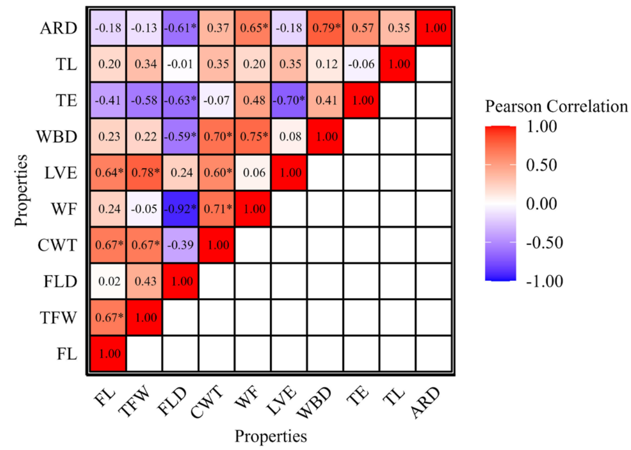

Figure 5. Pearson correlation matrix involving fiber length (FL), Total fiber width (TFW), Fiber lumen diameter (FLD), Cell wall thickness (CWT), Wall Fraction (WF), Length of vessel elements (LVE), wood basic density (WBD), total extractives (TE), total lignin (TL), and apparent relative density (ARD) of charcoal from 12 species native to the Amazonia. * Significant correlation ($p < 0.05$).

considering the WF (Figure 6e). For instance, woods with WF < 70% exhibited charcoal ARD ranging from 423 to 526 kg m^{-3}, while woods with WF > 70% resulted in higher ARD (464 – 620 kg m^{-3}). This last class includes the charcoals of *D. excelsa* (620 kg m^{-3}), *L. canescens* (604 kg/m^3), *L. lurida* (581 kg m^{-3}), *M. elata* (573 kg m^{-3}), *C. villosum* (464 kg m^{-3}), and *P. oblanceolata* (464 kg m^{-3}). These charcoals can be classified into ARD classes 2 ($400 \leq$ ARD < 550 kg m^{-3}) and 3 (ARD $\geq$ 550 kg m^{-3}) proposed by Lima *et al.* (2022).

Principal Component Analysis (PCA)

The first two principal components (PC) explained 76.1% of data variability, with 39.9% for PC1 and 36.2% for PC2. PC1 was primarily influenced by FLD with a negative loading, and positive loadings of CWT, WF, WBD and charcoal ARD. PC2 was mainly influenced by negative loadings of FL, TFW, CWT, LVE and a positive loading of TE (Table S1).

Four distinct groups of species with similar wood properties and ARD were identified in the bidimensional representation provided by the PCA (Figure 7). Group 1 is characterized by species (*C. guianensis* and *C. oblongifolia*) with the highest FLD and the lowest average values for WF, WBD and ARD (Table S1). Group 2 includes species (*P. oblanceolata*, *Pouteria* sp., and *P. suaveolens*) with the lowest average values for FL, LVE, TFW and TL. Group 3 comprises species (*C. villosum*, *L. canescens*, *V. parviflora*, and *P. rodolphii*) with the highest average values for FL, TFW, CWT, LVE and TL. Finally, Group 4 consists of species (*D. excelsa*, *M. ellata*, and *L. lurida*) exhibiting the highest WF, WBD, TE and ARD, along with the lowest FLD.

DISCUSSION

This study aimed to evaluate the influence of wood anatomical, chemical, and physical characteristics on charcoal

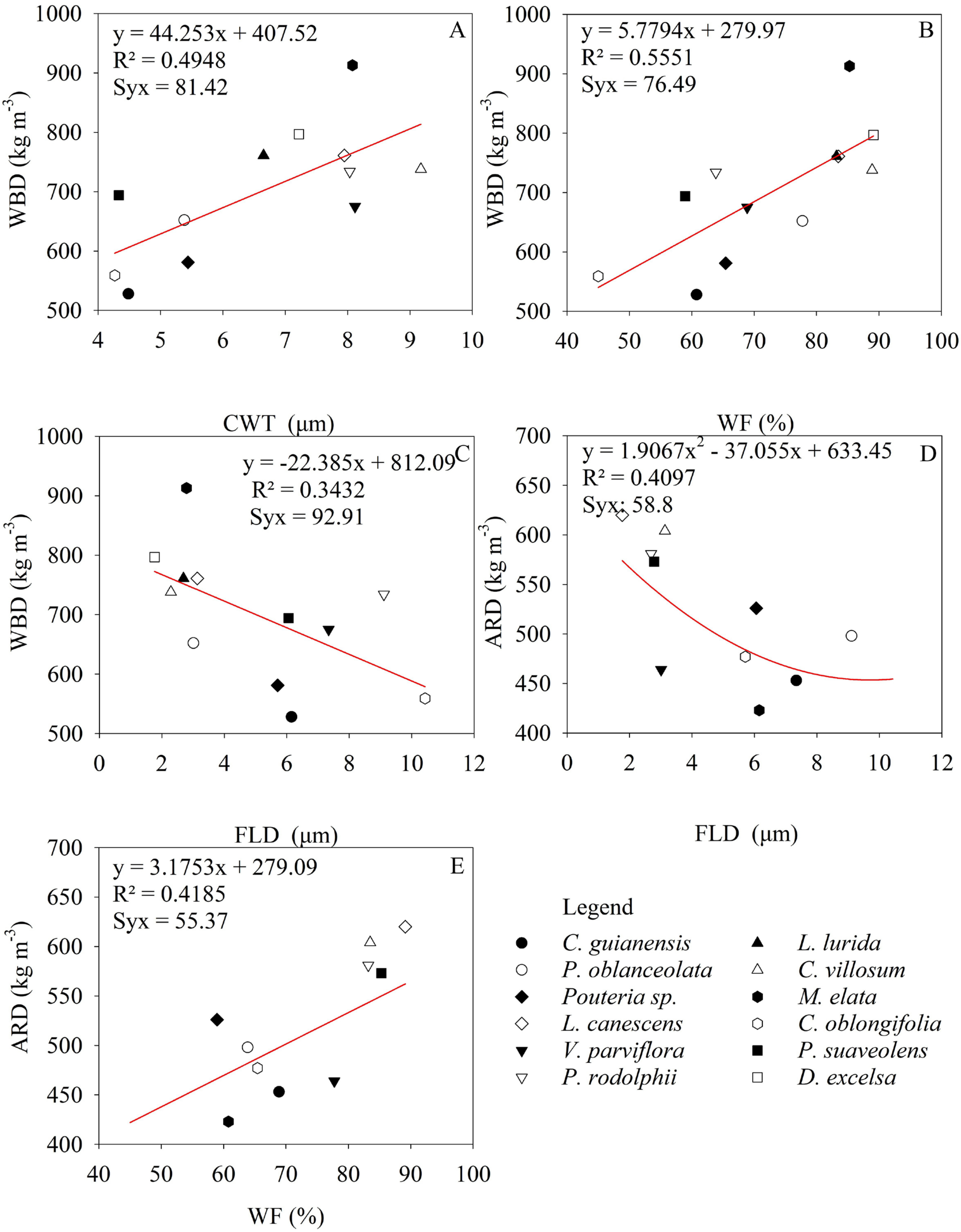

Figure 6. Regression analyses between morphological and anatomical properties of Amazonian woods and derived charcoal: (**A**-**C**) wood basic density (WBD) as function of cell wall thickness (CWT), wall fraction (WF), and fiber lumen diameter (FLD); (**D**-**E**) charcoal apparent relative density (ARD) as function of FLD and WF.

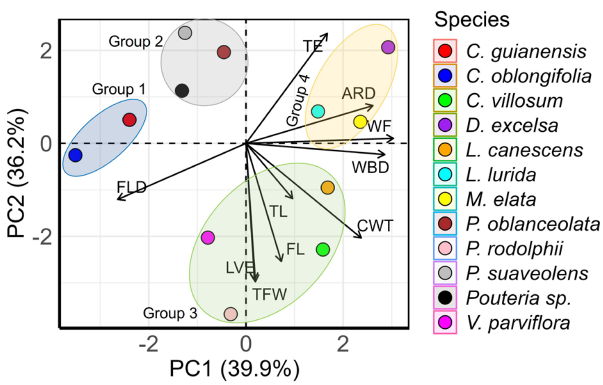

Figure 7. Division of species into groups with similar characteristics based on a classification superimposed on the PCA biplot. Group 1: *C. guianensis* and *C. oblongifolia*; Group 2: *P. oblanceolata*, *Pouteria* sp., and *P. suaveolens*; Group 3: *C. villosum*, *L. canescens*, *V. parviflora*, and *P. rodolphii*; Group 4: *D. excelsa*, *M. elata*, and *L. lurida*. Properties: total extractives (TE), apparent relative density of charcoal (ARD), wall fraction (WF), wood basic density (WBD), cell wall thickness (CWT), total lignin (TL), fiber lumen diameter (FLD), total fiber width (TFW), and length of vessel elements (LVE).

apparent relative density and their potential for segregating SFMP wastes to enhance charcoal quality and homogeneity. Our hypothesis, that anatomical characteristics effectively help group Amazonian wood waste for charcoal production, was supported. Variables such as fiber lumen diameter, cell wall thickness, and wall fraction showed strong associations with wood basic density and charcoal apparent relative density, reinforcing the utility of anatomical metrics in supporting classification for efficient charcoal production in Amazonia. Despite large variation of the anatomical traits among species, most had had low intra-specific variation. This within-species homogeneity in anatomical traits contributes to operational advantages in carbonization, such as standardized carbonization times and optimized kiln loadings. Conversely, species with highly variable wood, such as *P. rodolphii* and *C. guianensis*, may necessitate pre-sorting or blending to ensure consistent charcoal quality.

Species such as *D. excelsa*, *L. lurida*, and *C. villosum*, which exhibited thicker cell walls and higher wall fractions, tended to have greater wood basic density, particularly when associated with narrower fiber lumens and lower vessel frequency. Conversely, species such as *C. oblongifolia* and *C. guianensis* showed high fiber lumen diameter and low cell wall thickness and wall fraction, resulting in thinner-walled fibers and larger vessel diameters (Silva *et al.* 2024). These findings corroborate previous studies emphasizing positive correlations between cell wall thickness, wall fraction, and wood basic density, and a negative influence of fiber lumen diameter (Dong *et al.* 2021, Almeida *et al.* 2022). In this study, cell wall thickness and wall fraction were more relevant in explaining wood basic density variations than fiber length, length of vessel elements, and total fiber width.

Although no overall correlation was found between total lignin or total extractives and wood basic density, we hypothesize these properties may have influenced wood basic density at least for some species. Species with higher wood basic density had higher total lignin contents, except for *M. elata* (Lima *et al.* 2020*a*). Moreover, the highest total extractive contents were recorded for the species with highest wood basic density, suggesting a contribution of total extractives and total lignin to the increase in basic density. The deposition of lignin and extractives can alter cell wall mass (Santos *et al.* 2025), influencing wood basic density. However, in the present study, basic density was mainly influenced by anatomical characteristics such as cell wall thickness, wall fraction, and fiber lumen diameter.

Higher wood basic density enhances the apparent relative density, the mechanical strength (Abreu Neto *et al.* 2020) and kiln productivity metrics of charcoal (e.g., efficiency, specific consumption, volumetric conversion coefficient, and gravimetric yield) (Lima *et al.* 2023). This is likely due to the higher proportion of fibrous tissues in species with greater wood basic density. High-density species, such as *M. elata*, *D. excelsa*, *L. lurida*, and *L. canescens*, showed high potential for charcoal production due to their favorable anatomical traits and higher wood density, which allows greater mass loading and better carbonization efficiency (Protásio *et al.* 2021). In contrast, lower-density species with greater lumen volume produced lower-density charcoal, consistent with the negative correlation between fiber lumen diameter and charcoal apparent relative density reported by Couto *et al.* (2023).

Charcoal apparent relative density is directly proportional to wood cell wall thickness, wall fraction, and wood basic density, implying that wood with fewer empty spaces yields denser charcoal (Couto *et al.* 2023). Silva *et al.* (2024) showed that carbonization increases vessel density from 8 to 13 vessels mm^{-2}. Thus, denser woods with lower fiber lumen diameter and higher cell wall thickness produce charcoal with greater mass per unit volume. Charcoal with higher apparent relative density also exhibits greater resistance to breakage and lower friability (Couto *et al.* 2023) and tends to result in higher fixed carbon per kiln (Oliveira *et al.* 2023). Therefore, a higher wall fraction may also lead to greater fixed carbon yield. In 7.5-year-old *Eucalyptus* species, charcoal apparent relative density at 450°C ranges from 383.0 to 405.0 kg m^{-3} (Table S2). In contrast, all charcoals in this study exceeded 400 kg m^{-3}, showing properties comparable to commercial species.

Some species with higher wall fraction (*C. villosum*, *P. oblanceolata*, *V. parviflora*, and *M. elata*) showed lower charcoal apparent relative density than species with lower wall fraction. This discrepancy may result from anatomical changes during carbonization. Several species have been shown to increase in vessel density after carbonization (Perdigão *et al.* 2020, Silva *et al.* 2024). These changes occur due to the anisotropic behavior of wood during carbonization, which promotes greater tangential contraction of vessels, increasing vessel density. Furthermore, carbonization can reduce cell wall thickness (Arantes *et al*. 2020, Couto *et al*. 2023) and cause cracks (Dias Junior *et al*. 2020), further reducing apparent relative density.

The four species groups identified here showed potential for industrial charcoal production, as all exhibited average charcoal apparent relative density above 250 kg m^{-3}, suggesting higher mechanical strength. The proposed segregation of residual woods under operational conditions aims to improve carbonization control, enhance charcoal quality, and potentially increase kiln productivity. Among the groups, the one comprising *M. elata*, *D. excelsa*, and *L. lurida* stood out, driven by high wall fraction, wood basic density, total extractives, and charcoal apparent relative density.

These coherent groupings were particularly evident when analyzing the relationships among anatomical variables, wood basic density, and charcoal apparent relative density. However, other factors, such as ash and fixed carbon content, also influence the industrial suitability of charcoal. For example, *L. canescens* charcoal, while presenting high charcoal apparent relative density, has elevated ash values (2.5%, db) for the wood (Lima *et al*. 2020*a*) and derived charcoal (9.6%, db) (Lima *et al*. 2020*b*), which could compromise its performance in industrial settings.

Amazonian species demonstrated superior wood quality, with higher cell wall thickness, wall fraction, and wood basic density values than commercial species. Notably, nine of the 12 studied species showed wood basic density values between 527.8 and 619.9 kg m^{-3}, surpassing the typical range of 494.0 to 596.0 kg m^{-3} observed in plantation-grown energy species (Massuque *et al*. 2021, Protásio *et al*. 2021). Although all evaluated species had adequate wood basic density for energy use, segregating wood wastes based on density and anatomical traits, such as wall fraction and cell wall thickness, favors homogeneous charcoal production and optimizes the carbonization process. Moreover, the low intraspecific variation in wood basic density reinforces the potential for consistent charcoal quality.

CONCLUSIONS

This study highlights the value of Amazonian wood wastes for energy generation and demonstrates that anatomical characteristics are effective indicators for optimizing charcoal production in SFMP areas. Future studies should assess the effects of species grouping on kiln productivity, charcoal yield, gas emissions, and bioreducer quality, as well as investigate the influence of wood anatomy on other charcoal properties, such as friability and mechanical strength. Economic feasibility and life cycle assessments are also needed. Additionally, expanding the anatomical dataset to include more species from sustainable forest management areas can improve species grouping and enhance carbonization control at the operational level.

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SUPPLEMENTARY MATERIAL

Soares *et al*. Using wood anatomical characteristics and physicochemical properties to segregate Amazonian wood wastes for charcoal production

RESULTS

Table S1. Eigenvectors of the first two principal components (PC1 and PC2).

Variáveis	PC1	PC2
Fibre length (FL)	0.1134	**-0.4160**
Total fiber width (TFW)	0.0303	**-0.4877**
Fiber lumen diameter (FLD)	**-0.4119**	-0.1978
Cell wall thickness (CWT)	**0.3699**	**-0.3336**
Wall fraction (WF)	**0.4733**	0.0176
Length of vessel elements (LVE)	0.0272	**-0.4807**
Wood basic density (WBD)	**0.4455**	-0.0395
Total extractives (TE)	0.2609	**0.3874**
Total lingin (TL)	0.1497	-0.1947
Apparent relative density of charcoal (ARD)	**0.4075**	0.1331

PC1: principal component 1; PC2: principal component 2. Values in bold represent the most important variables in the formation of PC1 and PC2.

Table S2. Averages of the variables for each group formed by principal component analysis.

Group	FL (μm)	TFW (μm)	FLD (μm)	CWT (μm)	WF (%)	LVE (μm)	WBD (kg/m3)	TE (%)	TL (%)	ARD (kg/m3)
1	1332.82	17.04	8.29	4.37	52.89	464.73	543	4.52	33.10	427
2	1064.99	15.03	4.92	5.05	67.37	383.54	642	8.67	32.84	489
3	1564.09	22.10	5.47	8.32	76.29	566.24	727	3.21	35.62	505
4	1350.56	17.05	2.42	7.32	85.88	414.21	824	12.71	34.03	591

FL: fibre length; TFW: Total fiber width; FLD: Fiber lumen diameter; CWT: Cell wall thickness; WF: Wall fraction; LVE: Length of vessel elements; WBD: wood basic density; TE: total extractives; TL: total lignin; ARD: Apparent relative density of charcoal.

Table S3. Anatomical, physical, and chemical comparison of wood and apparent relative density of charcoal (ARD) between species from forest management waste and species of the *Eucalyptus* and *Corymbia* genera commonly used in charcoal production in Brazil.

Species	FLD	CWT	WF	WBD	ARD	TE	TL	References
	μm		%	kg/m3		% db	% efdb	
Manilkara elata	2.8	8.1	85.3	913.3	571.8	11.9	30.2	This study
Dinizia excelsa	1.8	7.2	89.1	796.9	619.9	17.9	37.6	
Lecythis lurida	2.7	6.7	83.2	761.0	575.8	8.4	34.3	
Licania canescens	3.1	7.9	83.5	760.7	604.0	3.6	36.6	
Caryocar villosum	2.3	9.2	88.9	737.7	464.2	4.9	34.5	
Parinari rodolphii	9.1	8.0	63.9	733.9	498.0	1.8	38.1	
Pseudopiptadenia suaveolens	6.1	4.3	58.9	694.1	517.2	8.0	32.9	
Vantanea parviflora	7.3	8.1	68.9	675.1	452.8	2.4	33.3	
Pouteria oblanceolata	3.0	5.4	77.7	651.6	463.5	9.0	32.3	
Pouteria sp.	5.7	5.4	65.4	580.6	476.4	9.0	33.3	
Couratari oblongifolia	10.4	4.3	45.0	558.8	430.9	3.8	32.6	
Couratari guianensis	6.2	4.5	60.8	527.8	423.1	5.3	33.6	

Table S3. Continued

Species	FLD	CWT	WF	WBD	ARD	TE	TL	References
	µm		%	kg/m3		% db	% efdb	
Corymbia citriodora + *Eucalyptus urophylla* (clones VM04 and TMN463) – 7 years old	7.6	4.8	79.4	527.0	360.0	-	-	Couto *et al*. (2023)
Eucalyptus urophylla – 7.5 years old	-	-	54.3	585.0	405.0	-	-	Pereira *et al*. (2016)
Eucalyptus camaldulensis – 7.5 years old	-	-	55.6	563.0	405.0	-	-	
Eucalyptus urophylla (clone 1009) – 6.75 years old	-	-	-	564.9	401.0	-	30.4	Protásio *et al*. (2019, 2021)
Eucalyptus camaldulensis hybrid (clone 1025) – 6.75 years old	-	-	-	570.7	383.0	-	31.3	
Eucalyptus grandis hybrid (clone 1039) – 6.75 years old	-	-	-	570.0	394.0	-	32.6	
Eucalyptus urophylla x *Eucalyptus grandis* hybrid – 9 years old	-	-	-	494.0	-	7.1	30.6	Ramos *et al*. (2023)
Eucalyptus urophylla x *Eucalyptus camaldulensis* hybrid – 10 years old	-	-	-	589.0	-	6.5	31.4	
Eucalyptus spp. – 5 years old	-	-	-	500.0	-	5.2	29.2	Pereira *et al*. (2025)
Eucalyptus spp. – 7 years old	7.0	-	63.1	596.0	396.0	5.9	29.9	Teixeira *et al*. (2024)*

FLD: Fiber lumen diameter; CWT: Cell wall thickness; WF: Wall fraction; WBD: wood basic density; ARD: Apparent relative density of charcoal; TE: total extractives; TL: total lignin. - Information not presented in the study. * Overall average for 64 *Eucalyptus* genotypes.