Wastes from Sustainable Forest Management as a Source of Biomass: The Case of Amazonia for Bioenergy Generation

Elvis Vieira dos Santos, Michael Douglas Roque Lima, Lina Bufalino, Paulo Ricardo Gherardi Hein, Paulo Fernando Trugilho, and Thiago de Paula Protásio

Abstract Knowledge about the availability and application of Amazonian wood wastes from sustainable forest management plans (SFMP) in energy generation is essential when considering a third of the world's population depends on wood as an energy source. In tropical countries such as Brazil, technological initiatives may be combined with scientific studies to add value to forest biomass and enhance its use as an energy input in the Legal Amazonia. The integral conversion of dense tropical forest vegetation to charcoal or supplying thermoelectric plants would not be admissible; however, forest wastes are sustainable and promising alternatives. This chapter aims to present: (i) the energy potential of wood wastes from SFMP in Amazonia and its importance in the sustainable expansion of energy systems and (ii) the potential of wood wastes to replace non-renewable sources, such as fossil fuels, to reduce the logging of tropical forests for energy generation. The biggest challenges

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E. V. dos Santos · P. R. G. Hein · P. F. Trugilho
Federal University of Lavras (UFLA), Department of Forest Science,
Campus Universitário—Aquenta Sol, S/N, Lavras, Minas Gerais 37200-900, Brazil
e-mail: elvisvieiradossantos@gmail.com

P. R. G. Hein
e-mail: paulo.hein@ufla.br

P. F. Trugilho
e-mail: trugilho@ufla.br

M. D. R. Lima · L. Bufalino
Federal Rural University of Amazonia (UFRA), Institute of Agricultural Sciences,
Av. Tancredo Neves, 2501, Belém, Pará 66077-901, Brazil
e-mail: lima_florestal@outlook.com

L. Bufalino
e-mail: lina.bufalino@ufra.edu.br

T. de P. Protásio (✉)
Federal Rural University of Amazonia (UFRA), Av. Duane Silva, S/N, Parauapebas,
Pará 68515-000, Brazil
e-mail: thiago.protasio@ufra.edu.br

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to producing sustainable energy from forest wastes in Amazonia are related to the low technological level of the kilns used to produce charcoal and the high variation in the wood characteristics concerning its dimensions and its physical, chemical, and energy properties. In that chapter, it was demonstrated that the diameter of the wastes varies from 0.123 to 0.760 m, and the basic density, for example, varies from 0.221 to 0.935 g/cm^3 between species. Studies were carried out to characterize these residual woods and solve these problems. This characterization promoted scientific development. The segregation of wastes according to their properties, mainly the basic density, increased the productivity of the kilns and the quality of the charcoal derived. Future research will address technological improvements in energy production through SFMP wastes to increase efficiency, quality, and sustainability.

Keywords Renewable energy · Wood quality · Residual biomass · Carajás pole · Bioreducer

1 Introduction

Using wood wastes from SFMP as fuel is a sustainable alternative for diversifying the national and even global energy matrix. In Amazonia, these lignocellulosic wastes are formed mainly by branches, buttresses, and stumps of felled trees, usually of large dimensions. Such wastes can represent up to two-thirds of the dry mass of the tree [29]. Therefore, they are highly available and economically viable. In addition, waste consumption is heading towards maximum efficiency in using natural resources.

Some studies have discussed interesting aspects of the environmental impact of extracting wastes from SFMP worldwide [1, 25] and found no negative effect on tree growth. On the contrary, they indicated positive effects of stump extraction on forest regeneration [25, 28]. Based on published data worldwide, the literature indicates that waste extraction increases nutrient export [1]. The export effect is complex because it is affected by the harvest cycle and specific characteristics of the logged forest ecosystem, such as the input of nutrients by weathering and output by leaching [32, 44]. Compared to fossil fuels, burning wood and charcoal emits low amounts of greenhouse gases [11]. The carbon emitted will be stored again during forest regeneration [9] promoted by techniques associated with SFMP [28].

Carbonization is an important conversion route for using by-products from forest management. In addition to its wide domestic use, charcoal is used in blast furnaces of steel mills as a biothermoreducer for pig iron, in the production of the called "green steel." The Carajás region, located in eastern Amazonia, has the largest pig iron production in northern Brazil [41]. Forest wastes partially supply the region's firewood demand for charcoal production [24].

The great challenge for the energy use of wastes from SFMP refers to the high variability of their characteristics. Lima et al. [19] found variation in the wood basic density from 0.525 to 0.895 g/cm^3. In addition, the wood presents high moisture, representing up to 45% of the wet mass without bark [24]. Basic density and moisture influence the productivity of the kilns [4]. This variability is increased by the lack of carbonization control [39] commonly carried out in brick kilns of low technologic level known as "hot tail." The carbonization in these handmade kilns is controlled empirically, without temperature control or waste separation into quality classes.

Studies have been carried out to understand the variation in the quality of charcoal derived from waste [19, 23]. In general, the separation of wastes into groups of species according to the different wood characteristics significantly improves the productivity of the kilns, increases the yield, and reduces the variation in the charcoal quality compared to the conventional method [5]. The next steps involve conducting research that will contribute to more effective control of carbonization, increase its yield, improve the quality of charcoal derived from forest wastes in Amazonia, and mitigate gas emissions during carbonization. This chapter aims to describe the advances obtained so far related to the energy use of forest wastes arising from SFMP in Amazonia.

2 Background of Studies with Wastes from SFMP

The project entitled "Valuation of wood wastes from sustainable forest management for bioenergy in Legal Amazonia" (Public Selection Notice for Scientific and Technological Research—Edition 2018) was developed by the Federal Rural University of Amazonia (website: https://novo.ufra.edu.br/) and financed directly by the Banco da Amazônia. Several advances were achieved in understanding the characteristics of primary wastes from SFMP in Amazonia. It was possible to understand the variability of the main physical, chemical, and energy properties of the forest biomass used for bioenergy in Amazonia [19, 23]. Consequently, the data collected will allow decision-making in industrial units, such as steel mills and ceramics.

The various studies analyzed the wood characteristics of species from 22 genera. The waste characteristics that varied the most were basic density (0.525–0.895 g/cm^3), ash content (0.3–2.5%), and total extractives (1.7–17.9%). However, the elemental carbon content (49.18–52.16%), total lignin (30.2–38.1%), fixed carbon (16.5–22.0%), volatile matter (76.7–82. 8%), and higher heating value (19.4–20.4 MJ/kg) were characteristics that showed the smallest variations between the studied species [19]. Within the same species, wood properties have smaller ranges of variation. In the study of Lima et al. [19], *Manilkara elata* and *Dinizia excelsa* had a basic density of 0.900 and 0.890 g/cm^3, respectively. On the other hand, Lima et al. [24] reported values of 0.872 and 0.927 g/cm^3 of basic density for the same species. Between the two studies, there was a difference of about 3%. This variation can be considered low since this residual biomass has no genetic, age, or site control. These findings indicate the reliability and possibility of data extrapolation to represent the overall quality of waste from these species.

Based on the physical, chemical, and energy characterization of the wastes, it was demonstrated that the wood of the species has the quality to generate electric energy in boilers [19] and in charcoal production for domestic and industrial use. Lima et al. [19] verified a species effect on the technological properties of residual woods, making it necessary to qualify them for energy production. The use of wood wastes with up to 30% moisture (wet basis) has proven to be viable in modern cogeneration systems.

The species studied, such as *D. excelsa*, *M. elata*, *P. altissium,* and *G. glabra*, showed better energy properties than species and clones traditionally used in energy forests. *D. excelsa* had the highest mass of CO_2eq fixed in 1 m^3 of wood wastes (1687 kg), meaning that the use of 1 m^3 of wood wastes of this species would mitigate the emission of 1687 kg of CO_2eq. Finally, the wastes of this species showed the best properties for bioenergy.

The second step of the project proposed waste segregation for charcoal production. Principal component analysis (PCA), a multivariate statistical technique, enabled forming species groups with similar properties [19, 34].

Correlations of the physical and energetic properties of the wood with colorimetry parameters were found [20]. Near-infrared (NIR) spectroscopy was also evaluated with the same objective [21]. Both methods were effective in separating waste.

Lima et al. [20] reported that woods with greater red pigmentation (*M. elata* and *D. excelsa* had higher energy density. All groups formed by PCA can be recommended for bioenergy; however, the group formed by the species *M. elata* and *D. excelsa*, with a purplish-brown color, is the most promising.

In general, waste segregation increases carbonization efficiency, mainly due to the effect of wood basic density. High-density waste has less moisture, allowing to add a greater amount of wood mass in the kiln, increasing production and productivity per carbonization cycle. Figure 1 shows the productivity parameters of segregated and non-segregated woods in the different studies carried out during the execution of the project.

Lima et al. [22] reported a species effect on the physical, chemical, and energy properties of charcoal derived from SFMP wastes. The results showed that the content of extractives in the wood positively influenced the gravimetric yields of charcoal, the carbonization mass balance, the heating value, and the energy performance index of charcoal. Apparent relative density, gravimetric yields of charcoal, gravimetric yields of non-condensable gases, ash content, fixed carbon yield, energy density, energy yield, and retained carbon were the properties with a wide variation between species. The PCA separated charcoal samples from SFMP wastes of 48 species into five distinct groups. These groups can be used in carbonization in brick kilns to supply the Carajás Steel Pole and cogeneration systems in remote Amazonian communities. Finally, the *D. excelsa* species wastes showed the best charcoal properties and processes.

Table 1 presents the project outputs to date. Seven articles were published aiming to understand the waste properties and improve charcoal production through its segregation.

Currently, the project "Generation of bioenergy from wastes from sustainable forest management: decentralization of the energy matrix and socio-environmental impacts in Amazonia" (CNPq/MCTI/FNDCT No. 59/2022) is in effect. The project aims to clarify the combustibility processes of burning co-products from SFMP in

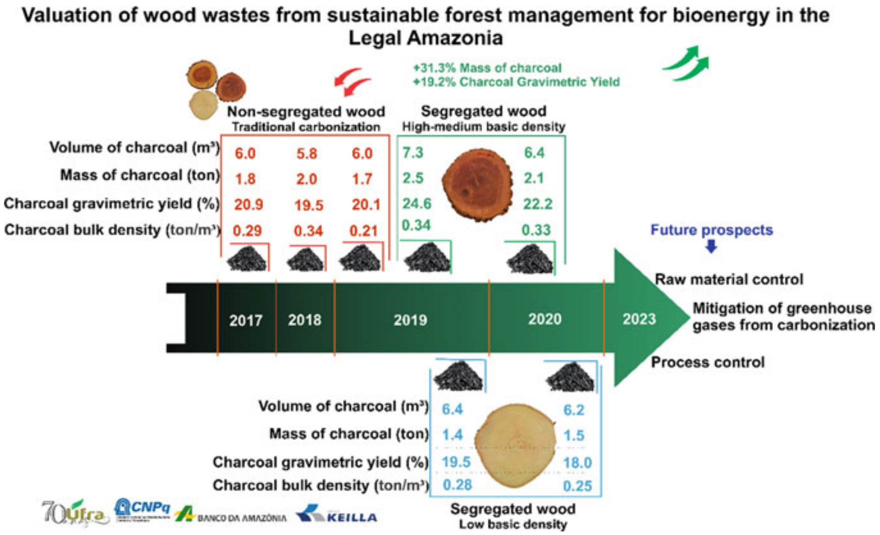

Fig. 1 Summary of results related to kiln productivity during project execution (*Source* The authors 2023)

Amazonia and mitigate the emission of greenhouse gases during the wood carbonization by implementing a furnace-kiln system, which allows the burning of gases formed during the carbonization.

3 Traditional Production of Charcoal from SFMP Wastes in Amazonia

The model of charcoal production in Brazilian Amazonia mainly includes rudimentary brick kilns of the hot tail type, which are semi-spherical kilns built by combining clay and sandy textured soil to avoid cracking. These relatively simple, handmade kilns present low conversion efficiency and are empirically controlled by experienced workers based on the color and amount of smoke expelled, in addition to touch. Consequently, these brick kilns have low productivity and gravimetric yields of charcoal between 15 and 25% on a wet basis [33, 34]. Typically, brick kilns do not include gas cleaning systems and may release unburned by-products into the environment [42]. A typical hot tail kiln is presented in Fig. 2.

The study conducted by Barros et al. [5] describes the carbonization model with wastes in Amazonia. The authors reported kilns with a base diameter of 3.20 m and a height of 2.5 m, with six openings at the base, six at the top, and one chimney, with a height of 70 cm for gas exhaustion. The kilns have a capacity of 10 m^3 of wood. The carbonization cycle normally ranges from 12 to 13 days, including filling, ignition, carbonization, cooling, and kiln discharge steps. The cooling stage refers

Table 1 Products of the project financed directly by the Banco da Amazônia "Valuation of wood wastes from sustainable forest management for bioenergy in Legal Amazonia"

Article	Goal	References
Logging wastes from sustainable forest management as alternative fuels for thermochemical conversion systems in Brazilian Amazon	Energy characterization of the wood wastes from twenty commercial Amazon species harvested in an SFMP and their energy equivalence to fossil fuels	[19]
Charcoal of logging wastes from sustainable forest management for industrial and domestic uses in the Brazilian Amazon	Characterization and production of charcoal from groups of wastes from SFMP in Amazonia according to their physical, chemical, and energy properties	[22]
Grouping of wood wastes from sustainable forest management aiming at bioenergy generation	Grouping of wood wastes from SFMP for firewood and charcoal production for steelmaking	[34]
Colorimetry as a criterion for segregation of logging wastes from sustainable forest management in the Brazilian Amazon for bioenergy	Use of wood color parameters to segregate SFMP wastes	[20]
Efficiency of near-infrared spectroscopy in classifying Amazonian wood wastes for bioenergy generation	Presentation of a method for classifying wood wastes from 12 Amazonian hardwoods based on near-infrared spectroscopy (NIR) and basic density	[24]
Classifying waste wood from Amazonian species by near-infrared spectroscopy (NIRS) to improve charcoal production	Classification of wood waste from 12 Amazonian species by near-infrared spectroscopy (NIRS) to improve charcoal production	[21]
Clarifying the carbonization temperature effects on the production and apparent density of charcoal derived from Amazonia wood wastes	Presentation of the effects of final carbonization temperature and different species of Amazonian wood on carbonization efficiency and apparent relative density of charcoal	[18]
Does the segregation of wood waste from Amazonia improve the quality of charcoal produced in brick kilns?	Comparison of the quality of charcoal derived from wood wastes previously segregated into four distinct and non-segregated groups of 23 Amazonian species carbonized in brick kilns	[5]

to the application of water mixed with clay on the kiln wall (Fig. 3a), with the aid of a tractor (Fig. 3b), intending to seal the kilns and reduce their internal temperatures to about 50 °C, which reduces the chances of charcoal reignition after opening the kiln.

Allied to the low technological apparatus used in the charcoal production model, the raw material used is very heterogeneous (Fig. 4). Typical wood wastes present low energy density, high moisture content, and variable diameters, hindering their use as energy sources, mainly for charcoal production with suitable quality for domestic and industrial applications. The empiricism of the activity is also related to raw material

Fig. 2 Rudimentary brick kiln commonly used in charcoal production with SFMP wastes in Brazilian Amazonia (*Source* The authors 2023)

Fig. 3 Cooling of the kilns through the application of water and clay (**a**) with the aid of a tractor, Massey Ferguson 275 model (**b**) (*Source* The authors 2023)

control, as it is carbonized without diametric standardization and moisture control. It is known that the higher the water content in wood, the lower its heating value, and the combustion will occur in an inadequate regime [12]. In addition, the charcoal yield reduces since the energy expenditure for the process's first stage, drying, is likely to be high. Canal et al. [7] demonstrated that the emissions of condensable gases (pyroligneous liquid) and non-condensable gases (CO_2, CO, CH_4, and H_2) increased, and the gravimetric yield of charcoal decreased with the increase in wood moisture during the carbonization processes.

Currently, there is no control over the moisture content of forest wastes for charcoal production in Legal Amazonia and, consequently, there is the excessive expenditure of energy, the appearance of cracks and internal fissures in the charcoal due to the sudden release of water in the form of steam and, consequent decrease

Fig. 4 SFMP wastes in the storage yard of a charcoal production unit in Brazilian Amazonia (*Source* The authors 2023)

in the mechanical properties of charcoal. Moreover, countless forest species are carbonized concomitantly; therefore, the wood's qualitative and quantitative aspects are not under control. Finally, it is necessary to improve carbonization by, for example, adjusting the process control ranges as a function of time and temperature, considering the thermal degradation of wood to maximize charcoal yield [8, 10, 30].

The effect of raw material heterogeneity and empirically controlled carbonization on charcoal production can be evidenced by data from a Brazilian Amazonia production unit (Table 2). SFMP wastes are carbonized in this production unit, especially branches. Table 2 shows the mass and volume balances obtained in twelve brick kilns in 2017, as well as the descriptive statistics associated with the analyzed variables.

The average values of the wet mass of wastes in the kiln (MW), estimated dry mass of wastes in the kiln (MSM), and estimated volume of wastes in the kiln (VW) obtained by the traditional carbonization model were 8.456 ± 0.371 t, 6.577 ± 0.295 t, and 17.16 ± 0.86 st, respectively. The evaluated kilns produce, on average, 1.762 ± 0.126 t of charcoal per cycle. The average volume of charcoal in the hot tail kilns was 6.01 ± 0.36 m^3.

The gravimetric and volumetric surveys performed were based on the operational conditions of the charcoal production unit and not necessarily on experimental conditions, which, in turn, are controlled. In this way, the factors inherent to the raw material, labor, and the control of carbonization can considerably affect the production and productivity of hot tail kilns. This effect can be verified by analyzing the mass of semi-carbonized pieces (MSP) produced per cycle, in which kiln 4 did not produce these by-products. In contrast, kiln 6 produced a high amount of semi-carbonized pieces (1.240 t) and, consequently, a low gravimetric yield of charcoal. Therefore, they cannot be considered wood or charcoal but a by-product of carbonization.

Table 2 Mass and volume balances per carbonization cycle of SFMP wastes in Brazilian Amazonia

Kiln	MW (t)	VW (st)	MSM (t)	Mch (t)	Vch (m^3)	MSP (t)
1	8.010	16.57	6.312	1.725	6.26	0.140
2	8.250	14.86	6.501	1.455	5.38	0.580
3	9.250	17.10	7.290	1.759	5.69	0.860
4	8.420	15.31	6.635	2.027	6.91	0.000
5	8.400	15.82	6.620	1.793	6.05	0.320
6	9.050	18.99	6.945	1.460	5.21	1.240
7	7.790	17.16	5.978	1.395	4.76	0.460
8	7.470	17.29	5.733	1.640	5.78	0.620
9	8.510	18.64	6.531	1.884	6.33	0.220
10	8.830	18.79	6.777	2.011	7.03	0.100
11	9.900	20.00	7.700	2.156	6.81	0.220
12	7.590	15.33	5.903	1.837	5.88	0.320
Average	8.456	17.16	6.577	1.762	6.01	423.3
CV (%)	8.46	9.70	8.64	13.75	11.68	83.98

MW wet mass of wastes in the kiln (in tons, t); *VW* estimated volume of wastes in the kiln (in stereo, st); *MSM* estimated dry mass of wastes in the kiln (t); *Mch* mass of charcoal (t); *Vch* volume of charcoal (in cubic meters, m^3); *MSP* mass of semi-carbonized pieces (t); *CV* coefficient of variation (%) (*Source* The authors 2017)

The following variations were reported for the gravimetric yield of charcoal—GYC (%, on a wet and dry mass basis) and gravimetric yield of semi-carbonized pieces—GYS (%, on a wet and dry mass basis): 16.13–24.20% (GYC, wet mass basis), 21.02–31.12% (GYC, dry mass basis), 0.00–13.70% (GYS, wet mass basis), and 0.00–17.85% (GYS, dry mass basis) (Table 3).

The production of semi-carbonized pieces is undesirable, as it decreases the kilns' production and productivity (Fig. 5a) and the gravimetric conversion coefficient (Fig. 5b). Kiln 6 presented GYC, wet mass basis, of 16.13%. Kilns 4 and 12, on the other hand, with lower production of semi-carbonized pieces, stood out in converting wood into charcoal. As already mentioned, the generation of semi-carbonized pieces is related to the raw material and the control of carbonization.

The kilns evaluated showed, on average, a GYC of 20.87 ± 1.35% (wet mass basis) and 26.84 ± 1.73% (dry mass basis). The GYS was 5.00 (based on wet mass) and 6.44% (based on dry mass), with high variation between kilns. These results indicate that the carbonization was performed differently in the kilns, probably due to the empirical character associated with charcoal production (lack of control based on specific temperature ranges and time).

Figure 6 shows the gravimetric yields of products and by-products generated in a charcoal production unit concerning the initial total wet mass (110.74 t). 67.51% of forest wastes are transformed into gases during carbonization, 19.09% result in

Table 3 Gravimetric yields of charcoal and semi-carbonized pieces per brick kiln in a charcoal production unit in Brazilian Amazonia

Kiln	GYC (%)		GYS (%)	
	Wet basis	dry basis	Wet basis	Dry basis
1	21.54	27.33	1.75	2.22
2	17.64	22.38	7.03	8.92
3	19.02	24.13	9.30	11.80
4	24.07	30.55	0.00	0.00
5	21.35	27.09	3.81	4.83
6	16.13	21.02	13.70	17.85
7	17.91	23.33	5.91	7.69
8	21.95	28.61	8.30	10.81
9	22.14	28.85	2.59	3.37
10	22.77	29.68	1.13	1.48
11	21.78	28.00	2.22	2.86
12	24.20	31.12	4.22	5.42
Average	20.87	26.84	5.00	6.44
CV (%)	12.46	12.42	80.10	80.53

GYC gravimetric yield of charcoal on a wet and dry basis (%); *GYS* gravimetric yield of semi-carbonized pieces on a wet and dry basis (%); *CV* coefficient of variation (%) (*Source* The authors 2017)

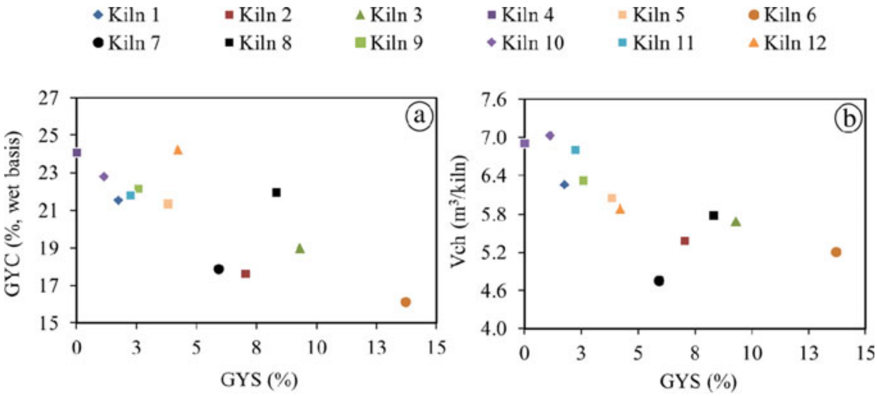

Fig. 5 Relationship between the gravimetric yield (GYC) (**a**) and volume of charcoal (**b**) with the gravimetric yield of semi-carbonized pieces (GYS) in the brick kilns of a charcoal production unit in Brazilian Amazonia (*Source* The authors 2017)

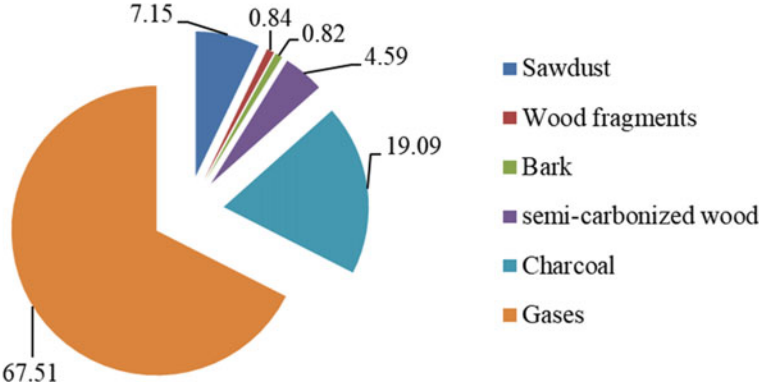

Fig. 6 Gravimetric yields of products and by-products generated in charcoal production, considering the initial total mass with 22.22% of moisture (*Source* The authors 2017)

charcoal, 4.59% in semi-carbonized pieces, and 8.81% are by-products generated in the sectioning wastes (sawdust, wood fragments, and bark).

The charcoal bulk density per kiln (CBD) evaluated in 2017 and the average value obtained for this initial prospecting can be seen in Fig. 7. On average, the CBD of waste was 0.293 t/m^3. The variation between the kilns was low; consequently, the minimum (0.270 t/m^3) and maximum (0.317 t/m^3) values were similar.

In summary, using different species with different physicochemical properties without prior separation for carbonization, combined with the diametric differences of the waste logs and empirical control of carbonization, help explain the previously reported results. Thus, alternatives are needed to maximize kiln productivity based on raw material and process control.

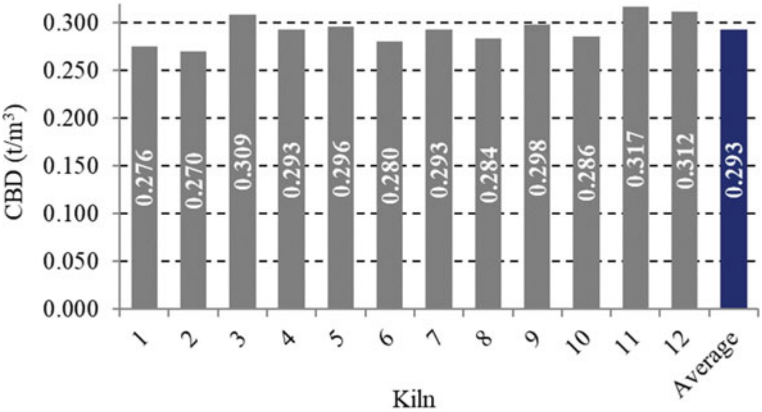

Fig. 7 Charcoal bulk density (CBD) per kiln evaluated in the production unit in Brazilian Amazonia (*Source* The authors 2017)

4 Characteristics of Wood Wastes from SFMP

According to previously published studies, the physical, chemical, and energy properties of SMFP wood wastes corroborate wide heterogeneity [19]. In addition, it is a heterogeneous biomass concerning diameter classes, formats, and origins (root, stem, and branches). A diametric variation of 0.123–0.760 m was reported by Barros et al. [5] for carbonized wastes in brick kilns in Amazonia. The wide variation in wood properties negatively influences charcoal production [23]. In addition, the need to classify woods based on diameter is highlighted since this property strongly influences the thermal profile, heat transfer, and carbonization rate [14, 17].

Regarding the physical properties of wastes, the basic density and moisture have already been studied. Pereira et al. [34] reported a variation of 0.221 (*Sterculia pruriens*) at 0.867 g/cm^3 (*Pseudopiptadenia psilostachya*), evaluating wood wastes of 18 tropical species from Brazilian Amazonia. Values ranging from 0.525 (*Couratari guianensis*) to 0.895 g/cm^3 (*M. elata*) were described by Lima et al. [19], evaluating wood wastes of 20 native species to the Amazonia. More recently, evaluating wood wastes with the near-infrared (NIR) spectroscopy technique, Lima et al. [24] reported basic density values between 0.354 (*Simara guianensis*) and 0.927 g/cm^3(*D. excelsa*).

A compilation of average waste basic density values from the previous studies and the basic density classes proposed by the International Association of Wood Anatomists [16] is shown in Table 4. Three classes were used, namely: low density (Db $\leq$ 0.500 g/cm^3); medium density (0.500 < Db $\leq$ 0.720 g/cm^3); and high density (Db > 0.720 g/cm^3). These are 55 tropical species, ranging from 0.221 to 0.935 g/cm^3.

The amplitudes reported for Amazonian wood wastes are within the variation range (0.140–1.210 g/cm^3) published by Fearnside [13], evaluating the wood properties of 268 tropical species from the same biome. The literature demonstrates that low-density woods (< 0.500 g/cm^3) are not suitable for energy purposes. Thus, they should not be carbonized with the high basic density woods to produce bioreducers.

In the reality of Amazonia, wood in all density ranges is carbonized, negatively influencing the gravimetric yield and charcoal productivity of brick kilns. Protásio et al. [37] reported a positive relationship between wood basic density and charcoal apparent relative density of *Eucalyptus* sp., indicating that denser woods result in dense charcoals.

Pereira et al. [34] also reported moisture values under operational conditions ranging from 24.99 (*Cordia goeldiana*) to 159.26% (*Sterculia* sp.) on a dry basis. Moisture is negatively correlated with the wood basic density [24], indicating that high-density woods present lower moisture due to the smaller volume of empty spaces in the wood [31]. For energy purposes, woods with moisture below the fiber saturation point (< 30%, dry basis) are recommended. Above that, the negative effects are significant in the gravimetric yield of charcoal, as a considerable part of the firewood is burned to release energy to meet the drying stage, as well as in the carbonization cycle, making it longer. In this sense, greater control of the moisture of wood wastes under operational conditions is necessary.

Table 4 Basic density of wood wastes of tropical species from Brazilian Amazonia

N	Species	Commercial name	BD (g/cm^3)	Class
1	*Sterculia pruriens*	Envira-quiabo	0.221 ± 0.016	Low
2	*Simaba guianensis*	Marupá-amarelo	0.354 ± 0.015	Low
3	*Simarouba amara*	Marupá	0.367 ± 0.015	Low
4	*Sterculia* sp.	Sucupira-babona	0.377 ± 0.052	Low
5	*Protium* sp.2	Breu-amesclim	0.392 ± 0.007	Low
6	*Tapirira guianensis*	Tapiririca	0.397 ± 0.017	Low
7	*Parkia gigantocarpa*	Fava-atanã	0.436 ± 0.033	Low
8	*Ocotea* sp.2	Louro-amarelo	0.452 ± 0.022	Low
9	*Cordia goeldiana*	Freijó	0.457 ± 0.023	Low
10	*Ocotea* sp.3	Louro-preto	0.470 ± 0.042	Low
11	*Anacardium giganteum*	Cajuaçu	0.486 ± 0.020	Low
12	*Parkia* sp.	Fava-branca	0.501 ± 0.010	Medium
13	*Couratari guianensis*	Tauarí-liso	0.525 ± 0.050	Medium
14	*Tetragastris altissima*	Amesclim	0.545 ± 0.042	Medium
15	*Couratari oblongifolia*	Tauarí-branco	0.545 ± 0.033	Medium
16	*Pouteria* sp.1	Guajará-bolacha	0.574 ± 0.028	Medium
17	*Ocotea* sp.1	Canela	0.586 ± 0.038	Medium
18	*Brosimum gaudichaudii*	Inharé	0.599 ± 0.006	Medium
19	*Peltogyne* sp.	Roxinho	0.641 ± 0.038	Medium
20	*Sclerolobium* sp.	Tachi	0.642 ± 0.042	Medium
21	*Pouteria* sp.5	Guajará-bolacha	0.667 ± 0.044	Medium
22	*Protium* sp.1	Breu-barrote	0.683 ± 0.057	Medium
23	*Pouteria oblanceolata*	Abiu	0.683 ± 0.038	Medium
24	*Vatairea sericea*	Angelim-amargoso	0.686 ± 0.051	Medium
25	*Lecythis* sp.	Sapucaia	0.690 ± 0.117	Medium
26	*Vantanea parviflora*	Uxirana	0.699 ± 0.070	Medium
27	*Pouteria* sp.4	Abiorana	0.701 ± 0.075	Medium
28	*Pouteria* sp.3	Abiorana	0.701 ± 0.061	Medium
29	*Caryocar* sp.2	Pequiarana	0.701 ± 0.029	Medium
30	*Caryocar glabrum*	Pequiarana	0.702 ± 0.074	Medium
31	*Caryocar villosum*	Pequiá	0.711 ± 0.048	Medium
32	*Protium altissimum*	Breu-barrote	0.721 ± 0.030	High
33	*Eschweilera pedicellata*	Matamatá	0.724 ± 0.045	High
34	*Eschweilera amazonica*	Jiboião	0.728 ± 0.050	High
35	*Pseudopiptadenia suaveolens*	Timborana	0.744 ± 0.086	High
36	*Eschweilera grandiflora*	Matamatá-preto	0.749 ± 0.057	High

(continued)

Table 4 (continued)

N	Species	Commercial name	BD (g/cm^3)	Class
37	*Goupia glabra*	Cupiúba	0.752 ± 0.035	High
38	*Pouteria* sp.2	Guajará-cinza	0.754 ± 0.011	High
39	*Lecythis lurida*	Jarana	0.755 ± 0.031	High
40	*Eschweilera* sp.1	Matamatá	0.779 ± 0.078	High
41	*Eschweilera coriacea*	Matamatá-branco	0.785 ± 0.012	High
42	*Eschweilera* sp.2	Matamatá	0.792 ± 0.029	High
43	*Parinari rodolphii*	Coco-pau	0.801 ± 0.046	High
44	*Caryocar* sp.1	Pequiá	0.802 ± 0.016	High
45	*Manilkara* sp.1	Maçaranduba	0.806 ± 0.079	High
46	*Hymenaea* sp.	Jatobá	0.811 ± 0.130	High
47	*Lecythis pisonis*	Sapucaia	0.812 ± 0.064	High
48	*Terminalia* sp.	Tanibuca	0.814 ± 0.021	High
49	*Enterolobium schomburgkii*	Orelha-de-macaco	0.836 ± 0.036	High
50	*Vantanea guianensis*	Uxirana	0.843 ± 0.114	High
51	*Licania canescens*	Casca-seca	0.858 ± 0.047	High
52	*Pseudopiptadenia psilostachya*	Timborana	0.867 ± 0.074	High
53	*Manilkara* sp.2	Maçaranduba	0.872 ± 0.010	High
54	*Manilkara elata*	Maçaranduba	0.903 ± 0.023	High
55	*Dinizia excelsa*	Angelim-vermelho	0.935 ± 0.044	High

N species number; *BD* wood basic density (g/cm^3). Commercial name in Brazil. Average ± standard deviation (*Source* The authors 2023)

Average values of the chemical properties of wood wastes, such as total lignin (LigT), total extractives (EXT), and elemental carbon (C), can be seen in Table 5. These are data on wood from branches of 20 logged tropical species by the reduced impact logging method in an SFMP certified by the Forest Stewardship Council (FSC) in Brazilian Amazonia, previously published by Lima et al. [19].

EXT (1.8–17.9%, dry mass basis), LigT (30.2–38.1, dry mass basis free of extractives), and C (49.2–52.4%, basis mass dry) demonstrated high variability in native tropical woods of Amazonia. Wood species with high levels of EXT, LigT, and C are promising for energy purposes, especially to supply the charcoal-producing complex in the Carajás region, located between Maranhão and Pará states, in Brazil. Lima et al. [23] demonstrated that the EXT had a positive relationship with the GYC, indicating that the species *D. excelsa*, *P. altissimum, M. elata,* and *G. glabra* showed the best carbonization mass balances.

The C value (42.82%) described by Haqiqi et al. [15] for *Eucalyptus pellita* and the variation range (47.23–48.80%) reported by Santos et al. [40] of four *Eucalyptus* hybrid clones (three *Eucalyptus urophylla* × *E. grandis* and one *Eucalyptus camaldulensis* × *E. grandis*) at seven years of age, were lower than the values found

Table 5 Total extractives, total lignin, and elemental carbon from SFMP wastes in Brazilian Amazonia

Species	Commercial name	EXT (%)*	LigT (%)**	C (%)*
Dinizia excelsa	Angelim-vermelho	17.9	37.6	51.7
Protium altissimum	Breu-barrote	12.6	31.0	50.9
Manilkara elata	Maçaranduba	11.9	30.2	51.0
Goupia glabra	Cupiúba	11.4	34.0	51.0
Pouteria sp. 2	Guajará-bolacha	9.0	33.3	50.3
Pouteria oblanceolata	Abiu	9.0	32.3	50.6
Lecythis lurida	Jarana	8.4	34.3	49.7
Pseudopiptadenia suaveolens	Timborana	8.0	32.9	52.0
Eschweilera grandiflora	Matamatá-preto	7.7	30.9	49.2
Caryocar glabrum	Pequiarana	7.7	32.6	50.7
Enterolobium schomburgkii	Orelha-de-macaco	6.0	33.0	51.8
Eschweilera pedicellata	Matamatá	6.0	32.4	52.4
Lecythis pisonis	Sapucaia	5.9	33.5	52.2
Couratari guianensis	Tauarí-liso	5.3	33.6	49.9
Caryocar villosum	Piquiá	4.9	34.5	51.0
Pouteria sp. 1	Abiorana	4.0	33.6	50.1
Couratari oblongifolia	Tauarí-branco	3.8	32.6	49.7
Licania canescens	Casca-Seca	3.6	36.6	49.7
Vantanea parviflora	Uxirana	2.4	33.3	50.0
Parinari rodolphii	Coco-pau	1.8	38.1	50.9

EXT total extractives (%); *LigT* total lignin (%); and *C* elemental carbon (%). *Based on dry wood mass. ** Based on dry wood mass free of extractives (*Source* Lima et al. [19])

for wood wastes, which ranged from 49.2 to 52.4%. This range of C indicates that the wastes are very promising since C is the main energetic element of biomass [2]. Woods of the *Eucalyptus genus* are the most used to compose energy forests, Brazil's main source of forest biomass. Thus, alternative renewable sources are important for diversifying the energy sector's raw materials.

Pereira et al. [35] discussed that woods with LigT above 28% are desired for charcoal production. All species shown in Table 5 showed values above the reference published by the authors, indicating that the species are suitable for this purpose. Wood species with high LigT values are more thermally stable and contribute positively to the gravimetric yield of charcoal of the production unit [27]. In addition, they have a high heating value, which indicates more energy is generated during combustion [43].

Although wastes from SFMP have suitable quality for charcoal production, the carbonization of wood with different physical and chemical characteristics negatively affects charcoal production unity, productivity in brick kilns, and the quality of the charcoal produced. Barros et al. [5] demonstrated that the carbonization of different woods together, which is the traditional model of carbonization in Amazonia, results in a reduction in the charcoal quality, negatively affecting friability, apparent relative density, ash content, volatile matter, fixed carbon, higher heating value, and energy density. The authors highlighted the need for better control of the raw material factor under operational conditions, especially with the wood segregation before carbonization, aiming to reduce the effect of heterogeneity on the production, productivity, and quality of the charcoal produced in traditional kilns.

5 Carbonization of Similar Wood Wastes

Several proposals were presented in the literature to reduce the heterogeneity of the residual raw material to produce charcoal based on the properties of the wood [19, 20, 34] and charcoal [23]. Carbonization should prioritize woods with similar properties to homogenize the process phases and the bioreducer quality. The wood basic density can be a criterion to separate wastes, as well as several combined properties, through multivariate statistical analyses of grouping.

Pereira et al. [34] proposed carbonization considering basic density classes. In this study, the authors separate wood wastes into classes of low (*Sterculia pruriens, Sterculia* sp., and *Cordia goeldiana*), medium (*Tetragastris altissima, Pouteria* sp., *Ocotea* sp., *Peltogyne* sp., *Sclerolobium* sp., *Protium* sp., *Lecythis* sp., and *Caryocar villosum*), and high (*Eschweilera amazonia, Lecythis lurida, Eschweilera* sp., *Manilkara* sp., *Hymenaea* sp., *Terminalea* sp., and *Pseudopiptadenia psilostachya*) density. They recommended wood of medium and high basic density for steel charcoal production, as it will result in a bioreducer with adequate apparent relative density.

Lima et al. [19] verified four groups of similar residual woods through the PCA technique, using physical (basic density, moisture, and maximum moisture content); chemical (proximate analysis: fixed carbon, volatile matter, and ash; and molecular analysis: total extractives, soluble, insoluble, and total lignin); and energy (higher heating value and energy density) properties; in addition to the specific consumption of firewood in charcoal production. This proposal promoted improvements of (+) 22, (−) 9.4, (+) 2.0, (−) 2.3, (+) 1.0, and (+) 23.6% in apparent relative density, ash content, fixed carbon, friability, higher heating value, and energy density of charcoal produced in brick kilns in Amazonia [5]. Table 6 presents the wood groups evaluated by the authors and the basic density variation ranges.

Lima et al. [23] used the same grouping analysis to separate species in charcoal production units in Amazonia based on physical, chemical, and energy properties. Furthermore, the authors considered the yields of the carbonization process under laboratory conditions. Colorimetric characteristics (lightness, green/red axis, blue/yellow axis, color saturation, and hue angle), physical (moisture and basic density), chemical (total extractives and total lignin), and energy density of these residual woods contributed to the formation of six species groups using the PCA technique

Table 6 Species groups segregated by PCA technique for carbonization in a charcoal production unit in Brazilian Amazonia

Group 1 (BD: 0.948–1.015 g/cm^3)	Group 2 (BD: 0.787–0.914 g/cm^3)	Group 3 (BD: 0.429–0.711 g/cm^3)	Group 4 (BD: 0.568–0.936 g/cm^3)	Group 5 (traditional) (BD: 0.352–1.015 g/cm^3)
D. excelsa	*P. rodolphii*	*A. giganteum*	*Pouteria* sp.1	*A. giganteum*
	L. canescens	*C. oblongifolia*	*V. sericea*	*C. glabrum*
		Ocotea sp.1	*P. altissimum*	*C. villosum*
		Ocotea sp.2	*G. glabra*	*C. oblongifolia*
		Pouteria sp.2	*L. lurida*	*D. excelsa*
			M. elata	*E. coriacea*
			E. coriacea	*G. glabra*
			C. glabrum	*L. lurida*
			C. villosum	*L. pisonis*
			L. pisonis	*L. canescens*
			P. suaveolens	*M. elata*
			V. guianensis	*Ocotea* sp.1
				Ocotea sp.2
				P. rodolphii
				P. gigantocarpa
				Pouteria sp.1
				Pouteria sp.2
				P. altissimum
				Protium sp.
				P. suaveolens
				S. amara
				V. guianensis
				V. sericea

BD basic density (g/cm^3) (*Source* [5])

[20]. In the study, the basic and energy densities were negatively correlated with lightness, blue/yellow axis, color saturation, and hue angle, demonstrating that darker woods, such as *D. excelsa* and *M. elata,* present greater energy potential.

Two methods were tested to segregate residual wood on an operational scale. The first was based on the basic density [34], and the second was based on several characteristics of the wood [19]. In this sense, positive effects are evident in the productivity of brick kilns with raw material control. Figure 8 shows the effects of separating wood into density classes (medium–high and medium–low) on charcoal production at an operational scale.

Medium–high basic density woods (0.739–0.993 g/cm^3) had lower average MC (41.1%, dry mass basis), while medium–low basic density woods (0.517–0.630 g/cm^3) had higher MC (67.5%, based on dry mass). The trend of water reduction in woods with high BD can be seen in Fig. 9a. Traditional carbonization brings

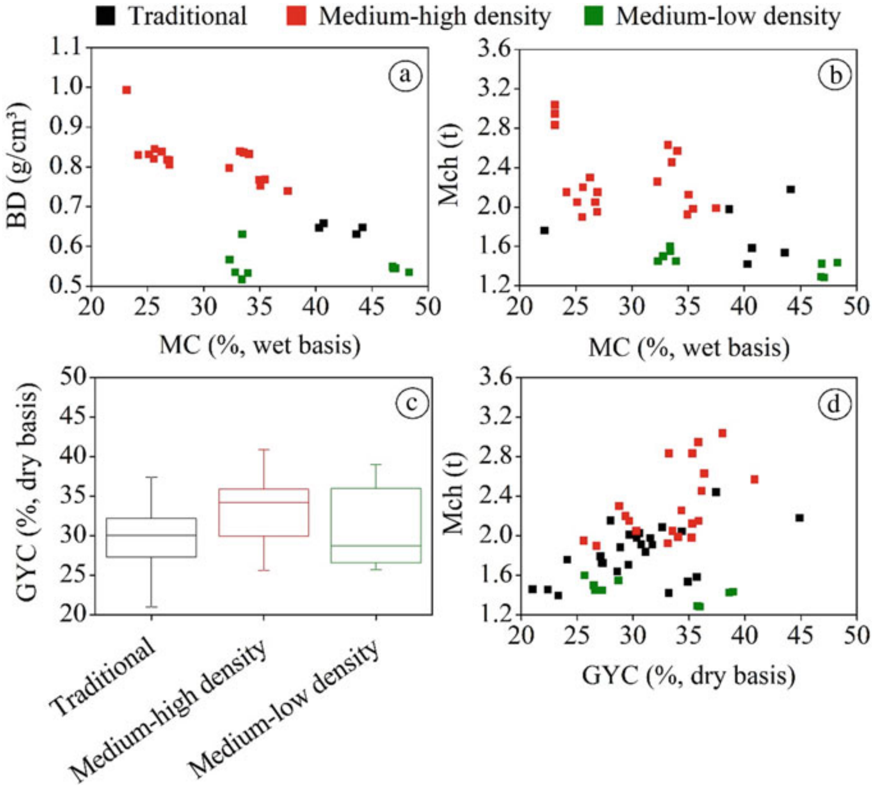

Fig. 8 Effects of waste segregation into density classes (medium–high and medium–low) on charcoal productivity at operational scale in Brazilian Amazonia. Relationship between basic density—BD (g/cm^3) and moisture content—MC (%) (**a**), mass of charcoal—Mch (t) and MC (%) (**b**), basic density—BD (g/cm^3) and gravimetric yield of charcoal—GYC (%) (**c**), and GYC (%) and Mch (t) (**d**) (*Source* The authors 2023)

together woods with a wide variation in BD, which is not interesting due to the different MCs of the woods, which makes it difficult to control the carbonization process, reducing Mch (Figs. 9b and d) and GYC (Fig. 9c). Traditional carbonization showed a GYC of 30.3% (based on dry mass), lower than the average values reported for the medium–high (33.4%, based on dry mass) and medium–low wood groups (31.6%, based on dry mass) density. It is important to note that traditional carbonization negatively affects bioreducer production, the unit's operational efficiency, and revenues. Segregation promotes greater production of charcoal with the same quantity of wood mass inserted in the kiln. From an operational and charcoal productivity point of view, BD as a criterion to separate residual wood is the most appropriate and simple method to be carried out by the employees.

Additional wood characteristics can be used as a separation criterion to improve the production and quality of the steel bioreducer. In this sense, the carbonization of the groups proposed by Lima et al. [19] was tested under operational conditions in brick kilns. Figure 9 presents weighted average data for moisture—MCw (Fig. 9a) and basic density—BDWw (Fig. 9b), wet mass—MW (Fig. 9c), and volume—VW (Fig. 9d) of wood per hot-tail kiln. Groups 2 (9.117 m^3) and 3 (9.500 m^3) filled the kilns with the highest average volumes of waste. Groups 1, 2, and 4 showed average MW, MCw, and BDWw above group 5 (conventional model).

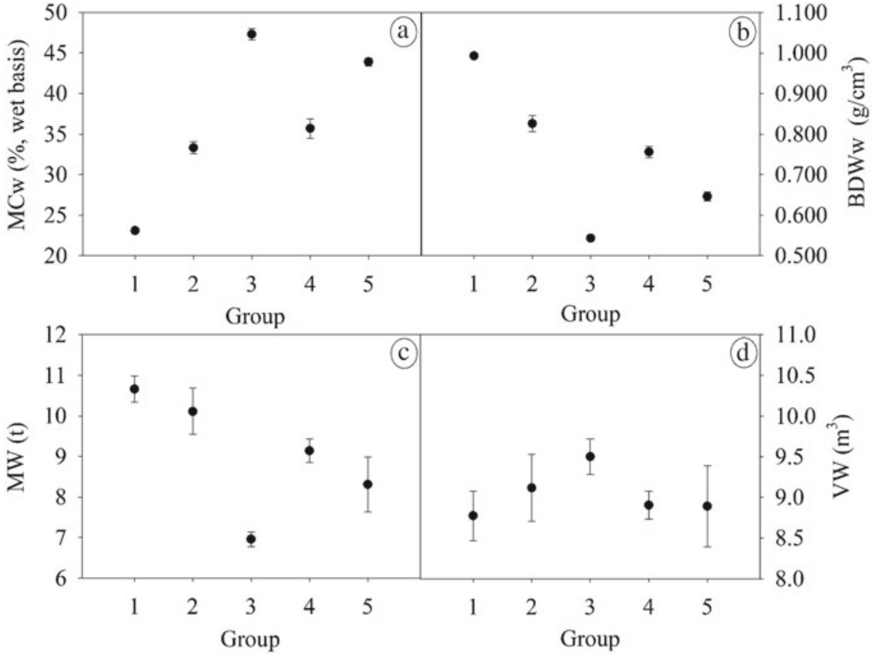

Fig. 9 Weighted moisture content of the wastes (**a**), weighted basic density of wastes (**b**), wet mass of wood (**c**), and volume of wood (**d**) by waste groups in brick kilns in Brazilian Amazonia. Error bars refer to standard deviations (*Source* The authors 2023)

Waste groups 1, 2, and 4, which combine medium and high-density species, had the highest MW. Consequently, they allowed better use of the kiln's internal space. In addition, such combined wood species had lower MCw and higher BDWw. The woods in group 3 presented a lower MW inside the kiln due to the lower BDWw. In summary, grouping similar tropical woods provided encouraging results related to the wood amount inserted in the kilns. It is known that the greater the dry wood mass in the kiln, the greater the mass of charcoal produced. The traditional model of carbonization promotes greater variation in the MW, and VW used in the process, which is not interesting, as it makes the monthly and annual planning of wood in the charcoal plant difficult.

Compared to the traditional model without wood separation, the charcoal productivity dataset from brick kilns demonstrates the positive effects of waste wood segregation in Amazonia (Fig. 10). In order, groups 1 (7.84 m^3), 2 (7.33 m^3), 4 (6.61 m^3), and 3 (6.43 m^3) showed better average values of charcoal volume (Vch), compared to the group without segregation, which produced 6.02 m^3. Regarding mass (Mch), gravimetric yield (GYC), and bulk density (CBD) of charcoal, the highest average values were reported for groups 1, 2, and 4.

The highest Mch and GYC results reported for group 1 (*D. excelsa*) are associated with the high content of extractives and lignin in the wood (see Table 5). The H/C

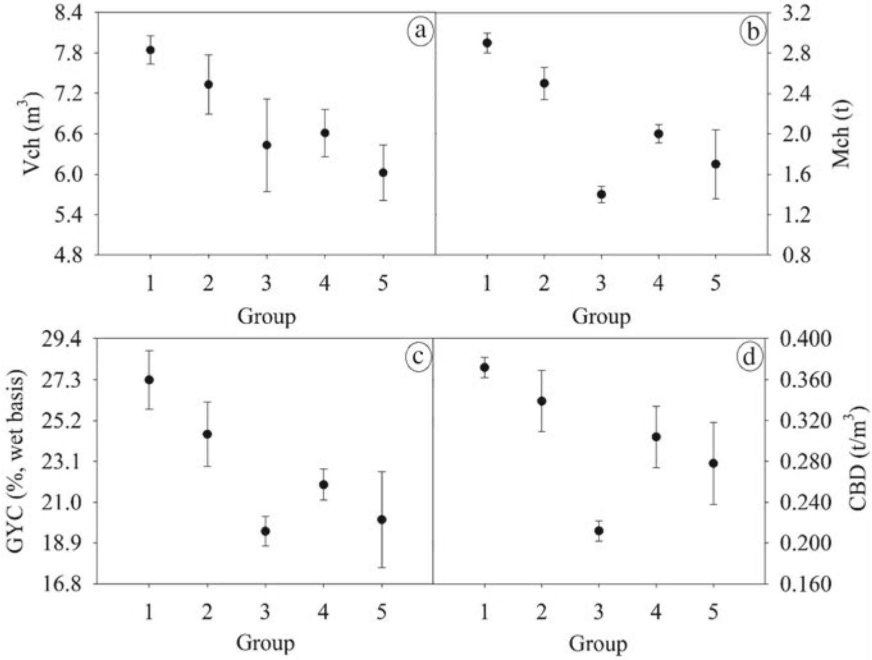

Fig. 10 Volume (**a**), mass (**b**), gravimetric yield (**c**), and bulk density (**d**) of charcoal produced in brick kilns at a production plant in Brazilian Amazonia using segregated waste groups (*Source* The authors 2023)

ratio and the high thermal stability of the extractives, mainly the phenolics, contribute to the increase in Mch and GYC [36]. In addition, this group will present reduced emissions of condensable and non-condensable gases into the atmosphere. Woods with higher densities explain the high CBD mean values of groups 1 (0.372 t/m^3), 2 (0.339 t/m^3), and 4 (0.304 t/m^3). In this sense, segregation will promote a greater mass of charcoal transported to the steel industries compared to group 5. On the other hand, the charcoal of group 3 is less dense and voluminous and can be considered as a basis for commercialization.

The production of charcoal must be better controlled, especially concerning raw materials and factors associated with the process. Clearly, the separation of wood promotes encouraging results related to the production and quality of charcoal, which can influence the operational and financial planning of the plant. Thus, the methodology to adequately control the quality of the consumed raw material must be adjusted. As charcoal is commercialized based on its mass, the basic density can be used as a qualitative index to discriminate the material by its quality. Furthermore, it is an easily determined property. The literature corroborates that dense woods generate charcoals with high apparent relative density [23]. On the other hand, groups with similar physical, chemical, and energy properties can clearly improve charcoal quality.

6 Future Prospects for Charcoal Production from Wood Wastes

The energy use of forest wastes contributes to reducing the environmental impact caused by improper disposal and the exacerbated use of “dirty” energy sources and, consequently, to the mitigation of greenhouse gas emissions. Forest biomass stands out among the various renewable materials used for energy purposes due to the numerous solid, liquid, and gaseous fuels obtained through thermochemical, biochemical, and mechanical routes and their conciliation. It is worth noting that Normative Instruction No. 5, of December 11, 2006, published by the Ministry of the Environment, mentions in Article 2, item XIV, that forest logging wastes (branches, buttresses, and remains of trunks, for example) can be used as secondary products of SFMP for wood and energy production [6]. However, there is still a lack of scientific research and technology transfer for the sustainable valorization of these resources for bioenergy generation on industrial and domestic scales.

Many advances have been obtained with the understanding of the quality of SFMP wastes destined for energy generation and steel charcoal production. However, there is a need to continue research to reach technological maturity for a real understanding of the energy potential of this biomass. Furthermore, converting this raw material into energy products is not sufficiently mastered. In this sense, thermochemical conversion routes must be sufficiently analyzed with integrated methodologies (energetic-environmental-economic). For example, the life cycle inventory will provide a technical–economic-environmental assessment of strategies for the sustainable use of residual biomass in SFMP associated with the carbon balance of conversion processes.

The studies carried out so far have promoted important advances in clarifying the quality parameters of forest wastes destined for energy production. Despite this, some aspects of its energy use need to be elucidated. As pointed out by Lima et al. [19], the thermal behavior and combustion kinetics of this fuel remains unclear. It is also necessary to know the energy performance of the wastes at different final carbonization temperatures. These studies will allow more efficient use of wood and subsidize new conversion routes, such as densification, torrefaction, gasification, and liquefaction. Biomass has been widely studied for producing electricity, bio-oil, and chemical compounds [26]. Although there is research on wood from Amazonian species [38] and other biomass types common in the region [3], there is no large-scale research on woody Amazonian wastes for this purpose.

From a strategic point of view, biomass energy conversion processes are economically viable techniques to generate energy for local communities and industrial production systems, even in remote locals, as in several regions of the Amazonia. In Brazil, direct combustion and carbonization are the two most widespread ways of using wood wastes from SFMP, the main legal tool for the rational use of timber and non-timber forest products in Brazilian Amazonia.

Previously reported studies were limited to a single charcoal production unit from waste wood. Future research needs to include more wooden species and Amazonian forest management regions in their studies. It is also necessary to know the amount of waste stored in the forests. Thus, efficient harvesting and storage strategies for these biomasses must be developed.

The sustainability of the entire production chain for the use of waste must become one of the main objects of future research, generating technological impacts for the full use of waste and improving sustainable technologies for bioenergy use of tropical forest resources; with new, creative, and viable solutions that contribute to technological, economic, and social developments, through research. Thus, the following questions must be answered: (i) How much carbon is emitted from the collection, transport, carbonization, and combustion of waste?; (ii) Does the carbon stored in the forest soil and the regeneration of trees after harvesting neutralize the carbon emitted by the production chain?; (iii) Are the strategies effective in minimizing environmental impacts?

The answers to these questions will support the development of new solutions in Amazonia for increasing the efficiency of waste use and minimizing polluting gas emissions during wood carbonization. The technologies used for planted forests burn polluting gases formed during carbonization [8] and can be improved, adapted, and applied to the carbonization of SFMP wood wastes.

7 Conclusions

SFMP wastes have suitable properties for charcoal production for domestic and industrial use. However, there are great challenges to producing sustainable energy with this Amazonian biomass, mainly due to the low technological level of the carbonization kilns and the high variation in the waste properties concerning their dimensions and physical, chemical, and energy properties.

For example, waste diameter and basic density show high variability among species, studies were carried out to characterize and classify these wood wastes into different groups to solve these problems. The results demonstrate an increase in the gravimetric yield of charcoal, the productivity of the kilns, and an improvement in the bioreducer quality.

Therefore, the importance of technological research is emphasized to enable the development of carbonization, direct heat generation, and other energy routes to adapt the industry in Brazil to the current requirements of the national and international markets. Future research should highlight technological improvements in energy production using SFMP wastes to increase efficiency, quality, and sustainability.

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References

1. Achat DL, Deleuze C, Landmann G, Pousse N, Ranger J, Augusto L (2015) Quantifying consequences of removing harvesting residues on forest soils and tree growth—a meta-analysis. For Ecol Manage 348:124–141. https://doi.org/10.1016/j.foreco.2015.03.042
2. Adamovics A, Platace R, Gulbe I, Ivanovs S (2018) The content of carbon and hydrogen in grass biomass and its influence on heating value. Eng Rural Dev 1(1):1277–1281. https://doi.org/10.22616/ERDev2018.17.N014

3. Araujo RO, Ribeiro FCP, Santos VO, Lima VMR, Santos JL, Vilaça JES, Chaar JS, Falcão NPS, Pohlit AM, de Souza LKC (2022) Renewable energy from biomass: an overview of the Amazon Region. Bioenergy Res 15(2):834–849. https://doi.org/10.1007/s12155-021-10308-x
4. Assis MR, Brancheriau L, Napoli A, Trugilho PF (2016) Factors affecting the mechanics of carbonized wood: literature review. Wood Sci Technol 50(3):519–536. https://doi.org/10.1007/s00226-016-0812-6
5. Barros DS, Lima MDR, Dias Junior AF, Bufalino L, Massuque J, Santos EV, Trugilho PF, Oliveira FA, Protásio TP (2023) Does the segregation of wood waste from Amazonia improve the quality of charcoal produced in brick kilns? Bioenergy Res. https://doi.org/10.1007/s12155-022-10551-w
6. Brazil (2006) Ministry of the Environment. Normative Instruction MMA No. 5 of December 11, 2006. Technical procedures for the preparation, presentation, execution, and technical evaluation of Sustainable Forest Management Plans—SFMP in primitive forests and their forms of succession in the Legal Amazon, and makes other arrangements. Brazil
7. Canal WD, Carvalho AMML, Carneiro ACO, Vital BR, Pereira BLC, Donato DB (2016) Effect of wood moisture on greenhouse gases emission from carbonization process. Sci For 44(112):831–840. https://doi.org/10.18671/scifor.v44n112.05
8. Cardoso MT, Damásio RAP, Carneiro ACO, Jacovine LAG, Vital BR, Barcelos DC (2010) Construction of a gas burning system resulting from carbonization to reduce pollutants emissions. Cerne 16:115–124
9. Crow SE, Reeves M, Turn S, Taniguchi S, Schubert OS, Koch N (2016) Carbon balance implications of land use change from pasture to managed eucalyptus forest in Hawaii. Carbon Manag 7(3–4):171–181. https://doi.org/10.1080/17583004.2016.1213140
10. Damásio RAP, Oliveira AC, Carneiro ACO, Barcelos DC, Pereira BLC, Magalhães MA, Silva MS (2015) Thermal profile and control of carbonization on circular kiln through the internal temperature. Ciência da Madeira 6(1):11–22. https://doi.org/10.12953/2177-6830/rcm.v61p11-22
11. Demirbas A (2005) Potential applications of renewable energy sources, biomass combustion problems in boiler power systems and combustion related environmental issues. Prog Energy Combust Sci 31(2):171–192. https://doi.org/10.1016/j.pecs.2005.02.002
12. Diniz VY (1981) Caldeiras a lenha. In: Gaseificação de madeira e carvão vegetal. pp 114–131
13. Fearnside PM (1997) Wood density for estimating forest biomass in Brazilian Amazonia. For Ecol Manage 90(1):59–87. https://doi.org/10.1016/S0378-1127(96)03840-6
14. Figueroa MJM, Moraes PD (2009) Wood behavior at high temperatures Manuel. Ambiente Construído 9(4):157–174
15. Haqiqi MT, Hudaya D, Septiana HA, Ramadhan R, Yuliansyah Y, Suwinarti W, Amirta R (2022) Short communication: analysis of the ultimate wood composition of a forest plantation species, *Eucalyptus pellita*, to estimate its bioelectricity potency. Biodiversitas 23(5):2389–2394. https://doi.org/10.13057/biodiv/d230516
16. International Association of Wood Anatomists - IAWA (1989) International association of wood anatomists: list of microscopc features for hardwood identification. IAWA J 10(3):219–232
17. Jesus MS, Carneiro ACO, Martinez CLM, Vital BR, Carneiro APS, Assis MR (2019) Thermal decomposition fundamentals in large-diameter wooden logs during slow pyrolysis. Wood Sci Technol 53:1353–1372. https://doi.org/10.1007/s00226-019-01133-9
18. Lima MDR, Massuque J, Bufalino L, Trugilho PF, Ramalho FMG, Protásio TP, Hein PRG (2022) Clarifying the carbonization temperature effects on the production and apparent density of charcoal derived from Amazonia wood wastes. J Anal Appl Pyrolysis 166:105636. https://doi.org/10.1016/j.jaap.2022.105636
19. Lima MDR, Patrício EPS, Barros Junior UO, Assis MR, Xavier CN, Bufalino L, Trugilho PF, Hein PRG, Protásio TP (2020) Logging wastes from sustainable forest management as alternative fuels for thermochemical conversion systems in Brazilian Amazon. Biomass Bioenergy 140:105660. https://doi.org/10.1016/j.biombioe.2020.105660
20. Lima MDR, Patrício EPS, Barros Junior UO, Silva RCC, Bufalino L, Numazawa S, Hein PRG, Protásio TP (2021) Colorimetry as a criterion for segregation of logging wastes from sustainable

forest management in the Brazilian Amazon for bioenergy. Renew Energy 163:792–806. https://doi.org/10.1016/j.renene.2020.08.078

21. Lima MDR, Ramalho FMG, Trugilho PF, Bufalino L, Dias Júnior AF, Protásio TP, Hein PRG (2022) Classifying waste wood from Amazonian species by near-infrared spectroscopy (NIRS) to improve charcoal production. Renew Energy 12(1):3224. https://doi.org/10.1016/j.renene.2022.05.048
22. Lima MDR, Simetti R, de Assis MR, Trugilho PF, de Carneiro ACO, Bufalino L, Hein PRG, de Protásio TP (2020) Charcoal of logging wastes from sustainable forest management for industrial and domestic uses in the Brazilian Amazonia. Biomass Bioenergy 142. https://doi.org/10.1016/j.biombioe.2020.105804
23. Lima MDR, Simetti R, Assis MRD, Trugilho PF, Carneiro ADCO, Bufalino L, Hein PRG, Protásio TDP (2020) Charcoal of logging wastes from sustainable forest management for industrial and domestic uses in the Brazilian Amazonia. Biomass Bioenergy 142:105804. https://doi.org/10.1016/j.biombioe.2020.105804
24. Lima MDR, Trugilho PF, Bufalino L, Dias Júnior AF, Ramalho FMG, Protásio TP, Hein PRG (2022) Efficiency of near-infrared spectroscopy in classifying Amazonian wood wastes for bioenergy generation. Biomass Bioenergy 166:106617. https://doi.org/10.1016/j.biombioe.2022.106617
25. Manolis EN, Zagas TD, Karetsos GK, Poravou CA (2019) Ecological restrictions in forest biomass extraction for a sustainable renewable energy production. Renew Sustain Energy Rev 110:290–297. https://doi.org/10.1016/j.rser.2019.04.078
26. Mednikov AS (2018) A review of technologies for multistage wood biomass gasification. Therm Eng 65(8):531–546. https://doi.org/10.1134/S0040601518080037
27. Moriana R, Vilaplana F, Ek M (2015) Forest residues as renewable resources for bio-based polymeric materials and bioenergy: chemical composition, structure and thermal properties. Cellulose 22(5):3409–3423. https://doi.org/10.1007/s10570-015-0738-4
28. Numazawa CTD, Krasovskiy A, Kraxner F, Pietsch SA (2020) Logging residues for charcoal production through forest management in the Brazilian Amazon: economic gains and forest regrowth effects. Environ Res Lett 15(11):114029. https://doi.org/10.1088/1748-9326/abb495
29. Numazawa CTD, Numazawa S, Pacca S, John VM (2017) Logging residues and CO_2 of Brazilian Amazon timber: two case studies of forest harvesting. Resour Conserv Recycl 122:280–285. https://doi.org/10.1016/j.resconrec.2017.02.016
30. Oliveira AC, Carneiro ACO, Pereira BLC, Vital BR, Carvalho AMML, Trugilho PF, Damásio RAP (2013) Optimization of charcoal production through control of carbonization temperatures. Revista Árvore 37(3):557–566. https://doi.org/10.1590/S0100-67622013000300019
31. Oliveira JTS, Hellmeister JC, Tomazello Filho M (2005) Variation of the moisture content and specific gravity in the wood of seven eucalypt species. Revista Árvore 29(1):115–127. https://doi.org/10.1590/S0100-67622005000100013
32. Paré D, Thiffault E (2016) Nutrient budgets in forests under increased biomass harvesting scenarios. Current Forestry Reports 2(1):81–91. https://doi.org/10.1007/s40725-016-0030-3
33. Peláez-Samaniego MR, Garcia-Perez M, Cortez LB, Rosillo-Calle F, Mesa J (2008) Improvements of Brazilian carbonization industry as part of the creation of a global biomass economy. Renew Sustain Energy Rev 12(4):1063–1086. https://doi.org/10.1016/j.rser.2006.10.018
34. Pereira AA, Lima MDR, Patrício EPS, Numazawa S, Goulart SL, Protásio TP (2020) Grouping of wood residues from sustainable forest management aiming at bioenergy generation. Sci For 48(127):1–14. https://doi.org/10.18671/scifor.v48n127.01
35. Pereira BLC, Carneiro ACO, Carvalho AMML, Colodette JL, Oliveira AC, Fontes MPF (2013) Influence of chemical composition of Eucalyptus wood on gravimetric yield and charcoal properties. Bioresources 8(3):4574–4592. https://doi.org/10.15376/biores.8.3.4574-4592
36. Pereira BLC, Oliveira AC, Carvalho AMML, Carneiro ACO, Santos LC, Vital BR (2012) Quality of wood and charcoal from Eucalyptus clones for ironmaster use. Int J For Res 2012:1–8. https://doi.org/10.1155/2012/523025

37. Protásio TP, Lima MDR, Scatolino MV, Silva AB, Figueiredo ICR, Hein PRG, Trugilho PF (2021) Charcoal productivity and quality parameters for reliable classification of Eucalyptus clones from Brazilian energy forests. Renew Energy 164:34–45. https://doi.org/10.1016/j.renene.2020.09.057
38. Rivera JEG, Merencio DO, Vistín ASR, Acosta RDL, Espinoza BDC, Abreu-Naranjo R (2022) Thermogravimetric characteristics and kinetic modeling of *Piptocoma discolor* pyrolysis and combustion processes to contribute to its use as a renewable energy source in the Ecuadorian Amazon region. Biomass Convers Biorefin. https://doi.org/10.1007/s13399-021-02178-2
39. Rodrigues T, Braghini Junior A (2019) Charcoal: a discussion on carbonization kilns. J Anal Appl Pyrolysis 143:104670. https://doi.org/10.1016/j.jaap.2019.104670
40. Santos RC, Carneiro ACO, Vital BR, Castro RVO, Vidaurre GB, Trugilho PF, Castro AFNM (2016) Effect of properties chemical and siringil/guaiacil relation wood clones of Eucalyptus in the production of charcoal. Ciência Florestal 26(2):657–669. https://doi.org/10.5902/1980509822765
41. SINDIFER. Sindicato da Indústria do Ferro no Estado de Minas Gerais (2021) Pig iron production in Minas Gerais and in Brazil. Statiscal yearbook reference: 2020. Minas Gerais
42. Surup GR, Trubetskaya A, Tangstad M (2020) Charcoal as an alternative reductant in ferroalloy production: a review. Processes 8(11):1432. https://doi.org/10.3390/pr8111432
43. Telmo C, Lousada J (2011) The explained variation by lignin and extractive contents on higher heating value of wood. Biomass Bioenergy 35(5):1663–1667. https://doi.org/10.1016/j.biombioe.2010.12.038
44. Vos MAE, den Ouden J, Hoosbeek M, Valtera M, de Vries W, Sterck F (2023) The sustainability of timber and biomass harvest in perspective of forest nutrient uptake and nutrient stocks. For Ecol Manage 530:120791. https://doi.org/10.1016/j.foreco.2023.120791