Effect of Wood Chips and Wood Board-Ends of *Gmelina arborea* on Yields and Process of Slow Pyrolysis Using a Semi-Industrial Reactor Prototype

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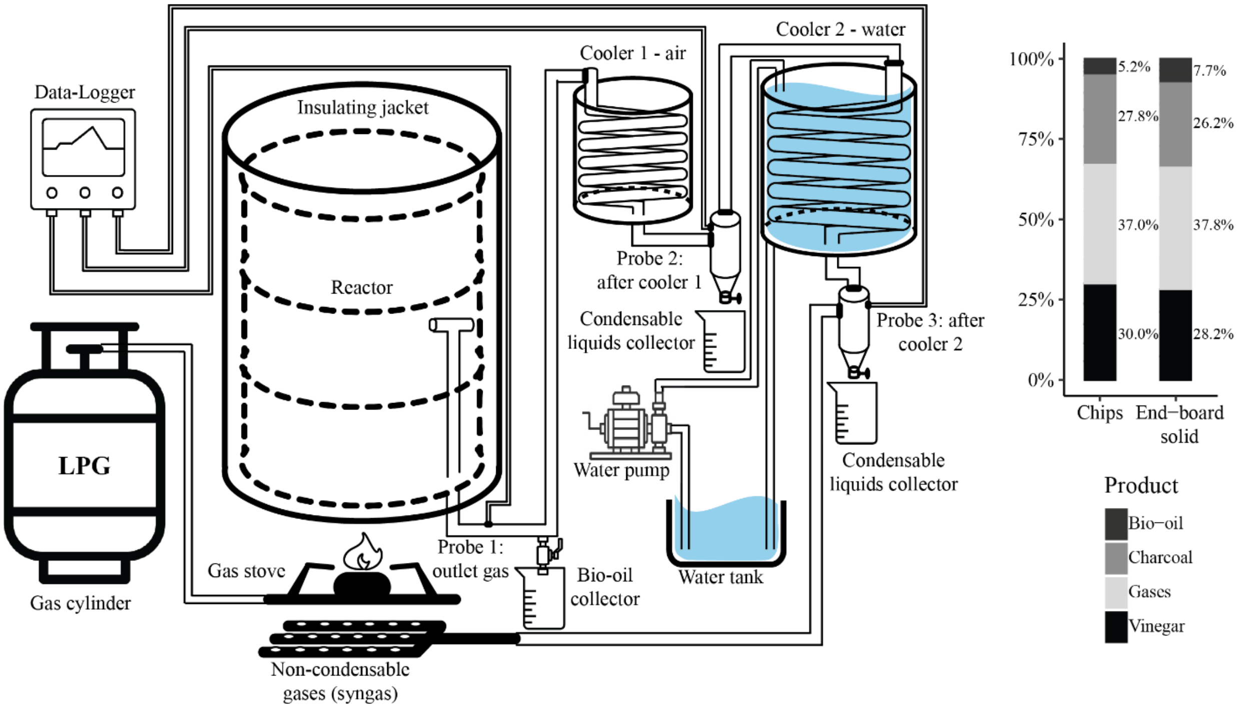
GRAPHICAL ABSTRACT



Cylindrical reactor designed and utilized for evaluation of the slow pyrolysis process and distribution of the products and yields from two types of residues of *Gmelina arborea* wood.

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Pyrolysis of biomass residues can generate savings in the value chains of forest products due to the potential uses of its products in the forestry sector. The aim of this study was to determine the performance during slow pyrolysis process and the yields of different products of two types of residues, wood chips and solid wood board-ends from *Gmelina arborea*. Results showed no significant differences in yields of charcoal (26 to 28%), wood vinegar (28 to 30%) and non-condensable gases (37%), but bio-oil yield was higher for the solid wood board-ends residues (7.7%). The evaluation of energy charcoal characteristics and wood vinegar was similar for two types of residues. So, results suggest that two types of residues provided similar charcoal, condensable and non-condensable gases yields, but solid board-ends are recommended to obtain higher yield of bio-oil and complete the process in less time. Charcoal and vinegar characteristic were affected by type of residues.

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Keywords: Pyrolysis; Biochar; Pyroligneous acids; Wood tar; Wood vinegar

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INTRODUCTION

Biomass pyrolysis is the thermal degradation of biomass in absence of oxygen and is one of the most common thermochemical biomass conversion processes for energy production (Tan *et al*. 2021; Velmurugan 2022). Biomass decomposition occurs at elevated temperatures (400 to 900 °C) by breaking down the long-chain hydrocarbons in the wood biopolymers (Tan *et al*. 2021). Pyrolysis can be categorized as slow pyrolysis or fast pyrolysis based on the heating rate and maximum reaction temperature (Tan *et al.* 2021). Slow pyrolysis occurs at temperatures between 300 to 700 °C with residence times of minutes to hours and heating rates of 0.1 to 10 °C min^{-1} (Tan *et al*. 2021).

Biomass from wood (chips or fiber) can be produced with different dimensions during its reduction, and then those differences can affect the pyrolysis process, and some problems can be encountered (Kaczor *et al*. 2020). Different dimensions of biomass affect the pyrolysis products yields, as higher yields of char have been observed for pyrolyzing biomass at temperatures lower than 400 °C, while at higher temperatures char and gas yields are favored by smaller particles (Yu *et al*. 2018). Cubic-shaped biomass pyrolyzes more slowly and has higher char yields than slender particles, which produce more volatile compounds (Atreya *et al*. 2017). Another wood characteristics related to different dimensions is its moisture. Smaller dimensions present lower values of moisture content and high dimensions present high moisture content. High moisture content affects the heat transfer, the pyrolysis reactions and product distribution in pyrolyzing biomass (Uddin *et al*. 2018) and is one of the main reasons for poor quality of crude bio-oil (Wang *et al*. 2020a,b). Moreover, high moisture content leads to more energy consumption (Uzakov *et al*. 2018).

Notably, 88% of the total roundwood produced in Central America and the Caribbean is used as fuel (Thiffault *et al*. 2023), showing the importance of fuel in the region. Moreover, in 2020, 90% of global bioenergy demand was produced in a traditional way in open fires or rustic kilns (International Energy Agency 2021). The Central America need for a structural transition towards the valorization of forest resources is evident. Feedstock of forest resources can be obtained from short rotation energy plantations, forest residues from logging of plantation or natural forest trees, and clear-cutting of tree in agriculture areas or cities (Duca and Toscano 2022). These resources share a common process; size reduction *in situ* is achieved by the production of chips (Oyedeji *et al*. 2020). The sawmill process produces different residues, such as board-ends, boards of small dimensions, sawdust, and other solid materials, which must be too reduced their size by chips production (Titus *et al*. 2021). Different dimensions of forest feedstock can be found for energy production: boards of small dimensions (solid wood board-ends) and chips. So, increasing the profitability of wood energy can be obtained by managing the wood residues and generating savings in the process (Béland *et al*. 2020).

Among the different methods or reactors used for slow pyrolysis in developing countries (Garcia-Nunez *et al*. 2017) are flame curtain kilns, drum kilns, among other equipment (Namaswa *et al*. 2023). Drum kiln reactors are used in many countries due to low investment costs and minimal knowledge required (Namaswa *et al*. 2023); the new model considers smoke condensation for wood vinegar productor and utilizations of combustible gasses (Ouattara *et al*. 2023). The yield of biochar is maximized (~35%) through slow pyrolysis (Tomczyk *et al*. 2020) and when the gases are condensed, one proportion is called as bio-oil (3 to 5%) and is a viscous mixture of organic compounds, mostly oxygenated hydrocarbons (Oasmaa *et al*. 2021). Another proportion of condensed gases (~25%) is called wood-vinegar (Ouattara *et al*. 2023). A proportion (~35%) of the gases are not condensed and named as syngas (Tomczyk *et al*. 2020).

In Costa Rica, fuelwood has gained popularity in recent years as a renewable alternative to meet the growing energy demand and an aid to sustainable rural development (Arias 2020). In that sense, energy production from forest biomass has been found viable for self-consumption (González *et al*. 2018). Short rotation energy plantations produce feedstock for energy production (Tenorio *et al*. 2016; Arias 2020). But some studies also recommend the use of forest residues as an innovative solution for different thermal and thermo-chemical process for energy productions, as gasification (Chaves *et al*. 2024), torrefaction (Gaitán-Álvarez *et al*. 2017), pyrolysis (Berrocal-Méndez and Moya 2022), besides the physical modification of this feedstock as pellet fabrication (Moya *et al*. 2015). Sawnwood yields are low, and residues of up to 78% of the standing tree volume have been reported, suggesting the need to find alternatives for the non-marketable volume (Espinoza-Durán and Moya 2013). The residues can be found in two different dimensions: solid wood board-ends from industrial process and chips from forest residues and solid residues in sawmill (Berrocal-Méndez and Moya 2022).

Gmelina arborea Roxb. ex Sm (melina), is the second most reforested forest species in Costa Rica (Instituto Nacional de Estadística y Censos 2022). It is the main species used in the manufacture of pallets, a product that dominates the national timber market (Oficina Nacional Forestal 2022). A high quantity of residues are produced during logging and sawmill (Espinoza-Durán and Moya 2013). *G. arborea* wood has desirable physical and chemical properties for different products of pyrolysis (Moya *et al*. 2024). However, *G. arborea* wood can present high moisture content and cellulose percentage (47%) in solid wood (Moya and Tenorio 2013). High moisture content and slow drying rate are main problem of *G. arborea* wood and affect many industrial process (Moya *et al*. 2024). During pyrolysis, the high moisture and cellulose lead to tar production and high cellulose influence the production of high char at low temperatures and the production of volatile products at high temperatures (Tripathi *et al*. 2016). These findings suggest that pyrolysis products of *G. arborea* can be optimized based on the wood characteristics and the type of pyrolysis. In fact, Moya *et al*. (2024) showed that the main variables of pyrolysis process and yields of different products were affected by pyrolysis temperature.

G. arborea is a potential species for residues-based charcoal production; however, it necessary to determine the performance and yields of different products of pyrolysis in semi-industrial drum kilns prototype according to social conditions of Costa Rica. This study aimed to (i) determine the yields of the different products (charcoal, wood vinegar, bio-oil, and non-condensable gases) and (ii) evaluate the conditions in three stages of the slow pyrolysis process of two types of wood residues (wood chips and solid wood board-ends) of *G. arborea*, from a semi-industrial prototype reactor. Results are going to be useful to estimate the production of biochar, condensable liquids (vinegar and bio-oil) and non-condensable gases from wood residues of *G. arborea*.

EXPERIMENTAL

Materials

Two types of wood residues from the sawmill process and secondary process of *Gmelina arborea* were used. The company Maderas Cultivadas de Costa Rica (MCC) provided the wood from fast-growing plantations between 9 and 15 years old. Two types of wood residues were used: wood chips and solid wood board-ends (Fig. 1a-b).

Raw Material Characterization

Wood chips were residues from sawlog processing with dimensions of 5 to 10 cm long x 2 to 5 cm width and air-dried. 50 kg of wood chips were sampled to be used in the five different batches or running in the experimental reactor. Although the amount of bark presented in wood chip was not measured, a previous study showed that the amount of bark was 13% in *G. arborea* (Chaves *et al.* 2024). Wood board-ends were residues from the secondary wood processing with dimensions of 4 to 25 cm long and 12 to 32 mm thick. These residues came from dried lumber utilized for fabrication of blockboards. 50 kg of this residues was also used for four running of the experimental reactor. From each type of residue, five random 500 g samples were taken of whole material for moisture content (MC%) determination. The MC was calculated according to the oven-dried secondary method of ASTM D4442-20 standard (ASTM 2020). Three samples per batch of type of residue were extracted, and the capacity varied with type of residue (Table 1). The different types of residues presented MC% differences as well; solid wood board-ends had a statistically lower MC% than wood chip. These difference in MC% in two type of residues was due to the fact that wood chips are dried at 16% in MC% for boiler of Maderas Cultivadas of Costa Rica (MCC); then this company planned to use these chips with same MC% condition. But wood end-boards were residues of blockboards production, where lumber was dried at 11%. The MCC company prefers not to change this MC for two types of residues. Then, although the differences in moisture content and differences in size and geometry of the source material have influenced in reactor performance, it was important to know the performance of reactor with two types of residues.

Table 1. Moisture Content and Pyrolizer Capacity for Different Types of Residues

Type of Residue	Moisture Content (%)	Weight for Batch or Running (kg)
Chips	16.11^{A}	6.50^{B}
Board-ends	10.20^{B}	10.79^{A}

Legend: Different letters between residues indicate statistical differences (p-value<0.05)

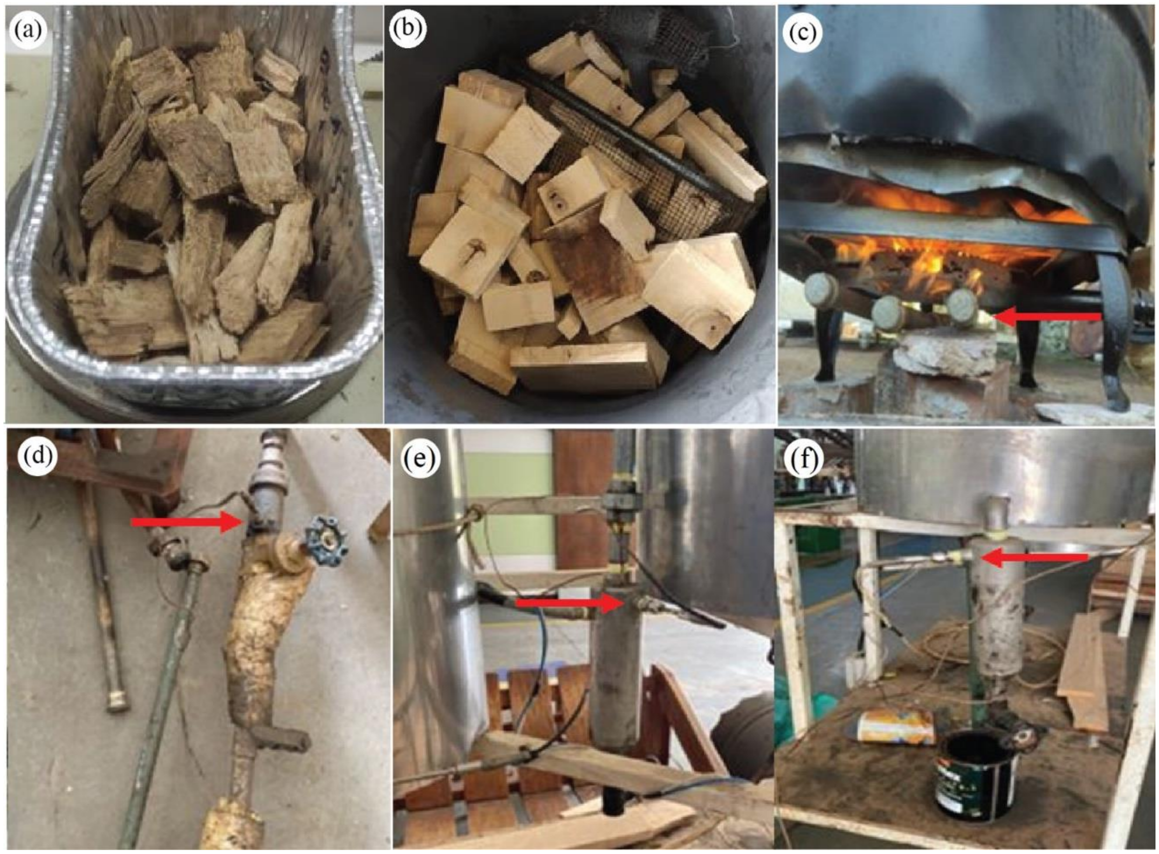

Fig. 1. Wood residues of *G. arborea* used in the pyrolysis process: (a) woo chips and (b) solid board-ends; Different parts in the rector: Non-condensable gases outlet (c) and temperature meter probes at three stages of the wood residues pyrolysis process: pyrolizer gas outlet (d), after the first cooler (e) and after the second cooler (f)

Slow Pyrolysis Process

The pyrolysis of wood residues was carried out in a cylindrical reactor of 58 cm diameter, 88 cm long, and 232 L capacity (Fig. 2). The reactor was covered with another cylinder with a glass fiber insulating jacket. First, the reactor was heated with liquefied petroleum gas (LPG) until the temperature began to decrease in the reactor. The temperature was observed using a datalogger Testo model 176/T4 (Testo SE & Co., Titisee-Neustadt, Germany), which will be explained later. The pyrolysis was finished when the syngas flame was over, and then the reactor was maintained closed until the temperature reached 25 °C, where the time varied from 5 to 6 hours. The pyrolytic gases were cooled through a system of two coolers made of two helical coil heat exchangers. The first heat exchanger was cooled with air at room temperature and the second cooler with a closed water circuit moved by a pump. Liquids were collected after each cooler. Non-condensable gases (syngas) continued its flow by pipe for the heating of the pyrolysis reactor (Fig. 1c, Fig. 2). The pyrolysis process was executed in five batches when processing wood chips and four batches when processing wood board-ends.

The pyrolysis process was studied using temperature variation from the start of heating the reactor until that the reactor cooled to a temperature of 25 °C. Temperature was registered in three different stages of the process and are shown in the Fig. 1d-f: pyrolizer gas outlet temperature (Probe 1, Fig. 1d), temperature of gases after the first cooler (Probe 2, Fig. 1e) and temperature of non-condensable gases after the second cooler (Probe 3, Fig. 1f). Temperatures were measured each minute with a datalogger Testo model 176/T4 and were registered for each running of the pyrolysis process.

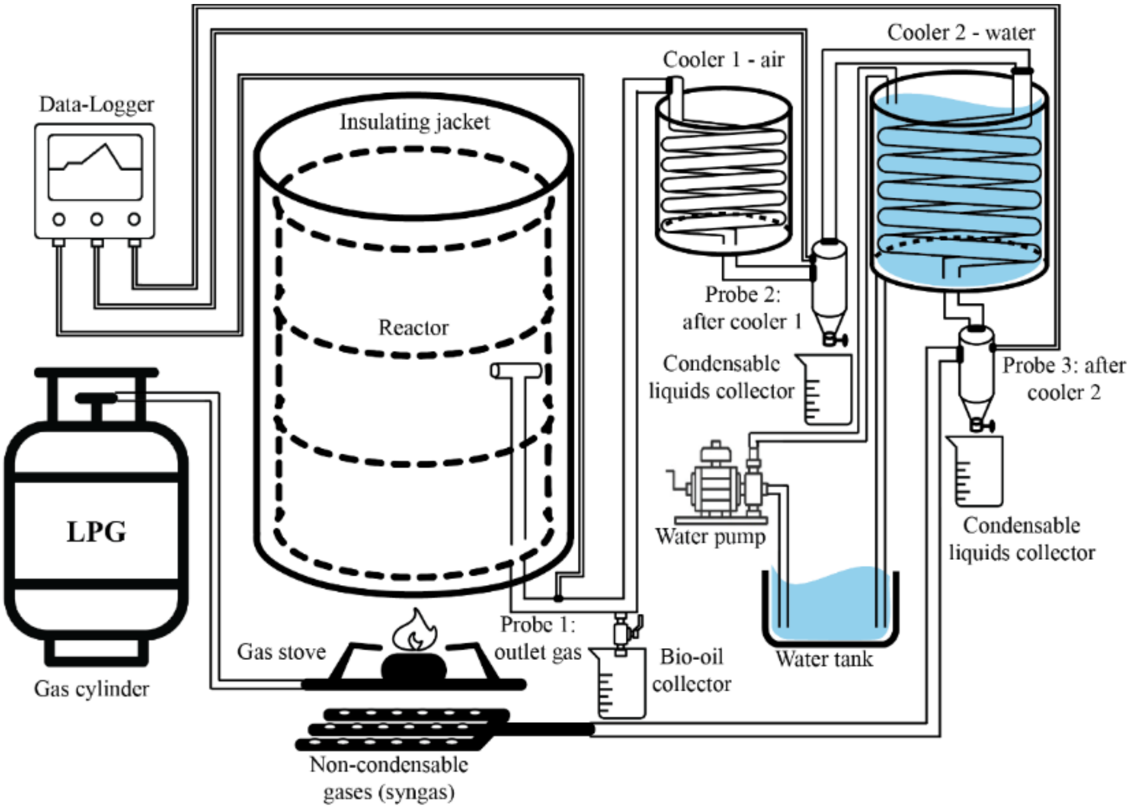

Fig. 2. Cylindrical reactor designed and utilized for evaluation of the slow pyrolysis process

Evaluation of the Yield of Pyrolysis Products

The yields of the different products were calculated as shown in Moya *et al*. (2024): charcoal, bio-oil, wood vinegar, and non-condensable gases. Wood residues were weighted before each running the pyrolysis process and at the end of the process. Charcoal, bio-oil and vinegar were weighed to calculate each yield. The yields of charcoal, bio-oil and vinegar were calculated by Eq. 1. Non-condensable gases yield was calculated according to Eq. 2.

$$Yield\ (\%) = \frac{Product\ weight\ (kg)}{Wood\ weight\ (kg)} * 100 \tag{1}$$

$$Non-condensable\ \ yield\ (\%) = 100 - (charcoal + vinegar + tar\ yields) \tag{2}$$

Evaluation of Conditions in Three Stages of the Pyrolysis Process

The temperature and time data were used to evaluate the pyrolysis process according to Moya *et al*. (2024) with some modifications. Temperature was recorded in three stages using probes: (1) outlet pyrolysis gas reactor, (2) outlet pyrolysis gas of cooler 1, and (3) outlet pyrolysis gas of cooler 2 (Fig. 1d-f). Four parameters for the outlet pyrolysis gas reactor and outlet pyrolysis gas of cooler 1, and three parameters for the outlet pyrolysis gas of cooler 2. Figure 3 presents the points and abbreviations of the parameters in the different stages, and Table 2 describes the parameters evaluated. Finally, the duration of the pyrolysis process was measured.

Table 2. Parameters of Time and Temperature of the Different Stages Evaluated During Pyrolysis Process of *Gmelina arborea*

Stage	Parameters	Abbreviations of points in Fig. 3
Outlet pyrolysis gas of reactor	1. Time when temperature began to increase 2. Time when water evaporation began 3. Temperature when water evaporation began 4. Time of stabilization in maximum temperature 5. Temperature of stabilization in maximum temperature 6. Time when temperature began to decrease 7. Temperature when it began to decrease	OR-1 OR-2 OR-2 OR-3 OR-3 OR-4 OR-4
Outlet pyrolysis gas of cooler 1	1. Time when the temperature begins to increase 2. Time when water evaporation began 3. Temperature when water evaporation began 4. Time of stabilization in maximum temperature 5. Temperature of stabilization in maximum temperature 6. Time when temperature began to decrease 7. Temperature when it began to decrease	OC1-1 OC1-2 OC1-2 OC1-3 OC1-3 OC1-4 OC1-4
Outlet pyrolysis gas of cooler 2	1. Time when temperature began to increase 2. Time when water evaporation began 3. Temperature when water evaporation began 4. Time when temperature began to decrease 5. Temperature when it began to decrease	OC2-1 OC2-2 OC2-2 OC2-3 OC2-3

Condensable Products and Charcoal Characteristics

The physical properties of condensable products were determined, specifically color, odor, insoluble particles, density, electric conductivity (EC), and pH of wood vinegar and bio-oil. Insoluble particles were obtained by filtering the products with a paper filter, and its value calculated as the difference between the initial and final weight. The density was determined by dividing the liquid mass by its volume. The pH was measured with a pH meter (PHS-3C) and EC was determined only for wood vinegar with a Hanna Instruments HI98312 (R.I, USA) water conductivity meter.

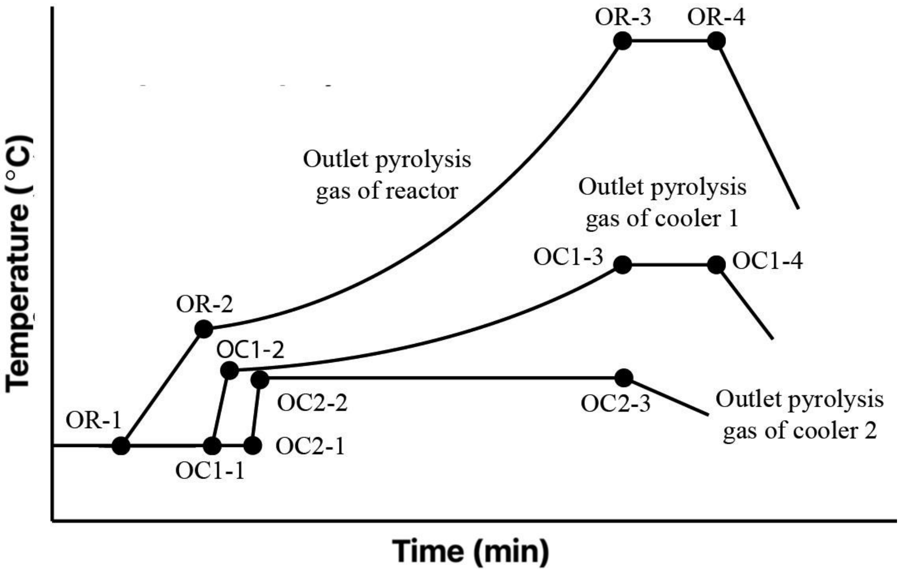

Fig. 3. Different stages of the pyrolysis process of *Gmelina arborea* wood residues in four points of the outlet pyrolysis gas reactor and outlet pyrolysis gas of cooler 1, and three points of the outlet pyrolysis gas of cooler 2

Charcoal characteristics determined were physical, energetics, and chemical properties for charcoal produced with two types of residues. The physical properties determined were color and visual aspects of charcoal, bulk, apparent density, and moisture content. According to different ASTM methods used, the charcoal was sieved from the 0.25 mm and 0.42 mm. Approximately 50 g of charcoal was obtained and dried at stove in 103 °C for 24 hours. For energy characteristics measured were gross caloric value, ash, and volatile content. GCV was determined at 0% of moisture content according to ASTM D5865-19 standard and using Parr's calorimetric test (ASTM 2019); for each material, ten samples of 300 mg per pyrolysis temperature were tested. Ash content was determined in three samples (2 g each) per material of each type of residue, according to ASTM D3173 standard (ASTM 2017). Three samples weighing 3 g each per type of residue were used following the ASTM D1762 (2021).

Another analysis was thermogravimetric analysis (TGA) using Thermogravimetric analyzer (TA Instruments Q500, New Castle, Denver, USA). An inert atmosphere was provided by ultra-high purity nitrogen with glow rates of 90.0 mL min^{-1}. One sample of 5 mg of charcoal were used for type of residue. Each analysis was developed beginning with a thermal stabilization and isothermal period at 30 °C and 10 min. The heat rate was 25 °C/min until 750 °C. TA Instruments Universal Analysis 2000 software was used in data acquired.

Statistical Analysis

The assumptions of normal distribution and homogeneity of variances were confirmed for the different product yields, the parameters evaluated during the pyrolysis process and charcoal characteristics. Two-sample t-tests were carried out to determine statistical differences between the average of the variables measured of the wood residues (MC%, yield of charcoal, condensable, vinegar, bio/oil and non-condensable content) and charcoal characteristics (physical, energy and chemical). The quantity of the samples was:

five for MC% in each residue, five for wood chips and four for end-boards residues for parameters of reactor, five samples for determination of physical, energy and chemical characteristics of charcoal. T-tests and multivariate analyses were conducted using the R programming language v.4.3.1 in the integrated development environment RStudio v.2023.16.0-421 (Core Team 2023).

RESULTS AND DISCUSSION

Evaluation of the Yield and of Conditions in Three Stages of Pyrolysis

The different products obtained during the pyrolysis process are presented in Fig. 4a. Charcoal and vinegar presented similar yields that ranged from 26 to 31% and from 27 to 32%, respectively (Fig. 4b and Fig. 4c). The yield of condensable (sum of vinegar and bio-oil) was statistically equal in two types of wood residues, which ranged between 33 and 38% (Fig. 4d). Bio-oil had the lowest yield among the different products (Fig. 4a), presenting the highest percentage when wood board-ends was used (7.7%) (Fig. 4e). The product with the highest yield was the non-condensable (syngas), which ranged between 34 to 40% (Fig. 4f).

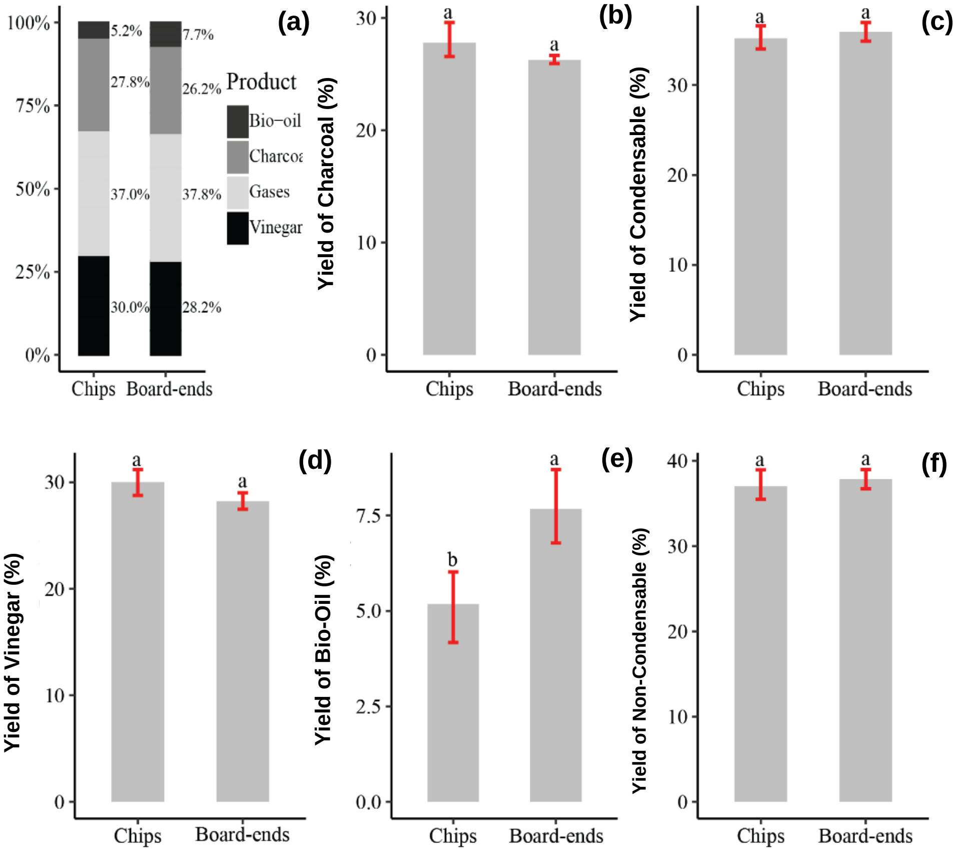

Fig. 4. (a) Distribution of the products and yields of (b) charcoal, (c) condensable gases, (d) wood vinegar, (e) bio-oil (e), and (f) non-condensable gases from the pyrolysis process of two types of wood residues of *Gmelina arborea*.
Legend: Confidence limits α=0.05 and different letters between residues indicate statistical differences (p-value<0.05).

Differences in the total duration of pyrolysis process resulted in significant differences among wood residues. Wood chips lasted longer, with 118 min, compared to the 93 min for wood board-ends. In the three stages evaluated of the pyrolysis process, the time when the temperature started to increase (OR-1, OC1-1 and OC2-1) and time and temperature when the water started to evaporate (OR2, OC1-2 and OC2-2) did not present significant differences between two type of residues (Table 3).

Outlet of the reactor

The time when the temperature started to increase (OR-1) ranged between 1 and 13 min after starting to heat the reactor (Table 3). The time and temperature when the water started to evaporate (OR-2) was between 12 to 20 min and 67.5 to 89.6 °C, respectively (Table 3); again, no significant difference was observed between the two types of residues. The time and temperature when the process (OR-3) reached the maximum temperature and when it began to decrease varied among two types of residues of wood (Table 3). Wood board-ends presented higher values of maximum temperature and shorter time than wood chips. After 5 min of stabilization of the maximum temperature, it began to decrease (OR-4) at between 205.5 and 273.0 °C for wood board-ends and 144.8 and 170.3 °C for wood chips (Table 3).

Outlet of the cooler 1

Temperature began to increase in cooler 1 (OC1-1) after 10 min later than the outlet of the reactor for two types of residues, between 12 to 18 min. The evaporation of water in the reactor was registered in the cooler (OC1-2) at a time between 18 and 21 min and temperature between 75.1 and 78.2 °C for two types of residues and there were not any statistical differences. Later, maximum temperatures (OC1-3) were reached, and wood board-ends presented statistically higher temperature and shortest time than wood chips (Table 3). Approximately 5 min later, the temperature began to decrease at 173 to 177.3 °C for wood board-ends and 90.9 to 95 °C for wood chips (OC1-4) and both types of residues were statistically different (Table 3).

Table 3. Temperatures and Times of the Different Stages during Pyrolysis process of Wood Residues of *Gmelina arborea*

Stage	Abbreviations of points in Fig. 3	Time (min)		Temperature (°C)	
		Board-ends	Chips	Board-ends	Chips
Outlet pyrolysis gas of reactor	OR-1	3.0	8.7	-	-
	OR-2	12.7	15.0	73.4	75.8
	OR-3	80.0	103.7	262.4	162.2
	OR-4	85.3	109.0	240.4	153.7
Outlet pyrolysis gas of cooler 1	OC1-1	14.3	17.0	-	-
	OC1-2	18.0	21.7	76.8	76.6
	OC1-3	82.0	104.7	182.1	97.5
	OC1-4	87.0	110.7	174.8	92.3
Outlet pyrolysis gas of cooler 2	OC2-1	21.3	31.7	-	-
	OC2-2	25.0	37.0	73.1	64.9
	OC2-3	77.3	103.0	64.8	59.9

Outlet of cooler 2

The time when the temperature started to increase (OC2-1) ranged between 19 and 40 min. The temperature when water started to evaporate in the reactor (OC2-2) was from

59.2 and 75.1 °C, and the range of time from 22 to 50 min did not show any differences. The temperature stabilized at water evaporation (OC2-2) and then started to decrease (OC2-3) at 71 to 86 min for wood board-ends, and this time was statistically lower than wood chips (Table 3).

Different dimensions of residues were used in this study (Fig. 1a-b). It is expected to obtain higher charcoal production using larger particles due to a low heat transfer rate (Tripathi *et al.* 2016). No significant difference of charcoal yield between the chips and board-ends were observed in this study (Fig. 4b). Instead, larger particles (wood board-ends) reached the maximum temperature faster than the smaller particles (wood chips) (Table 3). Higher moisture content of biomass has been found to increase the energy required to reach the pyrolysis temperature (Tripathi *et al*. 2016). In this study feedstock presented MC% below the fiber saturation point (Table 2), being suitable for pyrolysis (Tripathi *et al*. 2016). However, wood chips presented higher moisture content (Table 2), which means that more energy supplied to the pyrolyzer through the stove was consumed to remove the moisture and less is used to raise the temperature (Tripathi *et al*. 2016). In addition, this moist condition probably resulted in longer time and lower temperatures at the different points where these parameters were measured (Table 3). Besides presence of the bark is known to affect the pyrolysis performance (Şen and Pereira 2021) and wood chips presented a high percentage of bark.

No differences were observed for these products among the type of residue (Fig. 4a). The yields of charcoal, condensable and non-condensable gases agreed with percentages reported by Moya *et al.* (2024) for *G. arborea* pyrolyzed at 450 to 500 °C. Tripathi *et al.* (2016) mentioned that a high heating rate enhances biomass fragmentation and gaseous and liquid yield. They also reported that low temperatures contribute to high char yields while high temperatures produce the highest volatiles by cellulose decomposition and condensable products increase. According to percentage of yield, the utilization of wood with two different dimensions had little effect on these percentages, except for yield of bio-oil, for which wood chips produced the lowest percentage (Fig. 4e).

Wood chips pyrolysis had similar production of vapors (gases) as wood board-ends, probably because board-ends produced more gases by direct decomposition and less by secondary decomposition of wood tar due to a higher heating rate (Chen *et al.* 2017), in comparison to wood chips. However, wood chips did not produce higher temperatures inside of reactor (OR-2 and OR-3); it is known that higher temperatures promote cellulose decomposition and thereby increase the biol-oil production. At higher surface area to volume ratio, it is expected to enhance the production of bio-oil, due to a faster decomposition of the wood and shorter transportation of tar through the hot porous solids (Chen *et al*. 2017). However, the smallest particle in this experiment (*i.e.* wood chips) contained higher moisture, which slowed down the heating rate of the feedstock (Table 3), which favors the production of char rather than tar. The bio-oil from wood board-ends (Fig. 4e) can be produced from a higher volatilization of materials due to higher temperatures (Table 3) in this type of feedstock (Dias Junior *et al*. 2020).

The temperature of stabilization in maximum temperature of the reactor outlet (OR-3; Table 3) for wood chips and wood board-ends were the highest of whole reactor. Then the maximum reached temperatures inside the reactor were higher. In addition, the temperatures and the product yields obtained (Fig. 4) corresponded with the slow pyrolysis values (Tomczyk *et al*. 2020). However, the time and temperatures behavior varied with types of residues, especially inside the reactor in the outlet of pyrolysis gases (OR), but not when gases were cooled (Table 3). Wood chips extended the time of pyrolysis gas outlet, time of reaching the maximum temperature, time when temperature began to decrease, and temperatures were lower inside the reactor and for the gases produced by pyrolysis. These conditions are known to produce different chemical reactions for different feedstock (Ateş and Işıkdağ 2008).

Atreya *et al*. (2017) found that temperature when pyrolysis occurs influences the pyrolysis duration, which also vary with different dimensions of the particles and follows the mass of the decomposing particle. For moisture free feedstock, large particles with cubic or spherical shapes pyrolyze more slowly than small and thin particles (Atreya *et al.* 2017). Similarly, Peters and Bruch (2003) indicate that the start of the pyrolysis depends on the particle size and the heating temperature, and Bennadji *et al.* (2014) found that the time of heating and devolatilization increase with increasing the particle size. These findings of feedstock size and shape were conducted with moisture-free particles, which can explain the contrast with our results, where the larger and like cubic shape, but drier particles (board-ends) presented the higher temperatures and the shorter pyrolysis duration.

Charcoal and Wood Vinegar Characteristics

The charcoal produced with two different dimensions of wood varied with dimensions of charcoal pieces (Fig. 5a-b). End-boards produced bigger dimensions than wood chips (Fig. 5a-b). The color of wood vinegar presented similar color and visual color between two type of residues and the color appeared reddish (Fig. 5c). In general, it was difficult to observe the differences, besides their dimensions (Fig. 6).

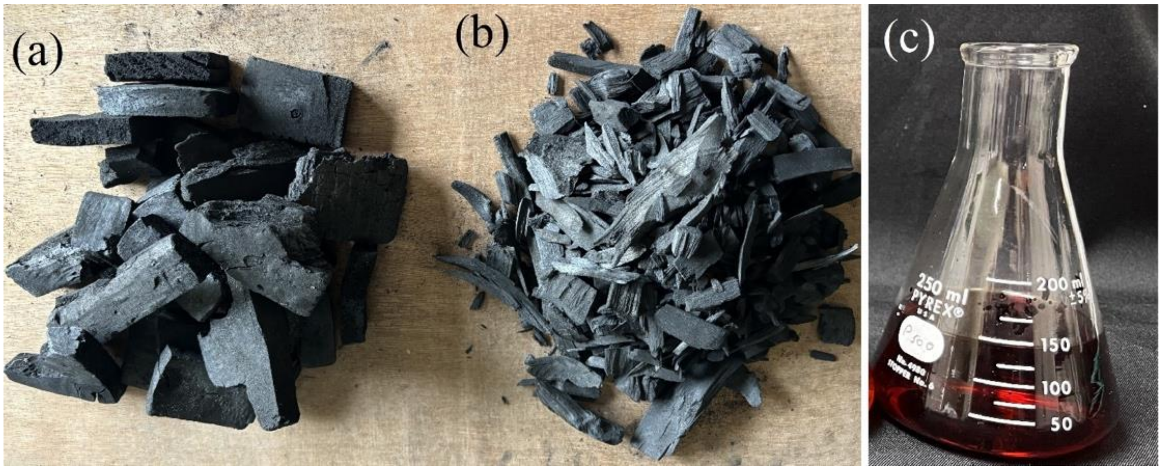

Fig. 5. Visual aspects of charcoal (a-b) and wood vinegar (b) produced with two types of wood residues of *Gmelina arborea*

The results of the analysis of the physical properties of wood vinegar (WV) and bio-oil are described in Table 4. Bio-oil was more viscous, with higher density and pH, stronger smell and darker color than vinegar. WV presented higher transparency and less suspended solids as insoluble particles. The comparison of these liquid products with other tropical wood species, *G. arborea* WV presented a low pH (2.9), but still within the range of 2.9 to 3.5, and higher density (1.02 g/mL) than the reported range of 1.005 to 1.016 g/mL (Theapparat *et al*. 2018).

Table 4. Physical Characteristics of Vinegar and Bio/Oil Produced with Two Types of Wood Residues of *Gmelina arborea*

Properties	Vinegar		Bio-oil	
	End-board	Chips	End-board	Chips
Color	Yellowish-brown	Yellowish-brown	Black	Black
Odor	Vinegar	Vinegar	Smoke	Smoke
Insoluble particles (%)	0.16 w/w%	0.15 w/w%	13.5 w/w%	13.4 w/w%
Density (g/mL)	1.02	1.01	1.10	1.02
Electric conductivity (mS/cm)	2.3	2.2	-	-
pH	2.9	2.9	3.1	3.0

The other physical and energy characteristics are presented in Table 5. Many statistical differences were observed in charcoal characteristics of two type of residues, but no significant difference was observed in physical characteristics of vinegar and bio-oil (Table 4). Charcoal produced with wood chips presented the highest values in gross caloric values, carbon content, and pH, but this carbon presented the lowest values in apparent density, volatile matter and oxygen content.

Table 5. Physical, Chemical and Energy Characteristics Produced with Two Type of Wood Residues of *Gmelina arborea*

Type of characteristics	Parameters	End-board	Chips
Physical	Bulk density (g/cm^3)	0.23A	0.23A
	Apparent density (g/cm^3)	0.237A	0.107B
	Moisture content (%)	4.44A	4.13A
Energy	Gross caloric value (MJ/kg)	28.33A	31.36B
	Volatile matter (%)	39.36A	33.51B
	Ash (%)	3.23A	3.21A
Chemical	Carbon content (%)	79.69A	86.53B
	Hydrogen content (%)	2.97A	2.48A
	Oxygen content (%)	14.11A	7.78B
	pH	8.91A	10.03B

Note: Confidence limits α=0.05 and different letters between residues indicate statistical differences (p-value<0.05).

TGA analysis (Fig. 6a) of charcoal produced with two types of residues of *G. arborea* showed typical behavior: in the first type (Fig. 6a), a slight weight decrease was presented between 25 and 100 °C. Later, a stable weight loss occurred between 100 °C and 200 °C and then there was a phase of substantial weight loss, between 200 °C and 800 °C (Fig. 6b) where maximum charcoal decomposition occurred. The maximum peak was between 450 and 550 °C. There were decomposition differences between charcoal produced with two types of charcoal: charcoal from end-boards wood presented faster decomposition in relation to charcoal from chips (Fig. 6). This can be observed in slope of mass remanent and derived mass, charcoal from wood chips presented stable values of derived mass; however, for wood end-boards there was a higher value of derived mass (Fig. 7b).

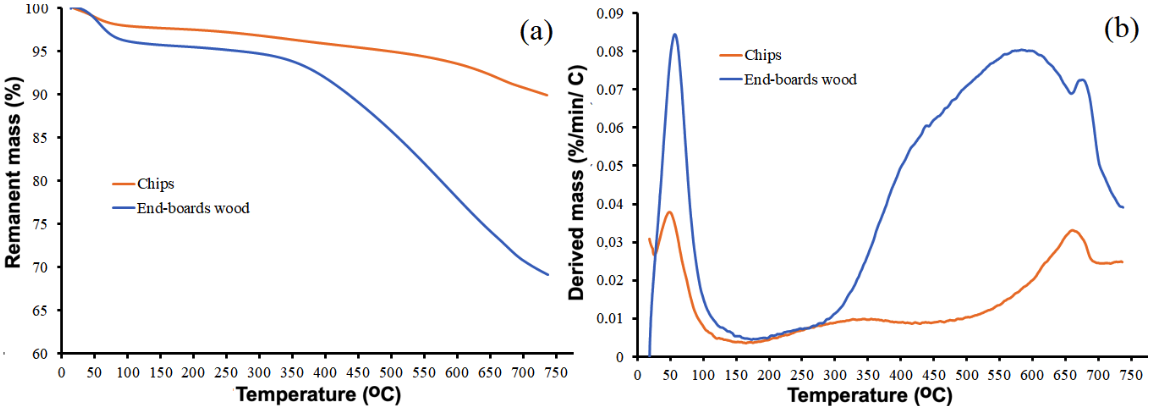

Fig. 6. TGA and DTG of charcoal produced with two types of wood residues of *Gmelina arborea* of *Gmelina arborea*

A slight weight decrease was observed between 25 and 100 °C in charcoal from two types of residues, which was attributed to water loss (Wang *et al.* 2016). A stable weight loss occurred between 100 and 200 °C, and this was ascribed to evaporation of the organics trapped on the surface of the samples (Moya *et al.* 2024). Maximum charcoal decomposition occurred between 200 and 800 °C (Fig. 2b), which was due to the decomposition of the side groups with low thermal stability and volatile matter emission due to oxidation of the carbonaceous materials, such as carboxyl, carbonyl, and aliphatic hydrocarbon groups (Balaguer-Benlliure *et al.* 2023). The maximum peak between 450 and 550 °C represented the splitting-off of the more resistant side groups and the formation of the aromatic rings. At the final stage of the TGA curve (Fig. 2), before ash, it represents the decomposition of the heat-resistant heteroaromatic structures and the formation of polyaromatic structures (Balaguer-Benlliure *et al.* 2023).

This can be observed in the slope of mass remanent and derived mass, charcoal from wood chips presented stable values of derived mass; however, for wood end-boards there was a higher value of derived mass (Fig. 7b). In the charcoal from wood end-boars, there was an inappropriate carbonization process, and the inflexion that occurred between 650 and 700 °C (Fig. 7b). These findings provide evidence of the presence of still unchanged wood components, hemicelluloses, celluloses, or lignin during pyrolysis (Várhegyi *et al*. 2002).

In general, charcoal properties were different for the two types of residues. The wood chips were smaller dimensions than wood end-boards (Fig. 1a-b) and according to the present results, smaller dimensions favored the productions of charcoal with the best energy properties. Charcoal from wood chips produced the best energy properties due to higher gross caloric value and carbon content (Table 5). In fact, TGA showed that wood end-boards presented an incomplete pyrolysis (Fig. 6b).

CONCLUSIONS

1. The transformation of *Gmelina arborea* wood residues into different products through the slow pyrolysis process offers the Costa Rican forestry stakeholders an opportunity to revalorize this material due to the charcoal and wood vinegar and charcoal characteristics are appropriated.

2. It was shown that a small-scale reactor prototype can be used to study the products yields and performance of the pyrolysis process form different wood residues,
3. This study suggests that wood chips and wood board-ends solid from *G. arborea* provide similar yields of charcoal, condensable gases, and non-condensable gases. Some differences in pyrolysis process were found, the use of wood board-ends is recommended to obtain higher yield of bio-oil and complete the process in less time, making it energetically more efficient. However, these differences were due to different in size and geometry of the source material
4. Charcoal characteristics were different; charcoal from wood chips was different than end-boards wood: higher gross caloric value and carbon content. TGA showed that wood end-boards evidenced the presence of still unchanged wood components, hemicelluloses, celluloses, or lignin during an incomplete process of pyrolysis.

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