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Mini-Rectangular Kiln to Produce Charcoal and Wood Vinegar

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Abstract

This research aimed to evaluate the production of charcoal and wood vinegar in a mini-rectangular kiln equipped with a condenser and vertical smoke burner. The kiln had a chimney, a condenser and a vertical smoke burner. The logs were 0.90 m long and had characterized. Ten carbonization runs were conducted to evaluate the kiln's performance, determining the gravimetric yields in charcoal, wood vinegar, and gases. The carbonization process took three days to conclude and four days to cool the charcoal. The results showed that the average yields for charcoal, wood vinegar, and gases were 34.0, 31.2, and 34.8%, respectively. The charcoal produced, despite the use of moderate-density wood, demonstrated favorable characteristics. The moisture content, ash content, volatile materials, and higher calorific values all fell within the ideal ranges. This, coupled with a good yield, confirms the technical viability of the system as an alternative for small producers.

Keywords: Carbonization process, Kiln performance, Charcoal quality.

1. INTRODUCTION AND OBJECTIVES

In the Brazilian metal sector, charcoal, besides providing heat, acts as a reductant agent of iron ore in blast furnaces, making the process highly efficient and clean since this carbon source is renewable. For such, the consumption of charcoal in Brazil exceeds 4.5 million metric tons per year (Indústria Brasileira de Árvores – IBÁ, 2022). To meet the annual charcoal demand, several kilns are used to produce charcoal, and the type of construction depends on some factors, such as the quantity of charcoal desired, the financial availability of the producer, and the necessary production capacity (Rodrigues et al., 2019).

Most of these kilns only produce charcoal, but using the proper technology, it is possible to recover liquid products from the residual smoke. After settling, the liquid products yield wood vinegar and vegetable tar. The remaining gases can also be burned if the system is coupled to a smoke burner (Cardoso et al., 2010). This way, the traditional pollution released during the carbonization process can be abated entirely, contributing to a cleaner and more sustainable environment. The mini-rectangular kiln, with its ability to recover liquid products and reduce pollution, offers a significant step towards a more sustainable future.

The use of carbonization systems that enable the recovery of liquid products efficiently adds value to the production chain because, in addition to charcoal, the charcoal maker will be able to obtain co-products that have applications in various industry sectors, such as automobiles, food, pharmaceutical and cosmetics (Almeida, 2012; Soares et al. 2021; Duan et al. 2021). In parallel, using a smoke burner, the system becomes sustainable with the thermal degradation of the pollution released during the thermal degradation of the wood (Cardoso et al., 2010).

In several small farms in Brazil, where most of the charcoal produced is for domestic use or sold to third-party suppliers, the wood carbonization process is still carried out in pits opened on the ground. These processes have low yields and are very polluting. In these primitive production processes, the gravimetric yield in charcoal is very poor, roughly 18 to 20% (based on the initial bone-dry weight of firewood), and significant amounts of pollutant smoke are released (Rodrigues et al., 2019). On the other hand, if rectangular kilns are employed, the charcoal yields can reach 30 – 34%, maximizing the potential of the firewood and resulting in higher incomes for the producer (Cardoso et al., 2010; Arruda et al. 2011).

In this sense, the concept of a mini-rectangular kiln deals with equipment directed to small and medium charcoal production, reaching a need of farmers currently lacking an adequate kiln that addresses their scale. Therefore, projects of kilns properly destined for this category of producers should be conducted to optimize charcoal-making in small farms in the same way the largest producers carry out the process. Yet, not only charcoal yields should be aimed but also wood vinegar and pollution abatement so the carbonization process reaches its maximum profitability, followed by environmental compliance. This means that by processing the same quantity of wood, the producer will obtain higher amounts of charcoal through an environmentally friendly system, reaching a higher total revenue if wood vinegar is also available to be marketed as a new alternative. Such a strategy fulfills the principles of the circular economy, which is highly desirable when the goal is to add value to sustainable production in small and medium-sized farms.

The present research aimed to assess the charcoal and wood vinegar yields produced in a mini-rectangular kiln model equipped with a liquids recovery system and a smoke burner. It also assessed the charcoal quality.

2. MATERIALS AND METHODS

The appraisal used a mini-rectangular kiln made of red ceramic bricks, clay soil, sand and water, a carbon steel condenser and a smoke burner made of the same material as the kilns depicted in Figure 1. The kiln measured 2.30 length x 1.50 width x 1.65 height and had a total capacity of 5.7 m^3 firewood stores. Albuquerque et al. (2023) thoroughly described and detailed the project and the kiln parts (Figure 1). Figure 2 displays the carbonization steps.

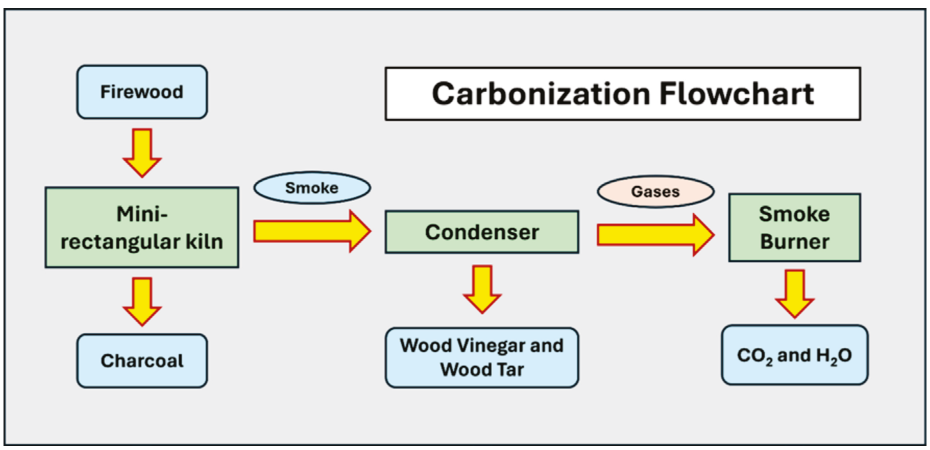

Figure 1. Carbonization flowchart.

Figure 2. Mini-rectangular kiln; (a) Door; (b) Condenser; (c) Smoke burner; (d) Chimney; and (e) Air-intake hole.

The firewood processed was collected from trees of an 8-year-old plantation with the GG 100 clone (a hybrid of *Eucalyptus urophylla* x *Eucalyptus grandis*) in Macaíba, Rio Grande do Norte, Brazil (5° 51' 36" South and 35° 20' 59" West). After harvesting, the trees were cut into 1.00 m logs, stacked, and left to dry in the open air for four months until they reached equilibrium moisture content. To characterize the wood used in the carbonization process, 12 randomly selected logs were removed, and three discs were removed from each, one from the central region and two 10 cm from each end, totaling 36 discs. The disks were divided into wedges and taken to determine the basic density and moisture content. Besides the physical properties, the diameter class and the stacking were also determined. The kilns method was employed to determine the moisture content (in % BS) according to the procedure described in NBR 7190 (ABNT, 1997). The basic density was determined by following the procedures described in the standard ASTM D2395-17 – Standard Test Methods for Density and Specific Gravity of Wood and Wood-Based Materials). Before loading the kiln, the firewood was weighed on a 500-kg scale for each carbonization run (Figure 3A).

Before loading the kiln, the firewood was weighed on a 500kg scale for each carbonization run (Figure 3A). The logs were placed upright inside the kiln until one layer was formed (Figure 3B and C). Then, to complete the loading, the firewood was placed horizontally until the kiln was filled. When the load was complete, the door was positioned and sealed with clay (Figure 3D). After loading the kiln, the carbonization run was started by igniting the firewood through a hole in the middle of one of the walls. Burning branches and small log pieces were used to conduct the ignition for three hours. After that time, the ignition hole was sealed with clay. When it detected the firewood was burning, the air entry was controlled through the air intake at the bottom of the wall (Figure 1E). To ensure the continuity of the process, small pieces of wood were burned inside the smoke burner until its internal walls were heated, and the exhaustion of the smoke was kept by convection. A total of 10 carbonization runs were accomplished to collect a representative dataset of yields in charcoal and wood vinegar.

During carbonization, cold water is circulated through the condensing apparatus, converting the condensable vapors into liquid, yielding wood vinegar and tar. The carbonization is followed by measuring the temperature of the smoke inside the chimney before the condensing system, and the process is considered finished when 200 °C is reached. In preliminary runs, it was established that this temperature corresponded to an internal temperature of 400 – 450 °C, an ideal range for finishing the process. From the ignition to the closing of the kiln to cooling, the total time is 72 hours. After this time, the chimney and the air-intake holes are sealed with clay to prevent any air entry, and the kiln is left to cool until the internal temperature is lower than 40 °C. The cooling process took 72 hours. When the cooling step was concluded, the kiln's door was opened, and the charcoal was unloaded, bagged, and weighed (Figure 4A, B, and C). The final amount of wood vinegar was collected, weighed, and stored for further analysis (Figure 4C). The gravimetric yields in charcoal, wood vinegar, and gases were calculated based on the initial weight of boned-dry firewood.

Samples were collected from each bag for immediate chemical analysis to characterize the charcoal quality, totaling 12 samples per carbonization run. The immediate chemical analysis of the charcoal (moisture content, fixed carbon, volatile matter, and ash contents) was obtained based on the procedures described in the standards D-1762 (ASTM, 1964) and NBR 8112 (ABNT, 1986). Still, the charcoal's bulk density was determined by following the standard NBR 6922 (ABNT, 2014). The higher heating value was obtained in a bomb calorimeter according to the procedures from the standards NBR 8633 (ABNT, 1983) and EN 14918 (DIN, 2010).

Figure 3. Sequence of the carbonization process: (a) Weighing the wood; (b) and (c) Filling the kiln; (d) Closing the door.

Figure 4. Products generated in the rectangular mini-kiln: (a) The moment of opening the oven door after the oven has cooled; (b) Coal produced and placed in raffia bags; (c) The collection of the pyroligneous extract directly at the condenser outlet.

3. RESULTS

Table 1 displays the different parameters found for the firewood. The average value found for the basic density indicates a clone with medium density. It is essential to highlight that the charcoal density is closely related to the wood density.

Table 1. Technical parameters of the eucalyptus clone GG100 wood.

Parameter	Mean	SD
Basic density (kg m^{-3})	513.5	42.4
Moisture content (%)	15.1	3.5
Diameter (cm)	16.1	3.5
Length (cm)	77.7	9.0
Stacking factor	0.6	0,1

According to Oliveira et al. (2010) and Carneiro et al. (2014), the higher the wood density, the higher the charcoal density. The same authors commented that when high-density woods are carbonized, the global efficiency of the carbonization increases because a higher mass of wood is loaded into the kilns. A consequently higher mass of charcoal is unloaded. The moisture content of 15% determined for the firewood is in the ideal range for carbonization in masonry kilns. The diameter of the firewood was in the 10 – 22 range, and the length varied from 62 to 94 cm. Concerning the stacking factor, a value of 0.6 was found, showing that the logs were straight, and when loaded into the kiln, a low volume of void spaces was formed.

Table 2 presents the gravimetric yields of the carbonization process. The charcoal yield of 33.9% is acceptable and in the range expected for rectangular kilns.

Table 2. Gravimetric yields found in the carbonizations conducted in the mini-rectangular kiln

Product	Gravimetric Yield (%)	Standard Deviation
Charcoal	34.0	3.7
Wood vinegar	31.2	4.4
Gases*	34,8	6.2

*The difference between the dry mass of the wood and the sum of the charcoal and pyroligneous extract yields estimated the non-condensable gases' content.

Table 3 shows the immediate chemical analysis of charcoal with fixed carbon, volatile matter, and ash contents. The values of the chemical components are within the range of charcoal quality acceptable for metallurgical purposes.

Table 3. Immediate chemical analysis of the charcoal produced in the mini-rectangular kiln

Parameter	Mean (%)	Desvio
Fixed carbon	73.0	1.8
Volatile matter	25.8	0.9
Ash	1.2	0.1

In Table 4, data on the performance of the charcoal are observed in terms of physical properties and the calorific value of the charcoal produced in the mini-rectangular kiln.

Table 4. Physical Properties and heat value of the charcoal produced in the mini-rectangular kiln

Parameter	Mean	Standard Deviation
Moisture content (%)	5.4	0.1
Bulk density (kg m-3)	124.9	13.1
Higher heating value (MJ kg^{-1})	29.63	102
Lower heating value (MJ kg^{-1})	28.27	97
Net heating value (MJ kg^{-1})	26.61	92

The calculated charcoal's average bulk density is below the value commonly used as a reference parameter for selecting forest species for charcoal production. This occurred most likely because wood with a moderate density was used, which led to the production of charcoal with a low density. The charcoal's calorific values range from 26.61 to 29.63 MJ kg^{-1}

4. DISCUSSION

According to Table 1, the mean basic density obtained for the GG100 wood is within the recommended range for carbonization. According to Oliveira (2012), the basic density must be higher than 500 kg m^{-3} to convert wood into charcoal satisfactorily. Several authors, including Vale et al. (2002) and Carneiro et al. (2014), observed that when using wood with lower densities, the result is low-density charcoal. This is undesirable since occupying kilns with a low mass of wood decreases the global productivity of the equipment.

For Leme (2016), wood with moisture content higher than 30% increases the carbonization time, reducing the yield. To start the carbonization process, the wood must be dried inside the kiln, consuming part of its initial mass to generate heat for wood drying. Furthermore, wood with high moisture content may result in the proliferation of fungi and insects. Besides that, wood with high moisture content implies increasing transport costs (Vale et al., 2011). According to Arruda et al. (2011) wood must contain moisture levels below 30%, as below this limit, there is a decrease in the time for the release of gases into the environment. Therefore, the mean moisture content value (15.1%), shown in Table 1, is within the acceptable range for adequate carbonization, with shorter times and higher yields.

The diameter and length of the wood (Table 1) used in carbonization directly influence the quality of the charcoal, as large diameters (above 20 cm) that are carbonized have a higher moisture content, which increases the carbonization time and consequently reduces the kiln's productivity. Furthermore, they tend to generate brittle charcoal, which is difficult to handle, increasing the carbonization time and forming semi-carbonized wood. For lower diameters (below 10 cm), there is a more significant amount of void spaces inside the kiln when it is baked, and this quantity is even higher when loading is mechanized, resulting in a lower quantity of wood being loaded, reducing productivity. Furthermore, loading activities are carried out manually since it is a smaller furnace. Therefore, adequate diameters are interesting to avoid fatigue and health problems among workers Donato et al. (2020).

At the same time, when working with low-diameter wood, difficulties arise in arranging the placed pieces, increasing the time required to organize them and, consequently, the cost of labor (Rodrigues et al., 2019; Donato et al., 2020). In this sense, the diameters used in this work are within the range of 10 to 20 cm, ideal for carbonization, according to Rodrigues et al. (2019). Donato et al. (2020) mentioned that using firewood in diameters within this range can result in gains of more than 15% in charcoal mass, a reduction in carbonization time of around 15% compared to wood with a higher diameter, in addition to cost savings in charcoal production around 2%.

Regarding the length of the logs, Rodrigues et al. (2019) mention that this dimensional factor depends on the size of the kiln. Thus, in traditional small and medium-sized kilns, wood logs usually are cut between 1 and 1.4 m in length. In this sense, it can be stated that the average diameter of 16.07 cm and an average length of 77.73 cm of the logs used in this experiment are within the ideal values for carbonization recommended in the literature, in addition to contributing positively to the filling activities of the kiln.

The mean gravimetric yield in charcoal found in this work was approximately one-third of the weight of the bone-dry firewood. The yields reached approximately 31% and 35% for WV and gases, respectively (Table 2). Concerning charcoal yield, the result follows what is indicated in the literature for rectangular kilns, with an average yield between 28% and 30%, according to Cardoso et al. (2010), who worked with a mini-rectangular kiln. Also, it is similar to the yields found by Arruda et al. (2011) for an industrial rectangular kiln. The yields found in this work are higher than those obtained by production systems traditionally used by small farmers, around 20% (Cardoso et al., 2010).

According to the determined yield values and taking into account that the system used can carry out up to 3.5 batches per month, where each one yields approximately 500 kg of charcoal and 500 L of pyroligneous extract, an estimate of the price for the sale of these products can be determined, according to the values practiced in the first half of 2024 in Rio Grande do Norte, where the 20 kg bag of charcoal is sold for approximately R$ 40.00 and the 20 L gallon of pyroligneous extract for approximately R$ 80.00.

It is important to highlight that using the liquid recovery system coupled to the kiln, around 30% of the wood's weight was captured as wood vinegar. In a traditional carbonization model, all the generated products would be wasted as pollutant smoke. This feat has the potential to add value to the coal production chain, obtaining a by-product that has been adopted for various purposes, and its demand in commerce is growing, such as insecticide, fungicide, bactericide, growth promoter of cultures (Theapparat et al. 2015; Araújo et al., 2018; Silva et al., 2022) preservative, source of chemicals and base for veterinary products (Soares et al., 2021; Medeiros & Gasparotto, 2022; and Feijó et al. 2022); influence on the development of plants such as orchids (Schnitzer et al. 2015); as a preservative agent for cosmetics and sanitizing products (Almeida, 2012) and as a substitute for chromium in anti-corrosion treatments on aluminum alloys. It is essential to highlight that these income values align with the average income values practiced in the market.

According to Carneiro et al. (2014), the charcoal bulk density used as a reference parameter for selecting forest species for charcoal production is approximately 200 kg m^{-3}. The low density of the wood can explain the lower charcoal density values obtained in this study (Carvalho, 2000). According to Santos et al. (2012) and Damásio et al. (2015), there is an average loss of 65% of mass during the carbonization of wood, resulting from the thermal degradation of its components. Consequently, this produces charcoal with a low density, as the mass of charcoal remaining per unit volume will be lower while maintaining the carbonization parameters.

The moisture content of the charcoal produced (Table 4) had an average value following that cited by Carneiro et al. (2014), which specifies a range of 1 to 6% as ideal for this parameter when charcoal for residential and industrial uses is considered. The average ash content observed for the charcoal is also within the range required to be considered a good quality product. According to Antal and Grønli (2003) and Oliveira et al. (2010), this parameter is best between 0.5 and 5%. This value is similar to the ash content of charcoals produced in industrial rectangular kilns, as determined in a study by Figueiró et al. (2019). The low value determined in this study indicates that the carbonization was carried out properly, with no contamination. For Vale et al. (2011), ash contents higher than 5% may indicate contamination of charcoal with soil residues, such as rock fragments, sand, and other elements. Other ash sources include minerals originating, in part, from chemical fertilizers such as calcium, potassium, phosphorus, magnesium, manganese, nitrogen, boron, zinc, copper, iron, and sodium, among others.

The average fixed carbon composition of 73% (Table 3) is within the desired percentage for industrial use, between 75 and 80% (Carneiro et al., 2014). Fuels with a high fixed carbon content burn slower, increasing productivity. Additionally, a higher percentage of fixed carbon per volume increases charcoal's mechanical resistance. The average composition of volatile matter was approximately 26%, within the ideal range of 15 to 30% volatile content to be considered for good use of charcoal (Leme, 2016). This way, the lower the volatile matter content, the better the quality of charcoal. The mean calorific value determined was 29.63 MJ kg^{-1}, 27.98 to 29.98 MJ $kg^{-1,}$ ideal for good quality charcoal (Oliveira et al., 2010). Heating value is directly related to the amount of carbon in the fuel, releasing large amounts of energy during its combustion, increasing, in the present case, the quality of charcoal for burning (Silva et al., 2014).

5. CONCLUSIONS

The quality parameters of the wood used and the production reached average values within the ideal ranges, except the fixed carbon content and bulk density, which reached values slightly below due to the use of wood with moderate density.

The charcoal yield (33.97%) is above the average yield currently practiced for kilns with the same characteristics. The other 66.03%, which according to traditional carbonization models would be completely wasted in nature (31.23% (approximately 534.23 liters), was recovered in the form of pyroligneous extract, and 34.80% was burned in its almost entirety (approximately 95%).

Given this, the prototype of the rectangular mini-kiln coupled to a condenser and smoke burner, presented a good yield, proving to be a technically viable and reliable alternative for small producers in the semiarid region. It adds productive and environmental value to the activity, with the recovery of the pyroligneous extract and the burning of non-condensable gases.

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Alexandre Santos Pimneta: conceptualization (equal), investigation (equal), methodology (equal), project administration (equal), supervision (equal), writing – original draft (equal), writing – review & editing (equal).

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