# Sustainable charcoal production from rubber tree branches (*Hevea brasiliensis*)

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**Abstract.** Dwindling firewood supplies for charcoal production necessitate exploration of alternative sources. Agricultural residues, particularly abundant rubber tree branches, present a promising solution. To evaluate their viability, a study employed a 200-liter charcoal retort kiln with wood gas circulation to carbonize rubber tree branches. The resultant charcoal underwent analysis for moisture content, fixed carbon, volatile matter, ash content, and higher heating value. The findings revealed a 6-hour carbonization process with a peak temperature of 600°C. The produced charcoal displayed favorable properties: 4.78±0.53% moisture content, 11.46±0.99% volatile matter, 6.03±0.22 ash content, 77.73±0.42% fixed carbon, and a higher heating value of 30.97±0.50 MJ/kg. Notably, rubber tree branch charcoal surpassed bamboo, coconut shell, and commercially available options in higher heating value, signifying its potential as a sustainable alternative. Furthermore, it complies with Thai Community Product Standards for wood charcoal used for cooking. These results underscore the promising potential of rubber branches as a sustainable charcoal feedstock, addressing the critical issue of firewood scarcity through waste repurposing.

## 1 Introduction

Historically, charcoal has been indispensable for human survival, serving as a critical heat source for cooking and heating. While contemporary alternatives like liquefied petroleum gas (LPG) and electricity have gained widespread adoption, charcoal remains a prevalent energy source, especially in disadvantaged communities. Its cost-effectiveness compared to LPG and electricity underscores its continued relevance as a primary energy resource [1]. This highlights the enduring importance of charcoal for a significant portion of the global population, despite advancements in alternative energy sources.

Charcoal, a derivative of wood, is produced through a process called carbonization. This process involves thermal decomposition at temperatures exceeding 300°C in an oxygen-depleted environment. Charcoal holds significant importance, particularly as a domestic fuel for heating and cooking. Its primary advantage lies in its superior higher heating value compared to firewood. For example, charcoal with a 5% moisture content boasts a higher heating value of 30 MJ/kg, whereas wood with a 15% moisture content only reaches 15 MJ/kg [1]. Furthermore, studies have shown that burning charcoal emits 87% fewer suspended particles than wood [2]. This suggests a potential decrease in respiratory health issues when transitioning from firewood to charcoal [3,4]. Beyond its fuel properties, charcoal offers additional benefits. Unlike firewood, it is resistant to decomposition by insects and microorganisms, ensuring longer storage life [5]. In agriculture, charcoal can improve soil quality, thereby promoting plant growth [6]. Additionally, its use in livestock farming has been linked to increased productivity and overall animal health [7]. Charcoal even finds applications in industrial settings, where it is used for air and wastewater treatment [8].

As forest depletion accelerates, securing firewood for charcoal production presents a growing challenge. This necessitates the exploration of alternative, sustainable raw materials. One promising option is bamboo, fast-growing and native to Thailand. Studies have demonstrated that bamboo charcoal offers quality comparable to traditional wood charcoal [9]. Research by S. Sangsuk et al. [10] reveals that bamboo charcoal boasts an impressive energy value of 30.35 MJ/kg with a notable moisture content of 8.50%. Furthermore, agricultural byproducts such as coconut shells present another potential source for charcoal. Research by K. Manatura [11] demonstrates that coconut shell charcoal delivers an energy value of 24.13 MJ/kg. Even corn cobs are being investigated for their biochar potential [5]. This shift towards alternative feedstocks, including bamboo and agricultural waste, holds significant promise for a more sustainable charcoal production industry.

The rubber tree (*Hevea brasiliensis*), primarily cultivated for natural rubber extraction, holds immense economic significance for Thailand. As of 2021,

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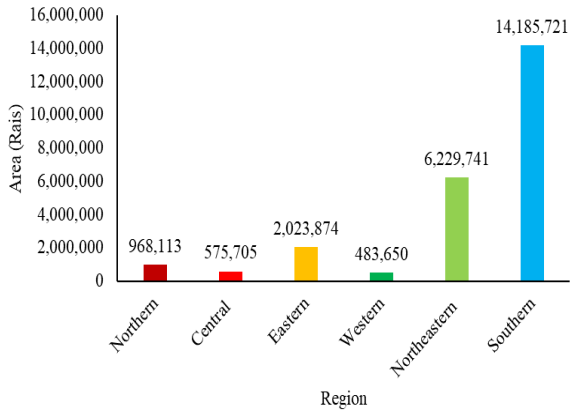


**Fig. 1**. Rubber plantation areas in each region of Thailand in 2021 [12].

Thailand boasts a rubber tree plantation expanse of approximately 24,466,804 rai, with a production output of 5.2 million tons, contributing 37.5% of global natural rubber production (Office of Agricultural Economics [12], Krungsri Research [13]). However, as these trees age (typically around 25-30 years), their latex yield diminishes. Consequently, farmers often resort to felling these trees, representing about 3-4% of the total plantation area (S. Prasertsan et al. [14]). This practice results in an annual by-product of approximately 6.92 million tons of smaller branches [15]. The common disposal method for these branches is incineration, (Jyrki Hytönen et al. [16]). However, repurposing waste rubber branches would be preferable. This study, therefore, aims to repurpose these rubber tree branches by transforming them into charcoal and subsequently assessing the resultant charcoal's quality.

## 2 Materials and methods

### 2.1 Sample preparation

Rubber tree branches (*Hevea brasiliensis*) with diameters of 2-5 cm and lengths of 30-70 cm were collected from eastern Thailand rubber plantations. These branches underwent a drying process under direct sunlight for 3-4 weeks, reducing their moisture content to below 30%. Subsequently, the dried branches were carbonized in a 200-liter charcoal retort kiln equipped with a wood gas circulation system. The temperature during carbonization was monitored using a K-type thermocouple (refer to Fig. 2 for the schematic diagram of the kiln). After carbonization, the resulting charcoal was pulverized to pass through a 250-µm (No. 60) sieve. The pulverized charcoal was then analyzed for various properties, including moisture content (ASTM D 3173), fixed carbon content (ASTM D 3172), volatile matter content (ASTM D 3175), ash content (ASTM D 3174), and higher heating value (ASTM D 5865). All measurements were conducted in triplicate.

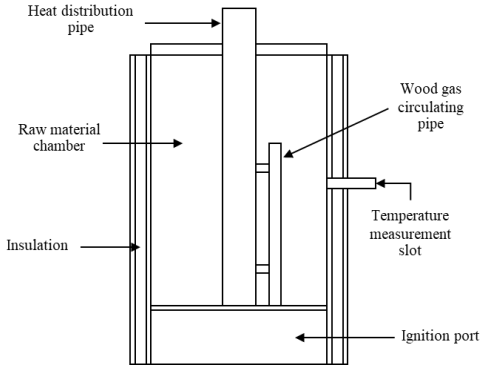


**Fig. 2.** Schematic diagram of 200-liter charcoal kiln equipped with a wood gas circulation system (charcoal retort kiln).

### 2.2 Moisture content

Crucibles, pre-dried in a Carbolite Gero Model PF200 oven at 105 °C for an hour, had their weights recorded post-cooling in a desiccator. A sieved sample weighing 1 gram was placed into these crucibles and further dried at 105 °C for an hour. Upon cooling, the residual weight was noted, and the moisture content was computed using Eq. (1).

$$\text{MC, \%} = \left(\frac{A-B}{A}\right)x100 \quad (1)$$

Where

MC = Moisture content (%)
A = Initial weight of charcoal sample (g)
B = Weight of charcoal post-oven drying (g)

### 2.3 Volatile matter

To determine the volatile matter content, 1 gram of the sieved sample was weighed into crucibles, sealed, and then heated in a Carbolite Gero Model AAF 11/18 muffle furnace at 950°C for 7 minutes. Post-heating, the crucibles were cooled in a desiccator, unsealed, and the residual weight was recorded. The weight loss was calculated using Eq. (2).

$$\text{WL, \%} = \left(\frac{C-D}{C}\right)x100 \quad (2)$$

Where

WL = Weight loss (%)
C = Initial weight of charcoal sample (g)
D = Weight of charcoal post-muffle furnace exposure (g)

The volatile matter was derived by subtracting the moisture content from the weight loss, as indicated in Eq. (3).

$$\text{VM, \%} = \text{WL, \%} - \text{MC, \%} \quad (3)$$

Where

VM = Volatile matter (%)
WL = Weight loss (%)
MC = Moisture content (%)

### 2.4 Ash content

Determine ash content by weighing the crucible and its lid, adding 1 gram of the sieved sample, and sealing the crucible with the cover. After placing the crucible in the Carbolite Gero Model AAF 11/18 muffle furnace, open the cover. Gradually heat to 500 °C over one hour, then increase the temperature to 750 °C over another hour. Maintain the temperature at 750 °C for two hours, then remove the crucibles from the muffle furnace, immediately seal, and cool them in a desiccator. Weigh the crucibles and use the weight to calculate ash content using Eq. (4).

$$\text{AC, \%} = \left(\frac{F-E}{G}\right)x100 \quad (4)$$

Where

AC = Ash content (%)
E = Weight of empty crucible and lid (g)
F = Weight of crucible, lid, and ash residue (g)
G = Initial weight of charcoal used for determine ash content (g)

### 2.5 Fixed carbon

Fixed carbon was deduced using the following Eq. (5).

$$\text{FC, \%} = 100 - (\text{MC, \%} + \text{VM, \%} + \text{AC, \%}) \quad (5)$$

### 2.6 Higher heating value (HHV)

The higher heating value of the charcoal was measured through the use of an oxygen bomb calorimeter (Parr Model 1341). To initiate the procedure, a gram of sieved charcoal powder was compacted into a pellet and placed within a combustion capsule. A 10-centimeter segment of Parr 45C10 nickel-chromium wire was affixed to a pair of electrode terminals, ensuring contact with the charcoal sample, and subsequently loaded into the bomb. This assembly was then placed atop a bomb head, anchored on a support stand. 1 ml of distilled water was introduced to the assembled bomb. Subsequently, the bomb head was sealed and oxygen gas was infused into the bomb, maintaining a pressure range of 25-35 atm (equivalent to approximately 30 bar). This assembly was then placed within a bucket that was placed within an insulating jacket, and ignition wires were connected to the bomb head. After the bucket was filled with 2000 ml of water, the insulating jacket was sealed. The system's stirrer was activated for duration of 10 minutes, facilitating equilibrium in water temperature. The temperature reader was then engaged, documenting temperature values at one-minute intervals for 5 minutes. Upon activating the ignition switch, temperature recordings were taken every 15 seconds until the peak temperature was observed. As temperature values began their descent, recordings were reverted to one-minute intervals for an additional 5 minutes. The cumulative data were used to compute the net corrected temperature rise, represented by Eq. (6).

$$t = t_c - t_a - r_1(b - a) - r_2(c - b) \quad (6)$$

Where

$t$ = The net corrected temperature rise (°C)
$t_a$ = Temperature at time of firing (°C)
$t_c$ = Temperature at time c (°C)
$a$ = Time of firing (minute)
$b$ = Time when the temperature reaches 60 percent of the total rise (minute)
$c$ = Time at highest temperature (minute)
$r_1$ = Rate at which the temperature was rising during the 5-min. period before firing (°C/minute)
$r_2$ = Rate at which the temperature was rising or falling during the 5-min period after time c (°C/minute)

The net corrected temperature rise was then utilized in the calculation of the higher heating value, depicted in Eq. (7).

$$H_g = \frac{(tW) - e1 - e2 - e3}{M} \quad (7)$$

Where

$H_g$ = The higher heating value (Cal/g)
$M$ = Sample mass (g)
$W$ = Calorimeter energy equivalent (Cal/°C)
$e1$ = Correction for the heat of formation of nitric acid in calories (Cal)
$e2$ = Correction for the heat of formation of sulfuric acid in calories (Cal)
$e3$ = Correction for the heat of combustion of fuse wire in calories (Cal)

The corrections e1, e2, and e3 can be computed using Eq. (8), Eq. (9), and Eq. (10), respectively.

$e1$ = Volume of standard alkali solution used in the acid titration (ml) (8)
$e2$ = 13.7 x percentage of sulfur in the sample x sample weight in grams (9)
$e3$ = 2.3 x centimeters of fuse wire consumed in firing (10)

The calorimeter's energy equivalent was discerned via its calibration against a known standard, benzoic acid, and can be represented by Eq. (11).

$$W = \frac{(Hm) + e1 + e3}{t} \quad (11)$$

Where

$H$ = Heat of combustion of the standard benzoic acid sample (Cal/g)
$m$ = Mass of the standard benzoic acid sample (g)

### 2.7 Charcoal comparison

Rubber tree branch charcoal will be compared to bamboo charcoal, coconut shell charcoal, and commercial charcoal. The compositional data for bamboo charcoal was sourced from a study by S. Sangsuk et al. [10], while the coconut shell charcoal data was derived from K. Manatura's research [11]. Commercial charcoal, procured from a local market and produced using an earth mound kiln with carbonization temperatures around 400°C [10], was analyzed using identical methods. For ease of comparison, the higher heating values were converted from calories per gram (Cal/g) to megajoules per kilogram (MJ/kg) using the conversion factor in Eq. (12).

$$CV = \frac{(Hg)(4.184)}{1000} \quad (12)$$

Where

CV = The higher heating value in megajoules per kilogram (MJ/kg)

$H_g$ = The higher heating value in calories per gram (Cal/g)

## 3 Results and discussion

During the later stages of their life cycle, typically between 25 and 30 years, rubber trees are commonly harvested for lumber. This practice generates an abundance of rubber tree branches. The present study seeks to repurpose these branches by transforming them into charcoal through carbonization in a 200-liter charcoal kiln equipped with a wood gas circulation system (charcoal retort kiln). The experiment revealed that converting rubber tree branches into charcoal takes 6 hours and reaches a maximum carbonization temperature of 600 °C. The resulting charcoal exhibits the properties shown in Table 1.

**Table 1.** Comparison of rubber tree branch charcoal properties to other charcoal types.

| Items | *Rubber tree branch charcoal** | *Bamboo charcoal [10] ** | *Coconut shell charcoal [11] ** | *Commercial charcoal** |
|---|---|---|---|---|
| Moisture content (%) | 4.78 (0.53) | 8.50 | 3.14 | 4.44 (0.34) |
| Volatile matters (%) | 11.46 (0.99) | 7.70 | 31.72 | 15.35 (0.58) |
| Ash (%) | 6.03 (0.22) | 11.30 | 3.40 | 5.80 (0.61) |
| Fixed carbon (%) | 77.73 (0.42) | 81.00 | 61.74 | 74.41 (0.31) |
| HHV (MJ/kg) | 30.97 (0.50) | 30.35 | 27.13 | 29.82 (0.47) |

* The values shown represent the mean of three replicates, with standard deviations provided in parentheses.
** These figures are derived from another study.

### 3.1 Moisture content

This analysis examines the moisture content of charcoal derived from various sources. As presented in Figure 3, rubber tree branch charcoal exhibits a moisture content of 4.78±0.53%. This value is comparable to commercially available charcoal (4.44±0.34%) and coconut shell charcoal (3.14%). Notably, bamboo charcoal has a significantly higher moisture content (8.50%). It is well-established that freshly produced charcoal typically possesses a moisture content below 1% [23]. However, exposure to ambient conditions can elevate this value to a range of 5-10%. This phenomenon is particularly pronounced in bamboo charcoal due to its inherently high surface area and porosity [24]. This unique characteristic translates to a significantly higher adsorption rate for atmospheric moisture, leading to its elevated moisture content compared to other charcoal types. Elevated moisture content can negatively impact the ignition process, requiring additional heat to evaporate the excess water. The Thai Community Product Standard for wood charcoal intended for cooking purposes specifies a maximum permissible moisture content of 10% [25]. Based on this standard and its low moisture content, charcoal derived from rubber tree branches emerges as a suitable fuel source for culinary applications.

### 3.2 Volatile matter

According to Fig. 4, the volatile matter content of the rubber tree branch charcoal was measured at 11.46±0.99%, which is lower than that of commercial charcoal (15.35±0.58%) and coconut shell charcoal (31.72%) but higher than that of bamboo charcoal (7.70%). The carbonization temperature and the type of raw materials used significantly influence the volatile matter content within charcoal. Both rubber tree branch charcoal and bamboo charcoal underwent carbonization at 600 °C, effectively removing volatile matter. In contrast, commercial and coconut shell charcoals underwent a 400 °C carbonization process, which resulted in lower volatile matter expulsion. Additionally, bamboo exhibits high porosity, allowing volatile matter to readily escape from the charcoal during carbonization. Consequently, bamboo charcoal has lower volatile matter content than rubber tree branch charcoal, even though they undergo the same carbonization temperature. Similarly, coconut shell charcoal retains a substantial amount of volatile matter following carbonization due to the intrinsic composition of coconut shells, which are dense and rich in volatile matter. This renders the expulsion of these compounds challenging during the carbonization process. Elevated levels of volatile matter in charcoal can lead to excessive smoke production during combustion, posing potential health risks if inhaled or consumed through grilled food. Therefore, charcoal with reduced volatile matter is preferable. The aforementioned Thai Standard [25] stipulates that volatile matter should not exceed 24%, indicating that the derived charcoal is suitable for cooking.

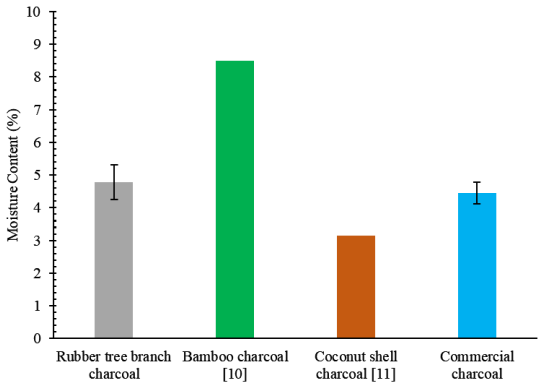


**Fig. 3.** The percent moisture content in rubber tree branch, bamboo, coconut shell, and commercial charcoal.

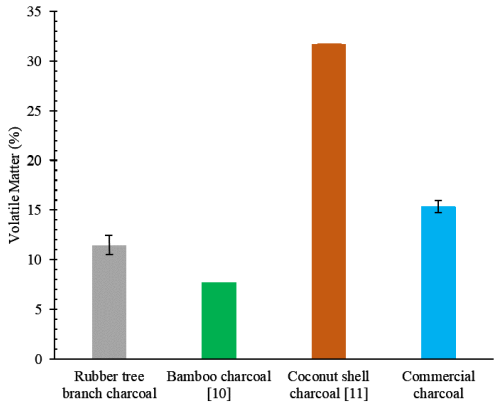


**Fig. 4.** The percent volatile matter in rubber tree branch, bamboo, coconut shell, and commercial charcoal.

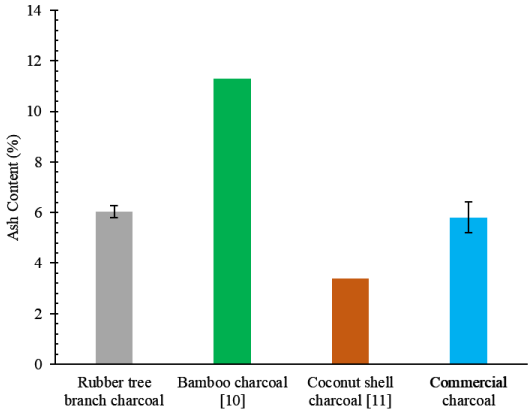


**Fig. 5.** The percent ash content in rubber tree branch, bamboo, coconut shell, and commercial charcoal.

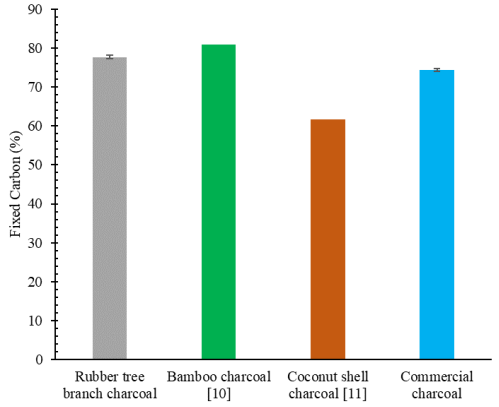


**Fig. 6.** The percent fixed carbon in rubber tree branch, bamboo, coconut shell, and commercial charcoal.

### 3.3 Fixed carbon

In terms of fixed carbon from Fig. 6, the 77.73±0.42% observed in rubber tree branch charcoal surpasses that of coconut shell charcoal (61.74%) and commercial charcoal (74.41±0.31%), but falls short of the 81.00% in bamboo charcoal. Fixed carbon is directly influenced by carbonization temperatures. Elevated carbonization temperatures enhance the fixed carbon within the charcoal [26]. Additionally, secondary tar reactions at 600 °C [27] further increase the fixed carbon quantity. European industrial charcoal standards demand a minimum fixed carbon content of 75% [28], although the Thai Standard does not specify a particular benchmark.

### 3.4 Ash content

In Fig. 5, the rubber tree branch charcoal exhibits an ash content of 6.03±0.22%. This value is slightly higher compared to coconut shell charcoal (3.40%) and commercial charcoal (5.80±0.61%). However, it remains lower than bamboo charcoal, which has a high ash content of 11.30%. The presence of silica within the cellular structure of bamboo contributes to this elevated ash content, resulting in greater combustion residues. As combustion-generated ash is considered waste and requires appropriate disposal methods, it can increase operational costs in certain facilities. Due to these factors, low ash content fuels are preferred by consumers. The Thai Standard [25] advocates for an ash content below 8%, rendering the charcoal derived from rubber tree branches a viable cooking fuel.

### 3.5 Higher heating value

Figure 7 shows that the higher heating value of rubber tree branch charcoal is determined to be 30.97±0.50 MJ/kg. This value is higher than that of both bamboo charcoal (30.35 MJ/kg) and commercial charcoal (29.82±0.47 MJ/kg). Among the charcoals compared, coconut shell charcoal had the lowest higher heating value at 24.13 MJ/kg. The higher heating value of charcoal is directly linked to its composition. Elevated moisture content tends to decrease the higher heating value, as it leads to heat losses during combustion. Additionally, higher volatile matter content also reduces the higher heating value, since the higher heating value of carbon is generally greater than that of volatile matter. Burning charcoal with a high volatile matter content generates less heat compared to burning the same amount of pure charcoal. The presence of ash also reduces the higher heating value and overall combustion efficiency. Conversely, a high fixed carbon content increases the higher heating value. Due to its low levels of moisture, volatile matter, and ash, rubber tree branch charcoal achieves a high higher heating value. Conversely, the higher volatile matter content in both coconut shell and commercial charcoals results in lower higher heating values. Although bamboo charcoal has a lower volatile matter content, its higher moisture and ash levels reduce its overall higher heating value, making it slightly inferior to rubber tree branch

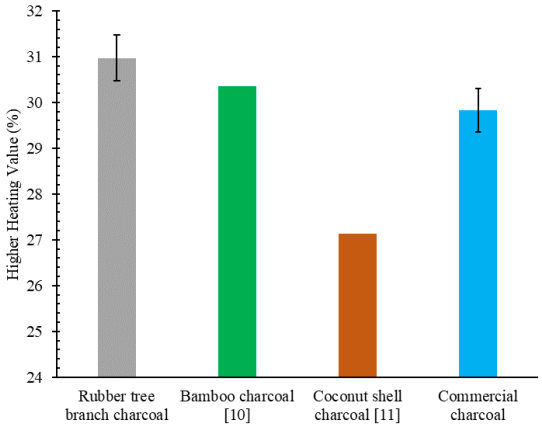


**Fig. 7.** The higher heating value of rubber tree branch, bamboo, coconut shell, and commercial charcoal.

charcoal. The Thai Standard [25] specifies that the higher heating value should exceed 6000 Cal/g or 25.10 MJ/kg, indicating that the derived charcoal is suitable for cooking applications.

## 4 Conclusions

Converting rubber tree branches into charcoal via carbonization in a 200-liter charcoal retort kiln with a wood gas circulation system takes approximately 6 hours and reaches a maximum temperature of 600°C. The produced charcoal exhibits properties such as 4.78±0.53% moisture content, 11.46±0.99% volatile matter, 6.03±0.22% ash content, 77.73±0.42% fixed carbon, and a higher heating value of 30.97±0.50 MJ/kg. Comparative analysis reveals distinct differences between charcoal derived from rubber tree branches and other sources like bamboo, coconut shell, and commercially available variants. Notably, rubber tree branch charcoal exhibits a higher volatile matter content than bamboo charcoal and higher moisture and ash content than coconut shell and commercial charcoals; however, its higher heating value is superior. Charcoal produced from rubber tree branches complies with the Thai Community Product Standard for wood charcoal intended for cooking. This demonstrates the potential of rubber branches as a charcoal feedstock, mitigating raw material shortages and promoting waste utilization.

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