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Biochar Production and Characterization from Pebble-Sized Feedstock Coconut Shells as an Alternative Solid Fuel

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ABSTRACT

This study aimed on the production and characterization of biochar derived from pebble-sized coconut shells, exploring its potential as an alternative fuel source. The pebble-sized material study is crucial for large-scale applications and real-world conditions. While smaller material sizes may offer efficiency in certain aspects, testing with pebble-sized offers a comprehensive understanding of how the pyrolysis process and biochar quality will perform in practical situations. Coconut shells, a widely available agricultural waste, were processed into pebble-sized feedstock and subjected to pyrolysis under controlled conditions. Practical and inexpensive thermal processes were performed at five various temperatures, starting at 250 °C to 450 °C to achieve the quality of expected produced biochar. A consistent temperature increase of 10 °C per minute and a holding period of 120 minutes was applied at each run. The resulting biochar was characterized using GC-MS techniques analysis to assess its physical and chemical properties. The findings demonstrate that biochar produced from pebble-sized coconut shells exhibits promising characteristics, including high carbon content, low moisture, and a stable structure, making it a viable candidate for use as a sustainable and eco-friendly solid fuel. The biochar produced has an average moisture content of 3.98%, ash content of 2.89%, volatile content of 18.56%, fixed carbon content of 78.53%, and a heating value of approximately 28.56 MJ/kg. It is concluded that biochar from pebble-sized coconut shell material can be an essential ingredient in briquettes, serving as an alternative solid fuel. This research contributes to the growing interest in converting agricultural residues into valuable energy resources, offering a potential solution for reducing dependence on conventional fossil fuels and ultimately contributing to mitigating pollution due to biomass waste.

Keywords: biomass, coconut shell, pebble size, pyrolysis, biochar, fixed carbon, heating value.

INTRODUCTION

The use of fossil-based fuels has significantly impacted the environment and society, primarily through greenhouse gas emissions that contribute to global warming and climate change (Armaroli and Balzani, 2011). As a result, global average temperatures are rising, leading to extreme weather events, rising sea levels, and various adverse ecological impacts (Gosh, 2020; Hansen et al., 2010). Burning fossil-based fuels also results in air pollution, which causes serious health problems, such as respiratory diseases, eye irritation, and cardiovascular disease (Kotcher et al. 2020). Delicate particulate matter and toxic chemicals like sulfur dioxide and nitrogen oxides pollute the air in urban and industrial areas (Jones, 1999).

The continuous exploitation and processing of fossil-based fuels will eventually lead to their depletion. Addressing the current situation requires bold and comprehensive action to transition to clean, renewable, and sustainable energy sources. One promising alternative to fossil fuels is wood-based biomass, especially coconut shell waste, due to its high heating value (Ahmad et al., 2022; Singh et al., 2024).

Coconut shell waste, when processed correctly, yields market-value products such as liquid smoke (Silaban et al., 2024; Sari et al., 2023). It serves as a renewable energy source, capable of producing thermal energy or heat through efficient and effective combustion (Hazman et al., 2023; Simanjuntak et al., 2021), with the heat produced being storable for further use (Simanjuntak et al., 2022). Additionally, coconut shell waste can be transformed into activated charcoal, a versatile material with numerous industrial applications, including water and air filtration (Cobb et al., 2012). Moreover, coconut shell waste can be developed as an alternative to fossil-based fuel in the form of biochar, which can be used as an ingredient in briquettes (Dalimunthe et al., 2021; Rudiyanto et al., 2023). This demonstrates the significant potential of coconut shell waste as a renewable energy source that can reduce dependence on fossil fuels and mitigate negative environmental impacts. With continued innovation and technological development, the use of coconut shell waste as an alternative fuel is expected to become more widespread and effective in supporting efforts to combat climate change and improve energy sustainability.

Although coconut shell waste is not as efficient or powerful as other renewable energy sources such as solar or wind energy, its use can help reduce dependence on fossil fuels and mitigate negative environmental impacts. Therefore, coconut shell waste should be considered a renewable energy source with the potential to reduce greenhouse gas emissions and improve energy sustainability (Azeta et al., 2021). Researchers are continually developing innovations to produce high-quality biochar using cost-effective and low-cost technology. The processing of coconut shells into biochar is highly dependent on the size of the material used (Suriapparao and Vinu, 2018; Zhang et al., 2017).

Various factors can influence biochar quality during pyrolysis, and feedstock size is one of them. The particle size of the feedstock material used in biochar production can impact the characteristics and performance of the resulting biochar because it significantly affects the heating rate during the process (Liu et al., 2017). The effect of biomass particle size on biochar quality has been widely studied. Figure 1 shows the original physical appearance of raw coconut shell waste as received and after being made into powder. Small particle sizes, ranging from millimeters (mm) to micrometers (μm), have been extensively studied due to their superior heat transmission capabilities. For example, with particle sizes ranging from 1.18 to 1.80 mm, an optimum yield of biochar was obtained, about 22–31 wt.% (Sundaram and Natarajan, 2009). Other researchers have used small feedstock sizes to produce 28.2% char products with a carbon content of 93.9% (Windeatt et al., 2014). Even particle sizes smaller than 250 μm have been studied concerning biochar quality and production (Castilla et al., 2020). With a particle size of < 0.50 mm, researchers obtained biochar with a heating value of 28.63 MJ/kg (Tsai et al., 2006). Additionally, Rout et al., (2016) found a biochar heating value of 23.68 MJ/kg at a particle size of < 1 mm.

Although coconut shell pyrolysis has advantages, such as producing renewable energy products and reducing organic waste, there are also disadvantages related to small particle sizes. Small-size or powdered coconut shells can produce low-quality biochar products. This can affect product biochar properties such as thermal stability, chemical composition, and purity. Moreover, controlling the pyrolysis process using coconut shell powder can become more difficult due to variability

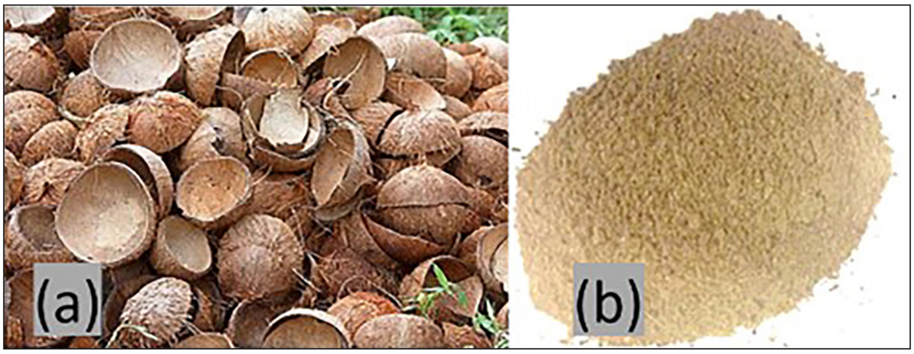

Figure 1. (a) As received coconut shell waste, (b) powdered coconut shell

in temperature, residence time, and raw material composition. Additionally, the production cost of pyrolysis products from powdered coconut shells may be higher compared to using larger sizes, driven by equipment costs, energy costs, and other operational expenses. Hasan et al. (2022) studied the pyrolysis of coconut shell feedstock material with the size of 1 to 7 cm² at a low temperature of 250 °C and found that a size of 5 cm² produces the best biochar based on its color. However, the quality of this biochar has not yet been analyzed. Interestingly, a simulation study concluded that the effect of size is not too significant at the same process temperature (Ahmad, 2020). Another conclusion is that at the same bulk temperature, the final char residue is not significantly affected by particle size (Sadhukan et al., 2009).

Studying with large material sizes has its importance, mainly depending on the final application of the biochar produced. Research with large material sizes can simulate real-world conditions on an industrial scale where raw materials are often used in their original form without much processing. This helps to understand how the pyrolysis process works at scale and whether the biochar results remain consistent. In some cases, using bulky materials can reduce initial processing costs such as cutting or grinding. Thus, pebble-sized studying can help assess the economic feasibility of biochar production without the need for additional investment in raw material processing.

Pebble-sized testing is important for evaluating the performance of pyrolysis machines or reactors designed to handle large quantities of raw materials. This can provide insight into how the reactor is performing under real load and whether any modifications need to be made to improve efficiency or yield. However, investigations with pebble-sized coconut shells have not been widely published and are rarely found. Thus, this work examines the quality of biochar obtained from the pyrolysis of coconut shells at larger sizes, averaging about 5 cm². Five different temperatures were tested to obtain the best-quality biochar with high carbon content. Large sizes of material are selected to reduce the operational and production costs of the pyrolysis process, making it a profitable venture for the industry.

MATERIALS AND METHOD

Material

The coconut shell utilized in this investigation was obtained from a local market near the research site. Figure 2 depicts the appearance of the materials following chopping and typical biochar manufacture in the farm field. The feedstock was cut into pieces diced to an average size of 5 cm² and pre-dried by exposing it to sunshine for several days. This step was necessary to minimize the moisture content and improve the effectiveness during the heating step. Table 1 shows the values of the elemental content and proximate analysis of the coconut shell, which in this study refers to the values obtained from previous researchers.

Method

The schematic of the pyrolysis system used is shown in Figure 3. A simple fixed-bed pyrolyzer heated by an LPG combustor was used in this work. This system can be found in (Silaban et al., 2024) which employed this system during liquid smoke production from coconut shells. Approximately 3 kg of the material was manually loaded into the stainless steel pyrolyzer for each run. Slow pyrolysis was conducted at temperatures ranging from 250 °C to 450 °C. The

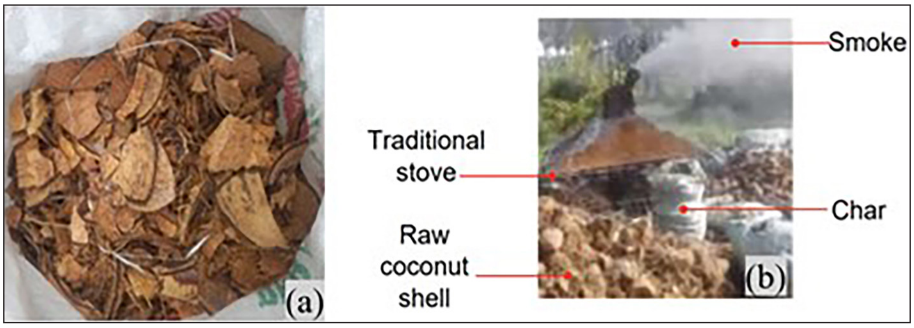

Figure 2. Biochar production: Pebble-size material sample used for biochar production (a), traditional biochar production (b)

Table 1. The elemental and proximate analysis of the material used

Elemental analysis	wt.%
C	58.83
H	6.37
N	0.54
O	33.44
S	0.18
Proximate analysis	wt.%
Moisture	10.68
Volatile	75.78
Fixed carbon	18.36
Ash	1.97

controlled pyrolysis parameters were a heating rate of 10 °C per minute and a hold time of 120 minutes. The temperature, the most significant parameter, was the main variable investigated in this work. The weight of the biochar was obtained by weighing it after every test run. For each test run, the average biochar yield from five pyrolysis runs was provided.

RESULTS AND DISCUSSION

Pyrolysis product

Figure 4 illustrates the physical appearance of biochar products produced from pebble-sized coconut shells. The solid byproducts of biochar synthesis found are distinctively black as discovered by (Kan and Strezov, 2016). The carbonization of biochar increased with increasing pyrolysis temperature, which ranged from 250 °C to 450 °C. Higher pyrolysis temperatures cause an overall exponential drop in biochar yield. This has also been stated by (Demirbas, 2004). Bio-oil generated from coconut shells often has high oxygen content, raised water content, decreased pH,

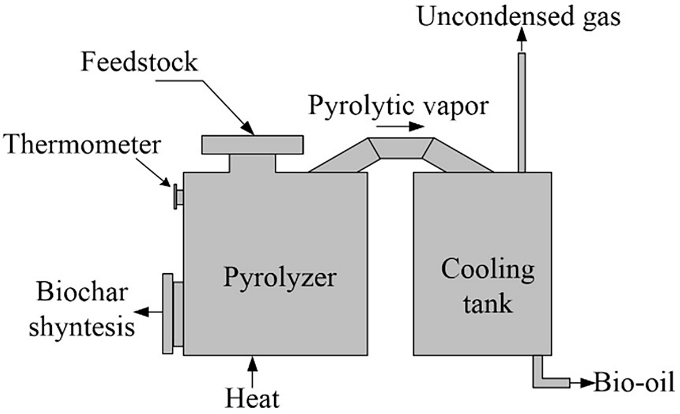

Figure 3. The diagram of the pyrolysis apparatus used in this investigation

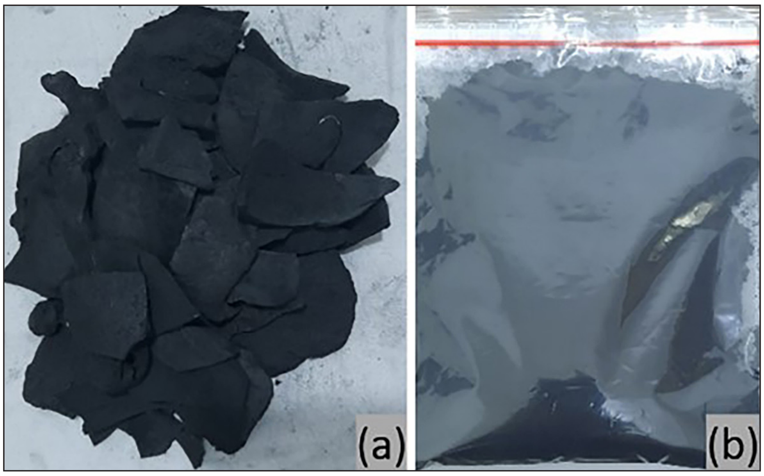

Figure 4. Biochar physical appearance; (a) raw product biochar, (b) sample for characterization test

and a medium heating value. Notably, the water concentration offers a considerable hurdle to efficiently using biochar as fuel.

Biochar production

The experiment's operational parameters to produce biochar included an average material size of 5 cm², about 10 °C/minute rate of heating, and a holding period of 120 minutes. Temperatures between 250 °C and 450 °C were used to find the best operating temperature for producing excellent biochar characteristics. A starting temperature of 250 °C was selected to indicate the initiation of the carbonization process as studied by Ahmad, 2020. In this study, it was found that optimal biochar characteristics based on fixed carbon content in the product were achieved at a temperature of 400 °C as shown in Table 2, consistent with previous research by (Demirbas (2024) and Sarkar and Wang (2020), indicating the nearing completion of carbonization. Hasan et al. (2022) recommended using a feedstock size of 5 cm² due to its ability to create biochar with an absolutely black color. Kan et al. (2016) reported similar results using 2 cm² average material sizes.

Figure 5 depicts the biochar yields at temperature ranges from 250 °C to 450 °C. It can be seen that the biochar yield decreases as the temperature rises. Biochar produced at 250 °C tends to be more than that produced at 450 °C. At a temperature of around 250 °C, pyrolysis occurs at an early stage where most of the volatile components have not yet been released from the raw material. At this temperature, organic matter undergoes dehydration and partial decomposition, producing more solid residues in the form of biochar. Due to the relatively low temperatures, only a small fraction of the organic matter is converted into gases and tar. Most of the raw materials remain in solid form, which produces larger quantities of biochar.

However, it is important to note that biochar produced at higher temperatures such as 450 °C typically has different physical and chemical properties, such as higher porosity and purer carbon content, which may be more desirable for certain applications. This phenomenon corresponds to the degradation of lignocellulosic materials, which is thought to occur more dramatically beyond 500 °C (Cheng and Li, 2018). Rafiq et al. (2016) found increased biochar yields at lower temperatures due to reduced loss of chemicals such as hydrogen (H_2), methane (CH_4), and carbon monoxide (CO), which results from less aliphatic component condensed.

Biochar characteristic

Table 2 presents the proximate analysis, absorption characteristics, and acidity levels of biochar synthesized at different pyrolysis temperatures. The average calorific value obtained is 28.58 MJ/kg. This calorific value surpasses values reported by researchers using average coconut shell sizes below 1 mm (Rou *et al.*, 2016) and is comparable to biochar produced from fast pyrolysis with particle sizes < 0.50 mm (Tsai *et al.*, 2006). Similarly, calorific values align with results obtained from particle sizes ranging from 3.35 to 10 mm (Windeatt *et al.*, 2014).

Table 3 shows the findings of proximate analyses performed by numerous researchers

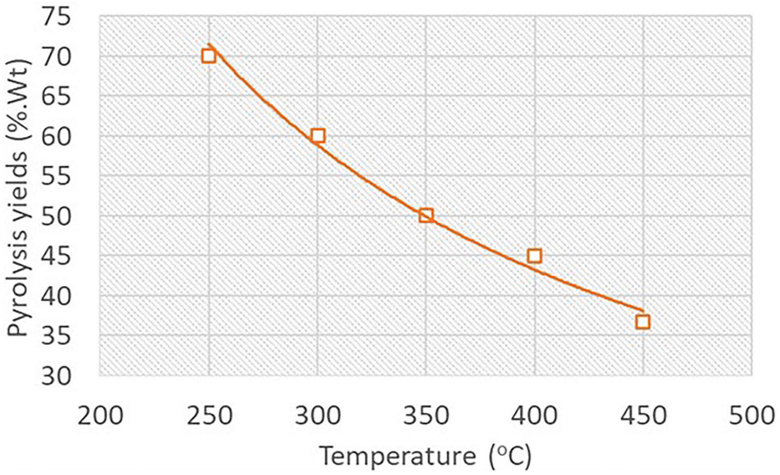

Figure 5. Biochar yield at different temperatures

Table 2. Characteristics of produced biochar at different temperatures

No	Parameter	Temperature (°C)				
		250	300	350	400	450
Proximate analysis (wt.%)						
1	Moisture	4.6	3.1	4.2	3.95	5.78
2	Ash (%)	3.4	2.5	3.4	2.56	2.96
3	Volatile (%)	16.9	20.6	20.4	17.0	19.7
4	Fixed carbon (%)	79.6	76.8	76.1	80.3	77.0
5	Heating value (MJ/kg)	30.3	29.1	31.4	30.2	21.7

Table 3. Proximate analysis (wt.%) of biochars from coconut shells at different sizes

No	Parameter	References				
		Windeatt et al. (2014)	Behera et al. (2020)	Rout et al. (2016)	Khawkomol et al. (2021)	[*]
1	Particle size (mm)	(1.4-2.8)	n.a.	(10 x 10)	n.a.	(50 × 50)
2	Moisture	7.1	4.40	2.7	2.96	3.9
3	Ash (%)	4.1	4.32	7.04	4.42	2.5
4	Volatile (%)	8.1	60.4	18.9	38.63	17.0
5	Fixed carbon (%)	91.9	38.8	71.3	53.99	80.3
6	Heating value (MJ/kg)	33.7	n.a	23.68	23.60	30.2

Note: *this study.

Table 4. GC–MS analysis of pyrolysis biochar derived from coconut shell pebbles at 400 °C

Peak no.	R. time (min)	Area %	Compound name
1	2.441	23.14	Toluene
2	3.890	5.64	Xylene
3	6.510	1.65	Benzaldehyde
4	7.100	2.43	Benzene
5	8.045	2.28	1-Hexanol
6	9.198	3.09	Undecane
7	9.335	1.53	Nonanal
8	10.489	10.59	Naphthalene
9	10.775	1.44	Octanoic acid
10	11.843	2.63	Tridecane
11	12.057	1.41	Naphthalene
12	12.807	3.18	4-Methyl
13	12.883	1.91	Tetradecane
14	13.020	1.54	Cyclododecanol
15	13.766	2.29	Cyclotetradecane
16	13.833	2.52	Pentadecane
17	14.510	1.89	Benzene
18	14.650	1.73	3-Eicosene
19	14.709	3.57	Hexadecane
20	15.535	2.37	Heptadecane
21	16.316	4.73	Nonadecane
22	17.062	3.88	Nonadecane
23	14.774	3.27	Decane
24	20.899	1.39	2-Iodoethyl
25	21.154	1.83	1,2-Benzenedicarboxylic acid
26	34.165	8.06	Dodecanoic

with different biomass or solid fuel materials and sizes. The examination covers the percentage of moisture, ash, volatile matter, carbon fixed, and caloric value. The moisture content values varied depending on the sample and the drying method used by each researcher. The percentage of ash reported by various studies also shows variation, which may be due to differences in the type of material and testing methods. The differing results between studies indicate variations in the chemical composition of the tested materials. Different fixed carbon values highlight variations in the type of material and its energy content. Differences in calorific value between studies can be attributed to variations in material types and measurement methods. Selecting the appropriate fuel for a specific application requires considering all these parameters to ensure efficient and effective fuel use. Knowing that each parameter in a proximate analysis may identify the quality and applicability of materials for a wide range of energy and industrial uses.

Table 4 displays the chemical components of charcoal constituents obtained at a pyrolysis temperature of 400 °C. The purpose of this analysis is to identify and measure the chemical composition of the resulting charcoal, which is essential for understanding its quality and potential usage as an alternate fuel or in various industrial uses. Compounds such as toluene and naphthalene, which are fuel elements, indicate that charcoal has the potential to be used as an energy source. The toluene compound has the largest percentage of area (23.14%), indicating that toluene is one of the main components in the charcoal produced. Naphthalene compounds were detected in two different peaks with significant total areas (10.59% and 1.41%), indicating that naphthalene is also an important component. Furthermore, aromatic chemicals such as xylene, benzaldehyde, and benzene are present in lesser but still considerable levels, demonstrating the existence of different aromatic compounds within the charcoal.

CONCLUSIONS

This study demonstrates that biochar produced from pebble-sized coconut shells is a promising alternative solid fuel, with high carbon content, low moisture, and a stable structure. The pyrolysis process, conducted under controlled conditions and varying temperatures, resulted in biochar with favorable properties, such as an average moisture content of 3.98%, ash content of 2.89%, volatile content of 18.56%, fixed carbon content of 78.53%, and a heating value of approximately 28.56 MJ/kg. These findings confirm that biochar from pebble-sized coconut shells is a viable and sustainable option for briquette production, potentially reducing reliance on conventional fossil fuels and mitigating pollution from biomass waste. The research underscores the importance of converting agricultural residues into valuable energy resources, contributing to environmental sustainability and energy efficiency. More studies are required to define biochar characteristics and improve manufacturing process parameters for higher grades. This study demonstrates that using larger material sizes may result in better biochar. Further studies could look into scaling up pyrolysis procedures above the scope of this investigation.

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