

Laboratory-Scale Production of Charcoal from Acacia Wood

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Article Information	ABSTRACT
Article History Received : September 27, 2025 Revised : October 04, 2025 Published : October 10, 2025	This study aims to analyze the production of charcoal from acacia wood (<i>Acacia</i> spp.) as a sustainable energy alternative, considering the depletion of fossil fuel reserves and the abundance of acacia biomass in Indonesia. The carbonization process was conducted through slow pyrolysis for 5 hours using a 12-kg gas cylinder reactor with used oil as fuel, and 1.8 kg of acacia wood pieces (5 cm in diameter, 5 cm in length) as raw material. The results showed a charcoal yield of 38.89% (0.7 kg), which is higher than the conventional range of 25–35%. Proximate analysis, based on estimates and supporting literature, indicated a moisture content of approximately 3%, volatile matter of 18%, ash content of 4%, and fixed carbon of 75%, meeting the SNI 01-1683-1989 standard for high-quality charcoal. Stable temperature distribution during the process ensured optimal decomposition of hemicellulose, cellulose, and lignin, producing charcoal with high calorific value and low emissions. These findings confirm the potential of acacia wood as an environmentally friendly charcoal feedstock, with recommendations for further optimization of temperature in the range of 400–600 °C to enhance production efficiency and reduce reliance on unsustainable forest resources.
Keywords: <i>Acacia wood charcoal;</i> <i>Slow pyrolysis;</i> <i>Yield;</i> <i>Proximate analysis;</i> <i>Sustainable energy.</i>	

INTRODUCTION

The demand for charcoal products, both globally and domestically, has shown a consistent upward trend in recent years. This increase is driven by the diversification of charcoal applications, which are no longer limited to traditional fuel use but have expanded to higher value-added products such as activated carbon, briquettes for shisha and barbecue, and boiler fuel for industrial sectors (Putri & Hidayat, 2023). Statistical data indicate that Indonesia's coconut charcoal export value in 2020 reached USD 151.88 million, marking a 4.68% increase compared to the previous year (Andri et al., 2024). Nevertheless, this figure has not surpassed the highest record achieved in 2018, which amounted to USD 155.60 million (Andri et al., 2024).

The rising global demand has created a substantial export market, particularly for charcoal briquettes from Indonesia, with major destinations including the Middle East and Europe (Ramayanti et al., 2024). Export demand is estimated to account for approximately 80% of total demand, significantly exceeding domestic consumption, which represents only around 20%. This vast market potential offers considerable foreign exchange prospects, with the export value of coconut shell charcoal briquettes projected to reach up to IDR 6.8 trillion annually for Indonesia (Ramayanti et al., 2024). Despite these promising opportunities and the higher selling price of briquette products compared to raw charcoal (up to IDR 18,590 per kg in export markets), ensuring

a stable and sustainable supply of raw materials remains a key challenge (Osman et al., 2023). This issue is not limited to the coconut shell briquette industry; other sectors, such as small and medium enterprises (SMEs) producing wood charcoal in Jepara, also face difficulties in meeting high export demand due to constraints in raw material availability and limited production capacity (Pebruary et al., 2018). Consequently, identifying alternative biomass sources that are abundant and efficiently manageable is crucial to bridging the gap between growing market demand and existing supply limitations.

Acacia wood, particularly *Acacia mangium* and *Acacia auriculiformis*, represents a highly promising candidate for alternative charcoal feedstock. These species are well known as fast-growing trees that have been widely utilized in forestry programs (Arnold et al., 2022). Studies have shown that the aboveground biomass of *A. mangium* in post-mining revegetation areas is substantial, averaging 61.49 tons/ha (E. Irawan et al., 2020; Mastur et al., 2021). Most of this biomass is concentrated in the stem (52.60%) and branches (33.57%), with the remainder distributed in twigs and leaves (E. Irawan et al., 2020; Mastur et al., 2021). In addition, harvesting of acacia wood also generates large volumes of bark residues, approximately 10% of the stem volume, which can likewise be valorized (Hidayah et al., 2021).

The utilization of acacia biomass provides an integrated solution across ecological and economic dimensions. In certain ecosystems, particularly in post-mining reclamation lands, *Acacia mangium* is classified as an invasive species that competes with native vegetation for nutrients and water (E. Irawan et al., 2020; Mastur et al., 2021). However, biomass resulting from control or thinning of unwanted acacia stands can be processed into charcoal products with high commercial value (E. Irawan et al., 2020; Mastur et al., 2021). This approach transforms an environmental challenge into a valuable resource, reflecting the principles of a circular economy. By doing so, it enables more effective restoration of degraded lands while simultaneously creating a sustainable value chain from resources that would otherwise be considered waste.

This research is motivated by three fundamental issues. First, the depletion of global fossil energy reserves necessitates the exploration of more sustainable alternative energy sources, one of which is the development of solid biofuels such as briquettes. Second, there is a significant untapped potential from forest plantation biomass residues, particularly acacia wood, which has not been optimally utilized. Third, an integrated solution is required to create cleaner environmental conditions while simultaneously providing economic benefits.

Aligned with these problem statements, the objectives of this study are threefold. The first is to provide a practical guideline on the method of producing charcoal from acacia wood as a potential renewable energy alternative. The second is to analyze the advantages and characteristics of the resulting acacia charcoal, thereby determining its quality based on established parameters. The third is to explain the potential applications and business feasibility of acacia charcoal production, ensuring that the research contributes not only to academic knowledge but also to practical applications in supporting the development of alternative energy and the sustainable management of biomass residues.

RESEARCH METHODS

Description

This study was conducted at the Mechanical Engineering Laboratory, Cenderawasih University, with a focus on charcoal production using acacia wood as the primary feedstock. An experimental method was employed, in which the carbonization process was performed using used oil as the fuel source. The equipment used in the experiments (Figure 1) comprised a 1-L graduated cylinder; a $\frac{3}{4}$ -inch blower (220–240 V, 50/60 Hz, 370 W, 3000/3600 r/min, 2 A, 280 m³/h); a digital scale (maximum capacity 150 kg); a stove fueled by used oil; a reactor modified from a 12-kg gas cylinder; a 10-channel thermocouple data logger; and K-type thermocouple wires. The materials (Figure 2) consisted of acacia wood pieces approximately 5 cm in diameter and 5 cm in

length as the feedstock for charcoal production, together with 1–2 L of used oil as the combustion fuel. The step-by-step stages of the charcoal production process are illustrated in Figure 3.

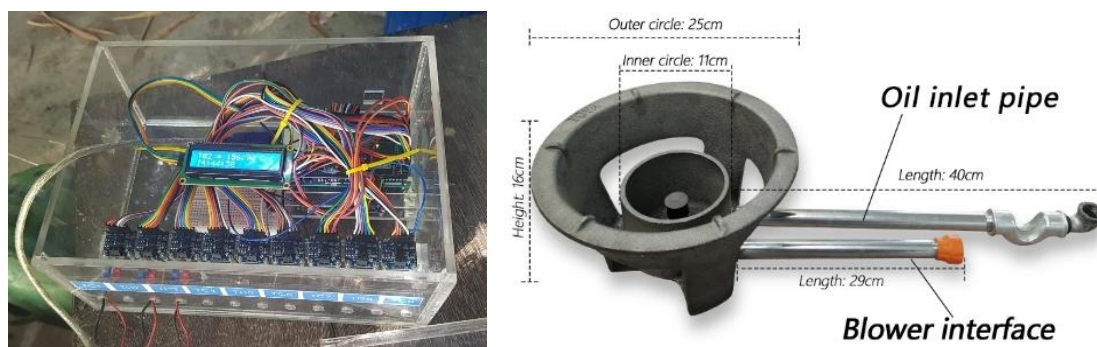


Figure 1. Datalogger temperature and oil stove

Charcoal process

The acacia wood samples were directly collected from trees growing in the vicinity of the Mechanical Engineering Laboratory, Universitas Cenderawasih. Selected wood logs with a diameter of approximately 5 cm were cut into 5 cm segments according to the reactor capacity. For each carbonization process, 22 pieces of acacia wood with a total mass of 1.8 kg were prepared. Used oil served as the combustion fuel, with a volume of 1.4 L consumed over a carbonization duration of approximately 5 hours (Figure 2).



Figure 2. Used oil and acacia wood pieces

The prepared acacia wood samples were carefully arranged inside the charcoal reactor. A specially designed stove fueled by used oil was employed, with the fuel flow regulated at a controlled rate to maintain stable flame intensity. Temperature measurement devices were installed by positioning K-type thermocouples at different points of the reactor, all connected to a data logger for continuous temperature recording. Once the setup was complete, the reactor containing the acacia wood samples was placed on the stove stand, and the carbonization process was initiated. The flame was maintained consistently throughout the 5-hour duration until the carbonization was completed.

Analysis

The proximate analysis of acacia wood charcoal was carried out to evaluate moisture content, volatile matter, ash content, and fixed carbon based on ASTM standards. Moisture content, determined according to ASTM D3173, represents the amount of water in the sample that influences storage stability, calorific value, and combustion efficiency, and is calculated as $\text{Moisture (\%)} = [(M_i - M_o) / M_i] \times 100\%$ (García-Quezada et al., 2023). Volatile matter, measured following ASTM D3175, refers to the fraction of hydrocarbons, oxygenated compounds, and nitrogen species released during thermal decomposition, with concentrations generally decreasing at higher carbonization temperatures (Mitchual et al., 2014). Ash content, analyzed using ASTM D3172, corresponds to the inorganic mineral fraction such as silica, alumina, and iron oxides remaining after combustion and is expressed as $\text{Ash (\%)} = (\text{mass of ash residue} / \text{original sample mass}) \times 100$. Fixed carbon, calculated by difference as $\text{FC (\%)} = 100 - [\text{moisture (\%)} + \text{volatile}]$

matter (%) + ash (%)], represents the non-volatile carbon fraction that provides the primary contribution to the thermal energy stability of charcoal. In line with the Indonesian National Standard SNI 01-1683-1989, high-quality charcoal is characterized by moisture content below 10% and fixed carbon above 75%, making proximate analysis essential not only for assessing product quality but also for informing the design of sustainable carbonization processes and supporting applications in energy, metallurgy, and filtration (C. Irawan et al., 2025).

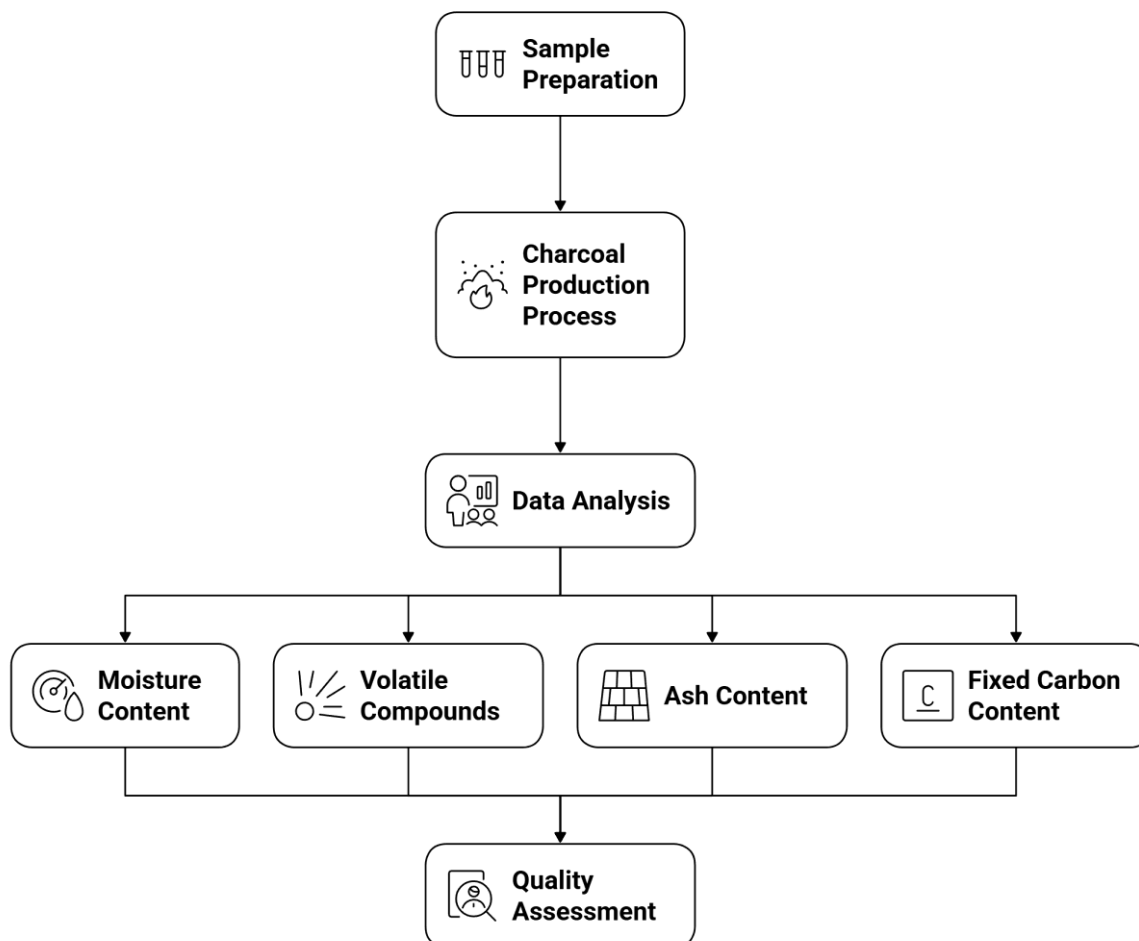


Figure 3. Flowchart process of acacia wood carbonization process

RESULTS AND DISCUSSION

The production process of charcoal from acacia wood logs with a diameter of 5 cm and an initial mass of 1.8 kg (22 pieces) yielded 0.7 kg of charcoal after a 5-hour pyrolysis treatment. Based on these measurements, the charcoal yield was calculated at 38.89%. This yield is considered highly favorable, as it exceeds the typical range of conventional charcoal production, which generally falls between 25% and 35%.

Charcoal Process and Temperature Distribution

The charcoal process, or pyrolysis, is the thermochemical decomposition of organic materials under conditions of lack of oxygen. The process that lasted for 5 hours indicated a slow pyrolysis method (Figure 4). This method is characterized by a low rate of heating, which allows the decomposition of biomass to occur gradually and thoroughly. According to Aboelela et al. (2023), slow pyrolysis in the temperature range of 400-600 °C significantly maximizes the production of charcoal (biochar) compared to liquid products (bio-oil) and gas.

The use of waste oil as fuel, while cost-effective, can pose challenges in maintaining a homogeneous temperature distribution within the reactor. Temperature fluctuations can lead to

uneven authoring, where some of the wood has become perfect charcoal while other parts are still in the decomposition stage (Zelinka et al., 2022). However, the duration of 5 hours provides enough time for heat to propagate and degrade complex compounds in wood such as cellulose, hemicellulose, and lignin more completely. This long time contributes to the high yield (38.89%) as more carbon is retained in solid form than evaporated as a volatile compound.

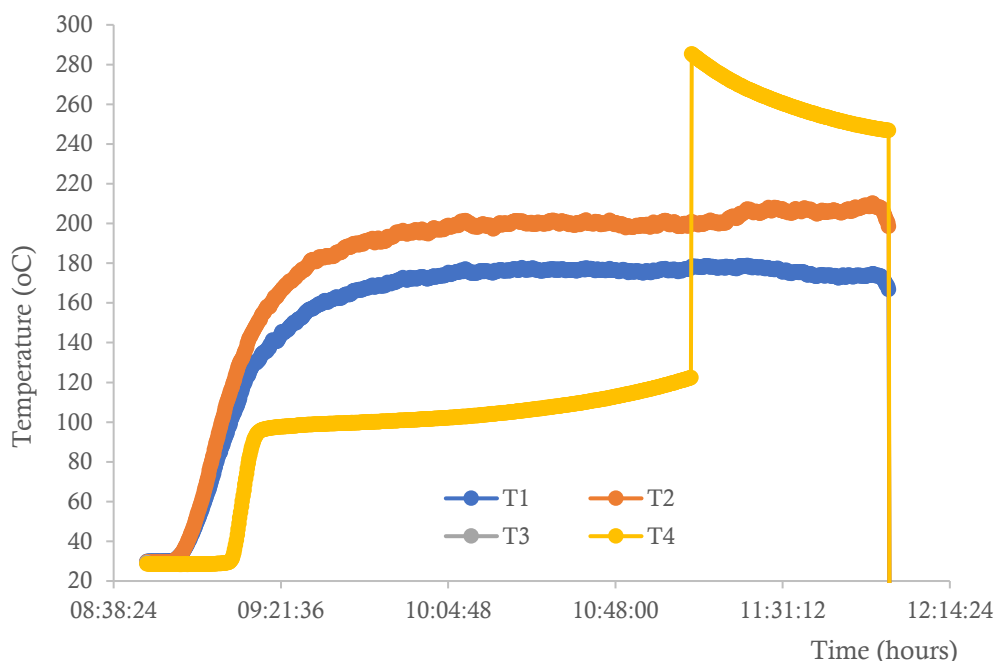


Figure 4. Temperature distribution in the carbonization reactor chamber

The temperature distribution in Figure 4 indicates that during the carbonization of acacia inside the reactor there is a rapid initial heating phase followed by a relatively stable plateau at the core sensors: T1–T3 stabilize at approximately 165–200 °C, whereas T4 remains lower (~90–120 °C) during the mid-stage, suggesting a radial temperature gradient within the reactor. Midway through the experiment T4 exhibits a sharp temperature spike to about 260–280 °C followed by a gradual decline, most likely associated with operational changes (fuel addition, blower adjustment, or shifts in airflow) rather than uniform heating; the abrupt drop at the end of the T4 trace appears to reflect a loss of sensor reading. This thermal inhomogeneity implies variability in charcoal quality—hotter zones tend to produce charcoal with greater devolatilization and higher fixed-carbon content, while cooler zones produce less-mature char—thereby affecting product consistency. To improve uniformity and reproducibility, it is recommended to enhance heat distribution through better thermal insulation or modification of the heating layout, regulate airflow/ventilation for more even heating, avoid direct flame contact with the material to prevent spot-heating, increase the number of temperature measurement points, and implement scheduled operating procedures (recording fuel additions and blower adjustments) so that thermal transients can be explicitly correlated with operational actions.

Moisture Content

Moisture content is the percentage of remaining water trapped in the pores of the charcoal after the pyrolysis process is completed, and is one of the important indicators of charcoal quality. High-quality charcoal generally has a moisture content below 8% according to the SNI 01-1683-1989 quality standard, because the low moisture content increases the calorific value and makes it easier to ignite (Hanum et al., 2024). Based on the research data, the initial mass of acacia wood of 1.8 kg produced a final charcoal mass of 0.7 kg with an as-received yield of 38.9%, which is in accordance with the range of charcoal recovery for the slow pyrolysis process (~32–38%) as reported in the small to medium-scale literature. To understand the effect of the initial moisture content, the yield was recalculated on a dry-basis by considering several moisture content (MC)

assumptions according to the literature references. If the initial wood MC is 10% (semi-dry), a dry mass of 1.62 kg and a dry-base yield of 43.21% is obtained; if MC is 20% (partially seasoned), a dry mass of 1.44 kg and a yield of 48.61% is obtained; while in the high MC of 50% (fresh/green wood), the dry mass is only 0.90 kg so that the dry-base yield appears very high at 77.78%. However, the yield value that is too high at MC 50% reflects the limitations of the mass-based approach, because in industrial practice productivity actually decreases at high water content due to energy absorbed to evaporate water (Canal et al., 2020). Thus, a dry-base yield of about 44–49% in woods with MC $\leq 20\%$ can be considered realistic for pyrolysis conditions at medium temperatures and medium heating times. A five-hour heating process at pyrolysis temperatures estimated above 400 °C proved effective in evaporating almost all free water and bound water from the wooden structure, resulting in charcoal with a very low moisture content. This condition shows that the carbonization process is complete, improving the quality of charcoal both in terms of calorific value and storage stability, while strengthening the relevance of acacia wood as a raw material for high-quality charcoal.

Volatile Matter

Volatile compounds (flying substances) refer to the remnants of tar, oil, and non-condensing gases that are still trapped in the charcoal after pyrolysis. High volatile levels are undesirable because they cause charcoal to produce a lot of smoke when burned, have a long flame, and have a lower calorific value. According to research by Moya et al. (2025), increasing the temperature and duration of pyrolysis effectively lowers the levels of volatile compounds. Recent studies related to slow pyrolysis of 500–700 °C report charcoal VMs at about ~10–25 wt.% (lower at temperatures >700 °C → 5–10%). Solar et al. (2018) reported VMs of ~24.8% (PR500), 10.5% (PR700), 5.4% (PR900).

The 5-hour authoring process provides sufficient time for the volatile compounds to further decompose (the secondary cracking process) into light gases and solid carbon. This suggests that the acacia charcoal produced is likely to have low levels of volatile compounds. Low volatile levels will result in charcoal burning clean (little smoke), with a short blue flame, and a focus on the release of heat energy through coal combustion, which is ideal for applications such as cooking or barbecue (Pahnila et al., 2023). The process lasted for 5 hours with heating via waste oil (the average kiln temperature is likely to be around 400–600 °C, depending on design & supply) → select the conservative assumption of slow pyrolysis in the medium range, VM $\approx 18\%$ (as-received basis). (This number corresponds to the range of 10–25% for 400–600 °C conditions) (Solar et al., 2018). Volatile mass $\approx 0.70 \times 0.18 = 0.126$ kg (126 g) and Volatile % (from charcoal) = 18% w/w charcoal.

Ash Content

Ash content is an inorganic residue (mineral) that is non-flammable, such as calcium, potassium, and silica, that comes from the natural wood. The ash content is an intrinsic property of the raw material and cannot be removed by the pyrolysis process; Instead, the percentage becomes concentrated as organic mass is lost. For clean hardwood, ash is low (generally 1–5%), but may increase if there is dirt or bark. Acacia wood, particularly species such as *Acacia mangium*, is known to have relatively low ash content. Verick Purba et al. (2021) showed that charcoal from *Acacia mangium* has an ash content below 1.5%. Solar et al. (2018) reported ash ≈ 3 wt.% stable at various temperatures. Quality charcoal proximates (for fuel/industrialists) are usually low ash (<5%).

If the material is just acacia wood pieces (without soil contamination), use 4% ash $\approx$ (conservative estimate). The calculation (charcoal mass 0.70 kg), is Ash mass ≈ 0 , Wood when cut/stored there is a lot of soil/dust or bark high in minerals, ash can be much higher — ash analysis (ASTM D3174) is needed for exact value (Gustafsson et al., 2024).

Assuming the acacia wood used has similar characteristics, the charcoal produced will also have a low ash content. Ash does not contribute to energy production and can form an insulating layer that inhibits combustion. Therefore, a low ash content is an indicator of good charcoal quality, resulting in more efficient and clean combustion with little combustion residue.

Fixed Carbon

Fixed carbon content is a fraction of non-volatile pure carbon in charcoal that is a major contributor to energy value and combustion stability. This value is calculated using the equation: Fixed Carbon (%) = 100 – (% Moisture Content + % Volatile Content + % Ash Content). Based on the assumption of acacia wood charcoal, the moisture content (MC) is in the range of 3% as commonly found in dry charcoal after cooling (<5%) according to the literature (Solar et al., 2018), volatile substance (VM) content is around 18%, and ash content is 4%. Thus, the fixed carbon content is obtained at 75% (w/w charcoal, as-received basis). If it is assumed that the mass of charcoal is 0.70 kg, then the mass of fixed carbon contained is $0.70 \times 0.75 = 0.525$ kg (525 g). This value can be categorized as realistic for wood charcoal resulting from slow pyrolysis at medium temperatures (400–700 °C), where the decomposition process produces charcoal with a fairly high carbon composition. Solar et al. (2018) reported a fixed carbon content of 68.1% at 500 °C, increased to 83.6% at 700 °C, and reached 90.6% at 900 °C, so that the value of 75% obtained in this study is consistent with the charcoal character of medium pyrolysis results. Thus, higher levels of fixed carbon indicate a greater degree of charcoal "maturity", which is advantageous for industrial applications such as solid fuels as well as metallurgical uses, as it provides more stable thermal energy and lower ash residues.

CONCLUSION

The experimental results demonstrate that acacia charcoal produced by slow pyrolysis in a small kiln (5 h retention at moderate temperatures) yielded a mass efficiency of 38.89% (0.70/1.80, as-received), which is within the range reported for slow pyrolysis in the literature and indicates adequate laboratory-scale performance with room for optimization. Proximate analysis estimated the charcoal composition as ~3% moisture, ~18% volatile matter, ~4% ash, and ~75% fixed carbon—corresponding to approximately 525 g of fixed carbon from the 700 g charcoal mass—consistent with typical slow-pyrolysis biochar characteristics (high fixed carbon, low moisture/volatiles). The initial moisture content of feedstock strongly influenced yields: pre-dried wood (MC ≤ 20%) yielded 44–49% on a dry basis, whereas high-moisture feedstock (MC > 30%) reduced process energy efficiency and charcoal proportion due to increased heat consumed for evaporation. In addition to feedstock moisture, non-uniform temperature distribution, core-to-wall temperature differentials, and ventilation/airflow configuration were identified as key factors affecting product homogeneity and fixed-carbon reproducibility; improvements in heating rate control, thermal insulation, and kiln design are therefore likely to enhance product consistency. For future work, a systematic experimental matrix varying pyrolysis temperature (300–600 °C) and residence time (1–5 h) is recommended to identify optimal operating conditions that maximize biochar yield, minimize undesirable volatiles, and improve energy efficiency, thereby strengthening the potential application of acacia charcoal in energy and environmental uses.

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