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Characterization and Energy Cost Implications of Corn Cob Biochar Produced at Different Temperatures

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A B S T R A C T

Carbonization temperature is a main parameter in physicochemical properties and the production economics of biochar. This study evaluates the influence of temperatures between 200 and 600 °C on corn cob biochar (CCB) characteristics. We also identified the electricity-based production costs of this process using a 2-kW furnace. Biochar yield decreased significantly from 7.21% at 200 °C to 2.56% at 600 °C. A similar trend was also seen in volatile matter, which declined with increasing temperature. Meanwhile, the ash content increased from 9.67% to 29.92 % due to progressive mineral concentration. Noticibly, fixed carbon content increased and reached a maximum at 400 °C (45.82%) before decreasing at higher temperatures, indicating excessive thermal severity. Energy consumption rose from 2.60 to 3.93 kWh, substantially increasing production cost per unit mass from Rp 520.97 g^{-1} to Rp 4,445.00 g^{-1}. The results demonstrate a clear trade off between biochar quality enhancement and energy efficiency. Overall, CCB produced at 400 °C provides the most balanced condition, delivering high fixed carbon content with comparatively moderate energy consumption. By this means representing the most economically viable temperature for scalable CCB production.

Contribution to Sustainable Development Goals (SDGs):
SDG 7: Affordable and Clean Energy
SDG 12: Responsible Consumption and Production
SDG 13: Climate Action

1. INTRODUCTION

1.1. Research Background

The growing demand for sustainable materials and low-carbon energy alternatives has intensified global interest in converting agricultural residues into value-added products to improve resource efficiency and support sustainable agricultural systems. Among such residues, corn cobs represent an abundant lignocellulosic waste with minimal competing uses and high carbon content. Previous studies have shown that corn cobs are rich in cellulose, hemicellulose, lignin, polysaccharides, and elemental carbon, making them a promising feedstock for biochar biochar production [1]. In many rural regions, corn cobs remain unutilized and are often discarded or openly burned, creating an environmental burden and wasting their economic potential. On a small scale, conversion into biochar typically employs simple electric furnaces, making energy consumption a significant—yet often overlooked—constraint. Producers often choose high carbonization temperatures to achieve superior biochar quality, without considering the associated increase in energy costs.

Biochar is a carbon-rich solid material produced through the thermal decomposition of organic biomass under oxygen-limited conditions, typically at temperatures ranging from 300 to 800°C, although lower-temperature carbonization (below 300°C) is also

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recognized as a transitional process bridging torrefaction and full carbonization [2] [3]. Its physicochemical properties are strongly governed by carbonization temperature, which directly determines its suitability for applications ranging from soil amendment to energy storage. Because of its high stability, porous structure, and diverse surface functional groups, biochar has attracted growing attention for soil amendment, environmental remediation, carbon sequestration, wastewater treatment, and energy-related materials [4].

Recent studies confirm that carbonization temperature is the dominant factor shaping biochar physicochemical properties across biomass feedstocks, including corn residues. Higher temperatures accelerate devolatilization and carbonization, leading to substantial increases in fixed carbon alongside corresponding reductions in moisture, volatile matter, and overall biochar yield, as a result of intensified devolatilization and secondary cracking reactions [5]. Agricultural waste-derived biochars showed fixed carbon rising to 82.4% at elevated temperatures, while moisture and volatile fractions declined significantly [6].

Ash content also responds strongly to temperature. Evidence from multi-feedstock and corn-related studies shows that ash often increases at moderate-to-high temperatures due to mineral concentration during devolatilization [7]. For corn cob biochar specifically, ash values can climb as carbonization temperatures surpass 500°C, influencing both material reactivity and suitability for environmental applications. However, higher carbonization temperatures inevitably require greater energy input, especially in electrically heated systems, which can significantly increase production costs and reduce economic feasibility.

This issue is particularly relevant for small-scale or decentralized biochar production units commonly used in rural and developing regions. Although numerous studies have investigated the influence of carbonization temperature on the physicochemical properties and performance of biochar, most emphasize material characteristics and environmental functions, while energy consumption and unit production cost are often overlooked [8] [9]. Quantitative evaluations linking temperature-dependent biochar quality with electricity-based energy demand and cost per unit mass remain limited, especially for corn cob biochar produced using electric furnaces. While previous studies thoroughly describe how carbonization temperature shapes the physicochemical properties of biochar—including fixed carbon, volatile matter, ash, and moisture content across various biomass types—they rarely evaluate the associated electricity-based energy consumption and production costs, leaving an important gap in understanding how temperature-dependent quality improvements relate to real operational energy requirements.

1.2. Research Objective

This study aims to characterize the physicochemical properties (proximate composition and estimated higher heating value) of corn cob biochar produced at carbonization temperatures of 200–600°C, and to evaluate the associated electricity-based energy consumption and production cost at each temperature. The findings are expected to identify the most energy-cost-efficient carbonization temperature for corn cob biochar production, providing practical guidance for small-scale and decentralized biochar production systems.

2. MATERIALS AND METHODS

2.1. Materials and chemicals

The sample was collected from West Pasaman Regency, West Sumatra, Indonesia. Ultrapure water was employed as the solvent for this dilution process.

2.2. Corn cob collection and preparation

The collected samples were carefully cleaned to remove adhering soil particles, sand, and other extraneous materials. They were then cut into small pieces using scissors. Subsequently, the samples were oven-dried at 105 °C for 4 h until a constant weight was achieved, ensuring the complete removal of residual moisture remaining after shade drying.

The dried materials were subjected to carbonise at three different temperatures (200, 300, 400, 500 and 600 °C) for 1 h (Carbolite AAF1100). These temperatures were selected to find the influence of temperature on the yield of biochar with favorable physicochemical properties, such as structural stability, while remaining economically feasible for practical applications. After thermal treatment, the furnace was allowed to cool naturally to room temperature, and the resulting biochar was collected and stored in a desiccator.

The biochar sample was weighted and sieved to 297 µm. It was then stored in airtight containers prior to further analyses. All experiments were performed in triplicate to ensure reproducibility.

2.3. Fixed carbon analysis

Corn cob biochar fixed carbon was assessed for its contents by utilizing proximate analysis, following an ASTM procedure. The process was based on the principles outlined by ASTM D3172 [5].

Moisture content was determined by oven-drying the biochar samples at 105 ± 5 °C until constant weight. Volatile matter content was measured by heating a known mass of dried sample in a covered crucible at high temperature (typically around 900–950 °C) for a specified duration under limited oxygen conditions to remove volatile compounds. Ash content was obtained by combusting the sample in a muffle furnace at 700–750 °C until complete oxidation of organic matter was achieved, leaving inorganic mineral residue. Fixed carbon was calculated by difference according to the proximate analysis mass balance equation:

$$\text{Fixed Carbon (\%)} = 100 - (\text{Moisture (\%)} + \text{Volatile Matter (\%)} + \text{Ash (\%)})$$

2.4. Energy consumption

CCB was produced using a 2 kW electric furnace operated at temperatures ranging from 200 to 600 °C. Electrical energy consumption for each run was determined by multiplying the furnace power rating by the operating duration, following established approaches for quantifying electricity use in thermochemical conversion systems. Production cost was calculated by multiplying the measured energy consumption by the Indonesia electricity tariff (1444,7 (Rp/kWh)). The cost of production per gram of biochar was determined by dividing the total energy-derived production cost by the mass of biochar

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obtained, consistent with normalization approaches used in techno-economic biochar assessments [10].

3. RESULT AND DISCUSSION

3.1. *Temperature effect on yield*

Several studies have shown that, for a range of biomass precursors, the carbonisation temperature used during processing strongly affects the resulting biochar yield. Figure 1 shows the biochar yield from corn cob at 200 to 600 °C.

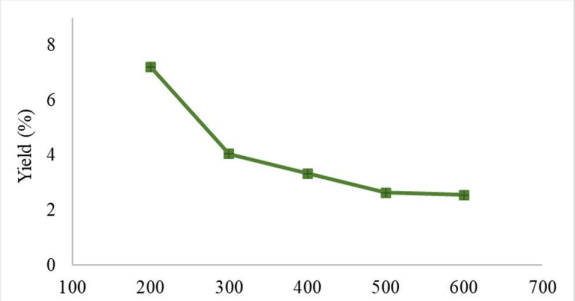


Figure 1. Yield of corn cob biochar (CCB)

The highest yield was obtained at 200 °C at 7.21 %, followed by a sharp decrease at 300 °C at 4.04%, and a more gradual reduction at higher temperatures, reaching around 2.5% at 600 °C. This trend was characteristic of lignocellulosic biomass undergoing thermal decomposition during carbonisation and has been widely reported in previous studies.

At relatively low temperatures, thermal treatment mainly induced dehydration and partial decomposition of hemicellulose, while much of the biomass solid matrix remains intact. As a result, a larger fraction of the original mass was retained as biochar, leading to higher yields [11][12] . The sharp yield reduction observed between 200 and 300 °C can be attributed to intensified devolatilization associated with the breakdown of hemicellulose and the initial depolymerization of cellulose, releasing significant amounts of volatile organic compounds and non-condensable gases such as CO and CO_2 [13].

With further increased in carbonization temperature (400–600 °C), cellulose undergoes more extensive breakdown. Lignin, being more thermally resistant, decomposes gradually across a broader temperature range. This stage was characterized primarily by secondary cracking and aromatization reactions, which lead to further mass loss and a gradual decline on yield [9]. Furthermore, a small change at 500 and 600 °C suggests that most thermally labile components have already been volatilized, leaving behind a condensed and carbon-rich char structure. A similar stabilization at higher temperatures had also been seen for biochars derived from agricultural residues, including corn cob and other crop wastes.

3.2. *Moisture and ash content of CCB*

Moisture and ash content are two crucial parameters in the characterization of biochar, as they directly influence its quality and potential applications. Figure 2 shows the ash and moisture content of CCB produced at temperatures ranging from 200 to 600 °C. Overall, it is clear that an inverse relationship is clearly observed: ash content increases steadily with increasing temperature, while moisture content decreases sharply from low to moderate and then stabilizes at higher temperatures.

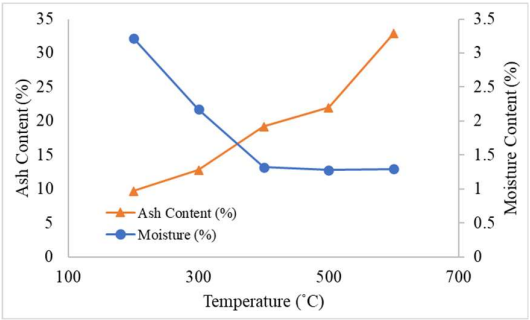


Figure 2. Moisture and ash content of CCB

The ash content rose linearly from 9.66 % at 200 °C to more than 30% at 600 °C. This increase is mainly due to the gradual loss of organic matter during carbonization, which leads to a relative concentration of inorganic minerals in the resulting char. As the carbonization temperature increases, more volatile substances from hemicellulose, cellulose, and some lignin are released, which lowers the overall mass of the carbon-based material. Because ash is the non-burnable mineral part left behind, its share becomes larger even though the actual amount of minerals stays about the same [14].

In contrast, the moisture content exhibited a pronounced decline with increasing carbonization temperature, decreasing from 3.2% at 200 °C to 1.3% at 400 °C, then which it remained relatively constant up to 600 °C. The reduction in moisture content is associated with the removal of physically adsorbed water and the elimination of oxygen-containing functional groups (e.g., hydroxyl and carboxyl groups) that contribute to hydrophilicity at lower temperatures [15]. The leveling off of moisture content after 400 °C suggests that most water-attracting (hydrophilic) groups have already broken down. Because of this, raising the temperature further has little extra effect on how much water the biochar can hold [16].

In practical terms, higher ash content can be both helpful and limiting, depending on how the biochar will be used. On one hand, more ash means more mineral nutrients and higher alkalinity. On the other hand, too much ash can dilute the carbon content and lower the biochar's ability to absorb organic pollutants [17]. Meanwhile, biochar produced at higher temperatures has low, stable moisture content, making it easier to store and cheaper to transport because it needs less drying before use. Because of these trade-offs, moderate temperatures (300–400 °C) may offer the best balance, keeping ash levels reasonable while still achieving low enough moisture content, making them a good choice both for performance and ceconomic

3.3. *Volatile matter*

The effect of different carbonization temperature on the volatile matter of CCB is illustrated at Figure 3. It can be clearly seen that a declining trend was observed as the carbonization temperature increased from 200 to 600 °C. It declined significantly from 50.2% at 200 °C to 29.6% at 600 °C. This reflects a typical pattern for lignocellulosic biomass, showing the gradual thermal breakdown of organic material during carbonization [15].

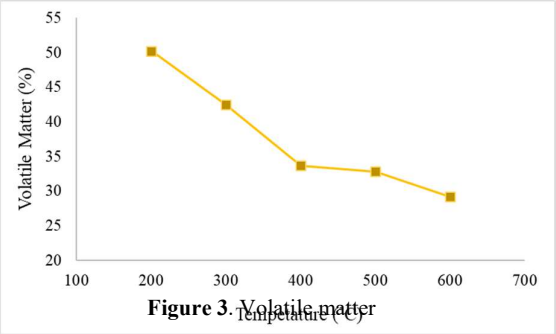


Figure 3. Volatile matter

This behavior lines up well with what has been reported elsewhere. Volatile matter, together with moisture content and fixed carbon, has been shown to be strongly influenced by temperature and holding time in biochar derived from various biomass precursors. Other work points to a similar explanation, noting that volatile matter tends to decrease as temperature increases because oxygen-containing functional groups such as -OH and -COOH — which have a major effect on biochar properties — are progressively lost during pyrolysis [15] [18]. In other words, as temperature rises, these functional groups break down faster, releasing more volatile compounds from the biomass and driving the overall decline in VM.

The VM trend at higher temperatures (400–600 °C) indicated that the biomass underwent substantial devolatilization, leaving behind a more thermally stable, carbon-rich residue. This behavious earlier research showing that biochar releases less CO_2 as temperature rises [19]. This is likely because it contains less volatile matter and dissolved organic carbon at higher temperatures. Higher temperatures also increase the biochar aromaticity and promote aromatic condensation, making the material more stable. Overall, the declining VM trend observed for CCB reflects the general devolatilization behavior widely reported for lignocellulosic biomass-derived biochars, confirming that higher carbonization temperatures favor the formation of a more stable, aromatic carbon structure at the expense of volatile organic content.

3.4. Fixed carbon

Fixed carbon (FC) is the solid carbon that remains in biochar after accounting for moisture, volatile matter, and ash. In simple terms, FC represents the proportion of pure stable carbon that does not easily volatilize. Figure 4 shows the variation of fixed carbon content in CCB as a function of carbonization temperature. Fixed carbon increased from 36.8 % at 200 °C to a peak at 45.82 % at 400 °C. Then it gradually decreased at higher temperatures, reaching 39.61%. This trend reflects a more complex relationship between carbon enrichment and further thermal degradation at higher temperatures.\

The initial increase in FC up to 400 °C can be explained by the progressive removal of moisture and volatile contain. The peak at 400 °C suggests that this temperature range effectively maximizes carbon retention in the solid phase for corn cob feedstock. This is resemble with previous studies, which report that the peak concentration of biochar is typically obtained at the lower range of carbonization temperature of 400 °C, attributed to the release of volatiles and aliphatic constituents that enhances the recalcitrant carbon [20].

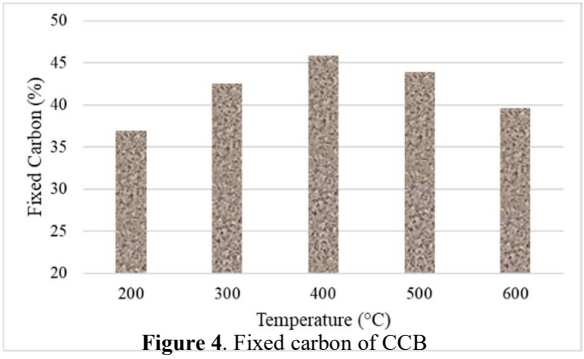


Figure 4. Fixed carbon of CCB

Then, there was a slightly declining in FC in the higher temperature may be explained by enhanced thermal cracking and secondary decomposition, which further volatilize carbonaceous fragments and reduce the relative fixed carbon fraction [14]. Additionally, higher ash proportions at higher temperatures dilute the carbon fraction, contributing to the observed decrease. From a practical standpoint, higher fixed carbon is a good thing, it means better carbon storage, more value, and a more stable structure. This makes biochar with high FC content more useful for both environmental and energy-related applications. However, temperatures above 400 °C may yield diminishing returns because of increased energy input and lower yield efficiency. Therefore, the 300–400 °C range appears to represent a practical balance between maximizing FC content and maintaining production efficiency.

3.5. Energy const to produce CCB

The decline in yield and FC with rising temperature was expected to affect both energy consumption and CCB production cost. Table 1 summarizes the electricity consumption, production cost, and unit cost of CCB produced at different temperatures using a 2 kW electric furnace. The results of the study showed a strong dependence between production costs and carbonization temperature, which was triggered by increasing energy requirements and decreasing biochar yield.

As temperature increased from 200 to 600 °C, electricity consumption rose steadily from 2.60 to 3.93 kWh, reflecting longer residence times and higher thermal energy requirements. This trend is expected, as higher temperatures require prolonged heating to achieve thermal stability and complete carbonization of lignocellulosic components [14]. Consequently, the total production cost increased linearly from Rp 3,756 at 200 °C to Rp 5,682 at 600 °C, reflecting the direct relationship between energy consumption and operating cost in electrically heated systems

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Table 1. The cost of CCB produced at different heating temperature

Cost Parameter: Electricity for 2 kW furnace	Temperatures (˚C)				
	200	300	400	500	600
Electrity cost (Rp/kWh)	1,444.70				
Time (Minutes)	78	88	98	108	118
Power (kWh)	2.60	2.93	3.27	3.60	3.93
Cost of production (Rp)	3,756.22	4,237.79	4,719.35	5,200.92	5,682.49
Biochar produced (g)	7.21	3.49	3.51	1.32	1.28
Cost of production (Rp/g)	520.97	1,214.27	1,344.55	3,944.87	4,445.00

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In contrast, the mass of biochar produced decreased sharply with increasing temperature, from 7.21 g at 200 °C to only 1.28 g at 600 °C. As a result, the unit production cost (Rp/g) increased dramatically with temperature, growing from 520.97 Rp/g at 200 °C to 4,445.00 Rp/g at 600 °C. The sharp increase in cost per gram highlights the economic trade-off inherent in high-temperature biochar production. Although higher temperatures are often associated with improved biochar properties—such as fixed carbon content, and long-term stability. The significantly lower yield and higher energy input substantially reduce cost efficiency [17]. Similar findings have been reported in techno-. economic assessments of biochar systems, where energy cost and char yield were identified as dominant factors controlling unit production cost [21].

From an economic point of view, the results suggest that moderate carbonisation temperatures at 400 °C are the more cost-effective choice for producing BBC at 1,344.55 Rp/g. At this temperature, there's a good balance between energy use, char yield, and overall performance, making it well-suited for uses like soil amendment or low-cost adsorbents. High-temperature biochars (≥500 °C) may be more stable, but the higher production cost only makes sense for high-value applications where those improved properties are really needed.

4. CONCLUSION

The different carbonisation temperatures have a substantial role in both the physicochemical properties and electricity-based production costs of CCB. Higher temperatures improve carbonization and lower volatile matter, but they also cause a significant drop in yield and push up production costs per unit mass. This highlights a clear trade-off between biochar quality and economic feasibility. Biochar produced at 400 °C offers the most balanced condition, delivering a high fixed carbon content of 45.82% with moderate energy consumption and a cost of 1,344.55 Rp/g. These findings provide practical insights for optimizing biochar production under energy and costconstrained conditions.

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