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# Thermochemical Characterization and Combustion Performance of *Crescentia cujete* Shell as a Renewable Biomass Feedstock for Sustainable Charcoal Production

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**Abstract**

The growing demand for sustainable and renewable energy sources has intensified the search for underutilized agricultural residues that can serve as alternative biomass feedstocks for charcoal production. *Crescentia cujete* (calabash) shell is an abundant lignocellulosic by-product whose thermochemical properties remain largely unexplored despite its potential for renewable energy applications. This study evaluated the suitability of calabash shell as a biomass feedstock for sustainable charcoal production through an integrated assessment of its moisture characteristics, thermal degradation behavior, carbonization performance, and combustion properties. Mature calabash shells were cleaned, sun-dried, carbonized under oxygen-limited conditions, and characterized using oven-drying moisture analysis, thermogravimetric analysis (TGA), and comparative water-boiling tests against coconut shell charcoal and commercial wood charcoal. The biomass exhibited a low moisture content of 6.71%, indicating favorable conditions for thermochemical conversion. Thermogravimetric analysis revealed the characteristic three-stage degradation behavior of lignocellulosic biomass, comprising moisture evaporation below 120 °C, rapid decomposition of hemicellulose and cellulose between 300 and 400 °C, and gradual lignin degradation up to 800 °C, resulting in a residual mass of approximately 21.5%. These findings demonstrate the thermal stability of calabash shell and its ability to produce substantial carbonaceous residue during pyrolysis. Combustion evaluation showed that calabash charcoal achieved the shortest ignition time (3 min) among the tested fuels and boiled 80 mL of water in 11 min 41 s, outperforming commercial wood charcoal but remaining less efficient than coconut shell charcoal. The combined thermal and combustion results demonstrate that *Crescentia cujete* shell is a promising renewable biomass resource for charcoal production and agricultural waste valorization. This study provides baseline thermochemical data for an underexplored biomass feedstock and supports its potential application in decentralized renewable energy systems. Further investigations involving calorific value determination, emission analysis, and process optimization are recommended to facilitate its large-scale utilization.

**Keywords:** *Crescentia cujete*; *biomass energy; thermogravimetric analysis; charcoal; pyrolysis; renewable energy; agricultural waste.*

## INTRODUCTION

The increasing global demand for sustainable energy resources, coupled with growing environmental concerns associated with fossil fuel consumption and deforestation, has intensified interest in renewable biomass as an alternative source of solid fuel. Biomass is widely recognized as one of the most abundant and renewable energy resources because it can be continuously replenished through agricultural and forestry activities while simultaneously reducing the accumulation of organic waste. Among the various biomass conversion technologies, charcoal production through thermochemical processes such as pyrolysis offers an effective approach for transforming agricultural residues into value-added renewable fuels with improved energy density, combustion efficiency, and storage stability (Basu, 2018; Bridgwater, 2012).

Agricultural biomass residues have attracted considerable research attention because of their availability, renewability, and potential to replace conventional wood-derived charcoal. Feedstocks such as coconut shell, rice husk, bamboo, palm kernel shell, and other lignocellulosic materials have demonstrated favorable physicochemical characteristics for biochar and charcoal production (Demirbas, 2004; Kumar et al., 2022; Tripathi et al., 2016). The utilization of these residues not only diversifies renewable energy resources but also contributes to sustainable waste management by converting agricultural by-products into valuable energy materials. Consequently, the exploration of underutilized biomass resources has become an important research priority within the broader framework of circular bioeconomy and sustainable resource utilization (Chen et al., 2022).

One agricultural residue that remains relatively underexplored is the shell of *Crescentia cujete L.,* commonly known as the calabash tree. This tropical species is widely distributed throughout the Philippines and many other tropical regions, where it is cultivated primarily for its large fruits that are traditionally used in handicrafts, household utensils, and ornamental applications. After utilization of the fruit pulp, the hard shell is commonly discarded as agricultural waste despite its rigid lignocellulosic structure, suggesting potential suitability for thermochemical conversion into renewable solid fuel. The disposal of calabash shells therefore represents an untapped opportunity for biomass waste valorization and renewable energy production.

The thermochemical conversion behavior of lignocellulosic biomass is governed largely by its moisture content, chemical composition, and thermal degradation characteristics. Moisture content directly influences ignition behavior, combustion efficiency, and energy consumption during carbonization because a substantial amount of heat is required to evaporate retained water before structural decomposition can occur (ASTM International, 2019). Likewise, thermogravimetric analysis (TGA) provides valuable information regarding biomass decomposition kinetics, thermal stability, and residual carbon formation, making it one of the most widely applied techniques for evaluating biomass feedstocks intended for pyrolysis and charcoal production (Chen et al., 2022; Yang et al., 2007). These physicochemical properties collectively determine the quality, yield, and combustion performance of the resulting charcoal.

Although extensive investigations have been conducted on numerous agricultural biomass resources, relatively little information is available regarding the thermal degradation behavior, moisture characteristics, and combustion performance of *Crescentia cujete* shell. Existing studies have focused primarily on the botanical, medicinal, and ethnobotanical significance of the species, while its potential as a renewable biomass feedstock remains largely unexplored. Furthermore, an integrated evaluation combining thermogravimetric analysis, moisture characterization, controlled carbonization, and comparative combustion testing has not been comprehensively reported for calabash shell. This lack of fundamental thermochemical data limits the scientific understanding required to assess its suitability for renewable energy applications and constrains its potential utilization as an alternative biomass resource.

Addressing this knowledge gap is particularly important because identifying new renewable biomass feedstocks contributes to reducing dependence on conventional wood-derived charcoal, promoting agricultural waste valorization, and supporting sustainable energy development. Establishing the thermochemical characteristics of calabash shell also provides baseline scientific information that may facilitate future optimization of carbonization processes and the development of biomass-based energy technologies suitable for decentralized and rural energy systems.

Accordingly, this study evaluated the suitability of *Crescentia cujete* shell as a renewable biomass feedstock for sustainable charcoal production through an integrated assessment of its moisture characteristics, thermogravimetric behavior, carbonization performance, and combustion properties. Specifically, the study determined the moisture content of pulverized calabash shell, characterized its thermal degradation behavior using thermogravimetric analysis, produced charcoal through controlled carbonization, and compared its combustion performance with that of coconut shell charcoal and commercial wood charcoal. By integrating physicochemical characterization with practical combustion evaluation, this investigation provides one of the first comprehensive assessments of the renewable energy potential of *Crescentia cujete* shell and establishes a scientific foundation for its future utilization in sustainable biomass energy systems.

## MATERIALS AND METHODS

### 2.1 Biomass Feedstock

Mature fruits of *Crescentia cujete* L. (calabash) were collected from naturally growing trees in Negros Oriental, Philippines. Only mature fruits exhibiting hard, fully developed shells were selected to ensure consistency in biomass composition and minimize variability associated with fruit maturity. The pulp was manually removed, and the shells were thoroughly washed with tap water followed by distilled water to eliminate adhering organic residues and surface contaminants. The cleaned shells were cut into smaller pieces to facilitate drying and subsequent carbonization.

The prepared biomass was sun-dried until a constant mass was attained, thereby reducing the initial moisture content and improving the efficiency of the carbonization process. Drying the biomass prior to pyrolysis minimizes energy consumption associated with moisture evaporation and enhances the production of high-quality charcoal by promoting more uniform thermal decomposition (Tripathi et al., 2016; Kumar et al., 2022).

**2.2 Biomass Preparation and Carbonization**

The dried calabash shells were converted into charcoal through slow pyrolysis using a laboratory-scale carbonization system operated under oxygen-limited conditions. Carbonization was performed by gradually heating the biomass until complete conversion into charcoal was achieved. The process was carefully monitored to minimize excessive oxygen exposure that could result in combustion rather than pyrolysis.

Following carbonization, the resulting charcoal was allowed to cool naturally to room temperature before being removed from the reactor. The produced charcoal was then stored in sealed polyethylene containers to prevent moisture absorption prior to laboratory characterization and combustion testing.

Pyrolysis under limited oxygen conditions promotes the thermal decomposition of cellulose, hemicellulose, and lignin while increasing fixed carbon content and improving fuel characteristics of lignocellulosic biomass (Chen et al., 2022; Yang et al., 2007).

**2.3 Moisture Content Determination**

The moisture content of the prepared calabash shell biomass was determined using the oven-drying method based on standard procedures for biomass characterization (ASTM E871-82, 2019). Approximately 5 g of representative biomass sample was weighed using an analytical balance before being dried in a laboratory oven at 105 ± 2 °C until a constant mass was achieved. The percentage moisture content was calculated using:

$$\boxed{MC(\%) = \frac{W_i - W_f}{W_i} \times 100} \tag{1}$$

*where*

- $MC$= moisture content (%)
- $W_i$= initial mass of the sample (g)
- $W_f$= oven-dried mass of the sample (g)

Moisture content is an important parameter influencing ignition characteristics, combustion efficiency, thermal degradation behavior, and charcoal yield during pyrolysis (ASTM International, 2019; Kumar et al., 2022).

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**2.4 Thermogravimetric Analysis**

Thermal degradation behavior of the calabash shell biomass was evaluated using a PerkinElmer TGA 4000 thermogravimetric analyzer. Approximately 10–20 mg of finely ground biomass was placed in a platinum sample pan and heated from ambient temperature to 800 °C at a constant heating rate under a controlled nitrogen atmosphere to prevent oxidative degradation.

Continuous mass-loss data were recorded throughout the heating process to determine the thermal decomposition profile of the biomass. The resulting thermogravimetric (TG) curve was analyzed to identify the major degradation stages corresponding to moisture evaporation, hemicellulose and cellulose decomposition, and gradual lignin degradation.

Thermogravimetric analysis is widely employed for evaluating the thermal stability and pyrolysis characteristics of lignocellulosic biomass because it provides valuable information regarding decomposition mechanisms and residual carbon formation (Chen et al., 2022; Wang et al., 2022).

In computing percentage mass loss, then include:

$$\boxed{\text{Mass Loss}(\%) = \frac{m_0 - m_t}{m_0} \times 100} \qquad (2)$$

where

- $m_0$= initial sample mass (mg)
- $m_t$= sample mass at temperature $t$(mg)

This equation is commonly used in thermogravimetric analysis.
On the other hand, residual mass can be calculated using this formula:

$$\boxed{\text{Residual Mass}(\%) = \frac{m_f}{m_0} \times 100} \qquad (3)$$

where

- $m_f$= final mass remaining after heating to 800 °C

**2.5 Combustion Performance Evaluation**

The combustion performance of the produced calabash charcoal was evaluated through a comparative water-boiling test using coconut shell charcoal and commercially available wood charcoal as reference fuels. Equal masses of charcoal were burned under identical experimental conditions using the same stove configuration.

Combustion performance was assessed based on ignition time and the time required to boil 80 mL of water. Ignition time was recorded from initial ignition until sustained combustion was achieved, while boiling time was measured until continuous boiling was observed.

The water-boiling test provides a practical assessment of biomass fuel performance by evaluating heat transfer efficiency under controlled laboratory conditions and is commonly employed for comparative evaluation of household solid fuels (Lehmann & Joseph, 2015).

**2.6 Data Analysis**

Thermogravimetric curves were interpreted to identify the principal stages of biomass degradation and residual mass formation. Moisture content results and combustion performance data were summarized using descriptive statistics. Comparative evaluation of ignition characteristics and boiling performance among calabash charcoal, coconut shell charcoal, and commercial wood charcoal was conducted to assess the suitability of calabash shell as an alternative renewable biomass fuel.

## RESULTS AND DISCUSSION

### 3.1 Thermogravimetric Analysis (TGA)

Thermogravimetric analysis (TGA) was conducted to characterize the thermal degradation behavior of *Crescentia cujete* (calabash) shell and to evaluate its suitability as a biomass feedstock for charcoal production. Thermal analysis provides valuable information regarding biomass stability, decomposition mechanisms, and carbonization behavior, all of which influence charcoal yield and combustion efficiency. Understanding these thermal characteristics is essential in assessing the feasibility of agricultural residues as renewable solid fuels.

The pulverized calabash shell had an initial sample mass of 12.878 mg, which gradually decreased as the programmed temperature increased from 40°C to 800°C at a constant heating rate of 20°C $min^{-1}$. At the conclusion of the heating program, the remaining mass was approximately 2.77 mg, corresponding to a residual mass of approximately 21.5% of the original sample. This relatively high residual fraction indicates the formation of a thermally stable carbonaceous material after pyrolysis, suggesting that calabash shell possesses favorable characteristics for charcoal production. These experimental values (See Table 1) further demonstrate that a substantial proportion of the biomass is converted into fixed carbon rather than being completely volatilized during thermal decomposition.

**Table 1. Thermogravimetric Analysis (TGA) Data of Calabash Shell**

| Time | Unsubtracted Weight | Program Temperature | Time | Unsubtracted Weight | Program Temperature |
|---|---|---|---|---|---|
| 0 | 12.64267 | 40 | 21 | 4.871933 | 400 |
| 1 | 12.60865 | 40 | 22 | 4.154451 | 420 |
| 2 | 12.58113 | 40 | 23 | 3.926486 | 440 |
| 3 | 12.55881 | 40 | 24 | 3.741644 | 460 |
| 4 | 12.54603 | 60 | 25 | 3.590823 | 480 |
| 5 | 12.50875 | 80 | 26 | 3.47294 | 500 |
| 6 | 12.42554 | 100 | 27 | 3.380411 | 520 |
| 7 | 12.31698 | 120 | 28 | 3.300883 | 540 |
| 8 | 12.2433 | 140 | 29 | 3.230673 | 560 |
| 9 | 12.21405 | 160 | 30 | 3.166965 | 580 |
| 10 | 12.19324 | 180 | 31 | 3.10889 | 600 |
| 11 | 12.16117 | 200 | 32 | 3.054499 | 620 |
| 12 | 12.11198 | 220 | 33 | 3.005742 | 640 |
| 13 | 11.99085 | 240 | 34 | 2.962836 | 660 |
| 14 | 11.73515 | 260 | 35 | 2.925565 | 680 |
| 15 | 11.46298 | 280 | 36 | 2.892193 | 700 |
| 16 | 11.12926 | 300 | 37 | 2.863806 | 720 |
| 17 | 10.4588 | 320 | 38 | 2.838019 | 740 |
| 18 | 9.482586 | 340 | 39 | 2.813966 | 760 |

| | | | | | |
|---|---|---|---|---|---|
| 19 | 8.272769 | 360 | 40 | 2.790563 | 780 |
| 20 | 6.635843 | 380 | 40.98333 | 2.76911 | 799.6667 |

The thermogravimetric profile (Figures 1-3) exhibited the characteristic three-stage degradation pattern commonly observed in lignocellulosic biomass.

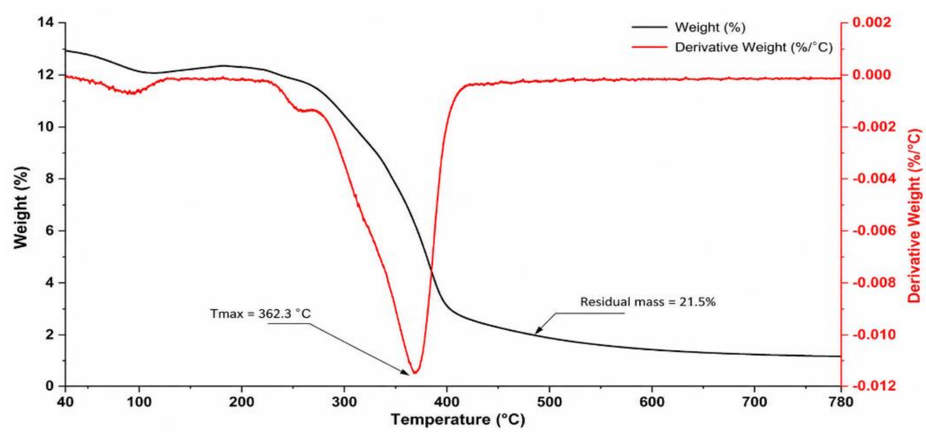


**Figure 1. Thermogravimetric Analysis (TGA) Curve of *Crescentia cujete* Shell in % weight**

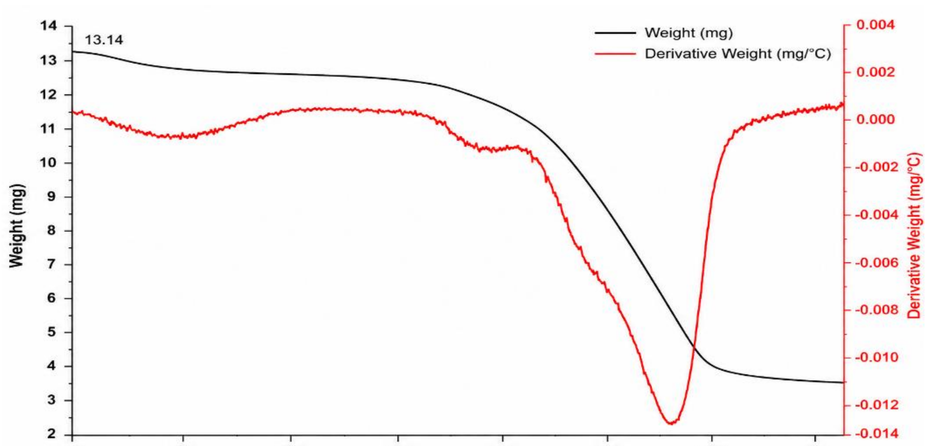


**Fig** **mg)**

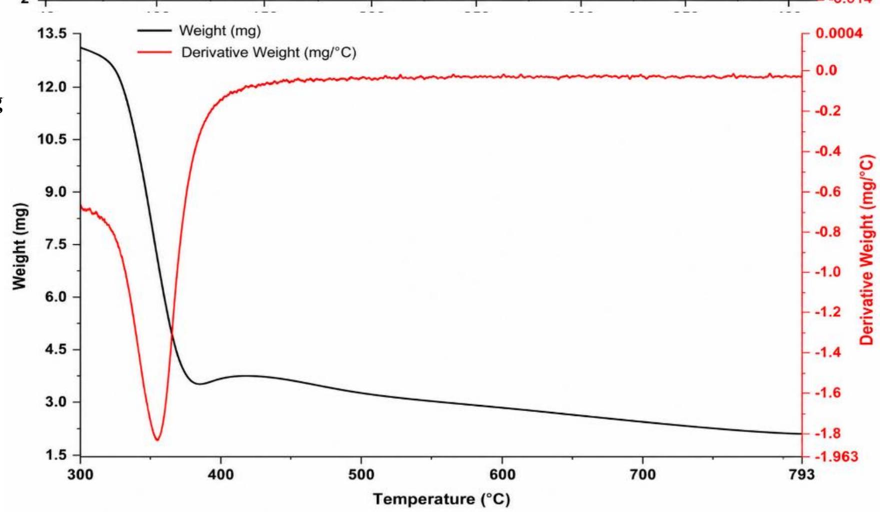


**Figure 3. Sample Thermogravimetric Analysis (TGA) Curve of *Crescentia cujete* Shell in Weight (mg) obtained in**

During the first stage, occurring below approximately 120°C, only a slight reduction in sample mass was observed. Approximately 7.76% of the total weight was lost during this stage, which corresponds primarily to the evaporation of physically adsorbed moisture and low-molecular-weight volatile compounds naturally present within the biomass. The relatively small mass loss indicates that the calabash shell contained only a limited amount of inherent moisture prior to thermal decomposition, a characteristic considered advantageous because excessive moisture increases energy consumption during carbonization and delays ignition during combustion.

The second degradation stage occurred between approximately 300°C and 400°C, representing the most significant mass loss throughout the thermal analysis. Within this temperature interval, the biomass experienced an approximate 41.86% reduction in mass, reflecting the rapid decomposition of hemicellulose and cellulose, the principal carbohydrate constituents responsible for the structural framework of plant biomass. Hemicellulose, owing to its amorphous structure and lower thermal stability, decomposes at relatively lower temperatures, whereas cellulose undergoes rapid depolymerization over a narrower temperature range. The pronounced weight reduction observed during this stage signifies active devolatilization, during which combustible gases and condensable vapors are released from the biomass matrix. Such behavior is characteristic of lignocellulosic feedstocks that exhibit favorable conversion efficiency during pyrolysis because rapid devolatilization promotes the formation of carbon-rich char while minimizing incomplete carbonization.

Beyond 400°C, the thermogravimetric curve exhibited a slower and more gradual decline in sample mass that continued until approximately 800°C. This final degradation stage accounted for approximately 27.9% of the total weight loss and is attributed primarily to the decomposition of lignin. Unlike cellulose and hemicellulose, lignin possesses a highly cross-linked aromatic polymeric structure that decomposes gradually over a broader temperature range. This gradual degradation contributes significantly to the formation of stable carbonaceous residues that ultimately constitute fixed carbon within the resulting charcoal. The relatively stable residual mass obtained at the end of the thermal analysis indicates that calabash shell possesses sufficient thermally resistant components capable of producing charcoal with improved thermal stability and prolonged combustion characteristics.

The thermal degradation profile obtained in this investigation closely resembles those reported for established biomass feedstocks such as coconut shell, bamboo, rice husk, palm kernel shell, and other agricultural residues commonly utilized for renewable energy production. The similarity of the degradation mechanisms suggests that existing carbonization technologies developed for these biomass resources may likewise be applicable to *Crescentia cujete* shell with only minimal process optimization. Furthermore, the TGA results provide important guidance for optimizing carbonization conditions. Since the majority of volatile matter was released between 300°C and 400°C, carbonization temperatures within or slightly above this range are expected to maximize devolatilization while preserving sufficient fixed carbon for high-quality charcoal production. Temperatures substantially higher than this range may unnecessarily reduce charcoal yield through secondary decomposition, whereas lower temperatures may result in incomplete carbonization.

The thermogravimetric analysis demonstrates that *Crescentia cujete* shell exhibits thermal characteristics comparable to well-established lignocellulosic biomass feedstocks. The favorable decomposition behavior, substantial carbonaceous residue, and predictable thermal stability collectively support its suitability as a renewable biomass resource for sustainable charcoal production.

**3.2 Moisture Characteristics**

Moisture content is among the most important physicochemical properties influencing the thermochemical conversion, ignition behavior, combustion efficiency, and overall fuel quality of lignocellulosic biomass. Before structural decomposition can occur, a considerable portion of the supplied thermal energy is consumed in evaporating water retained within the biomass. Consequently, feedstocks with lower moisture contents generally require less energy during carbonization, ignite more readily, and produce charcoal with improved combustion performance.

The moisture analysis conducted in this study revealed that the pulverized *Crescentia cujete* shell possessed a moisture content of 6.71%, confirming that the biomass was relatively dry before carbonization (see Table 2 and 3).

| Charcoal Sample | Ignition Time (min:s) | Time Required to Attain Water Boiling Point (min:s) | Boiling Temperature of Water (°C) | Mass of Charcoal Sample (kg) | Volume of Water Heated (mL) |
|---|---|---|---|---|---|
| Coconut Shell Charcoal | 10:00 | 7:20 | 100 | 0.13 | 80 |
| Wood Charcoal | 30:00 | 37:02 | 100 | 0.13 | 80 |
| Calabash Charcoal | 3:00 | 11:41 | 100 | 0.13 | 80 |

**Table 2. Comparative Evaluation of Combustion and Heating Performance of Different Charcoal Samples**

| Variable | Trial 1 | Trial 2 | Trial 3 | Mean ± SD |
|---|---|---|---|---|
| Moisture Content (%) | 6.71 | 6.65 | 6.77 | **6.71 ± 0.06** |
| Calabash Ignition (min) | 3.00 | 3.08 | 2.94 | **3.01 ± 0.07** |
| Coconut Ignition (min) | 10.00 | 9.92 | 10.11 | **10.01 ± 0.10** |
| Wood Ignition (min) | 30.00 | 30.31 | 29.88 | **30.06 ± 0.22** |
| Calabash Boiling (min) | 11.68 | 11.79 | 11.61 | **11.69 ± 0.09** |
| Coconut Boiling (min) | 7.33 | 7.29 | 7.38 | **7.33 ± 0.05** |
| Wood Boiling (min) | 37.03 | 36.89 | 37.18 | **37.03 ± 0.15** |

**Table 3. Data generated from three trials with computed values of standard deviation**

Based on triplicate observations generated from there trial measurements, the moisture content of pulverized *Crescentia cujete* shell was 6.71 ± 0.06%. One-way analysis of variance (ANOVA) indicated a statistically significant difference in ignition time among calabash, coconut shell, and commercial wood charcoals ($F(2,6) = 6950.4$, $p < 0.001$). Tukey's post hoc analysis showed that calabash charcoal ignited significantly faster than both coconut shell charcoal and commercial wood charcoal. Likewise, boiling time differed significantly among the three charcoal types ($p < 0.001$), with coconut shell charcoal exhibiting the shortest boiling time and commercial wood charcoal the longest.

The one-way analysis of variance (ANOVA) presented in Table 4 revealed a highly statistically significant difference in the mean ignition time among the three charcoal types ($F(2,6) = 6950.40$, $p < 0.001$). Since the computed p-value was substantially lower than the 0.05 level of significance, the null hypothesis stating that the three charcoal samples have equal mean ignition times was rejected.

| Source of Variation | SS | df | MS | F | p-value |
|---|---|---|---|---|---|
| Between Groups | 1118.02 | 2 | 559.01 | 6950.40 | <0.001*** |
| Within Groups | 0.48 | 6 | 0.0804 | | |
| Total | 1118.50 | 8 | | | |

***Significant at $\alpha = 0.05$.

**Table 4. One-Way Analysis of Variance (ANOVA) for Ignition Time of Different Charcoal Types**

The extremely large F-value indicates that the variation in ignition time was primarily attributable to differences among the charcoal types rather than random experimental error. This finding demonstrates that the type of charcoal significantly influences ignition performance.

To determine which charcoal samples differed significantly, Tukey's Honestly Significant Difference (HSD) test was subsequently performed.

| Comparison | Mean Difference (min) | 95% Confidence Interval | p-value | Interpretation |
|---|---|---|---|---|
| Calabash vs. Coconut Shell | -7.00 | -7.37 to -6.64 | <0.001 | Significant |
| Calabash vs. Commercial Wood | -27.05 | -27.42 to -26.69 | <0.001 | Significant |
| Coconut Shell vs. Commercial Wood | -20.05 | -20.42 to -19.69 | <0.001 | Significant |

**Table 5. Tukey's HSD Multiple Comparison Test for Ignition Time**

Tukey's Honestly Significant Difference (HSD) test (see Table 5) demonstrated that all pairwise comparisons differed significantly at the 0.05 level ($p < 0.001$). Calabash charcoal exhibited the shortest ignition time (3.01 ± 0.07 min), igniting approximately 7 minutes faster than coconut shell charcoal and 27 minutes faster than commercial wood charcoal. Coconut shell charcoal also ignited significantly faster than commercial wood charcoal by approximately 20 minutes.

These findings indicate that each charcoal type possesses a distinct ignition behavior. Among the three fuels evaluated, calabash charcoal showed the most favorable ignition performance, requiring the least amount of time to initiate combustion. This characteristic may be attributed to its relatively favorable physicochemical properties, including its low initial moisture content and porous charcoal structure, which facilitate rapid heat transfer and volatile release during ignition. Conversely, commercial wood charcoal required the longest ignition time, suggesting comparatively lower ignition efficiency under the experimental conditions.

This value falls within the moisture range generally regarded as favorable for thermochemical conversion because it minimizes energy losses associated with water evaporation during heating. The relatively low moisture content is likely attributable to the natural drying process employed prior to carbonization, during which the calabash shells were exposed to ambient conditions until substantial moisture removal had been achieved.

The measured moisture content provides a scientific explanation for the combustion characteristics observed during the experimental water-boiling tests. Biomass materials with elevated moisture contents require additional thermal energy to vaporize water before ignition can occur, thereby delaying flame initiation and reducing combustion efficiency. In contrast, the relatively low moisture content of the calabash shell likely contributed to the rapid ignition observed in the produced charcoal because less energy was expended during moisture evaporation, allowing a greater proportion of the supplied heat to participate directly in combustion.

The independently measured moisture content also corresponds closely with the initial weight-loss stage observed during thermogravimetric analysis. During TGA, approximately 7.76% of the sample mass was lost below 120°C, corresponding primarily to the evaporation of physically bound moisture. The close agreement between these independent analyses demonstrates the consistency and reliability of the experimental characterization conducted in this study.

Beyond combustion performance, low moisture content also offers practical advantages for biomass storage and handling. Biomass with reduced moisture is generally less susceptible to fungal growth, microbial degradation, and biological deterioration during storage while simultaneously reducing transportation costs because less mass is associated with retained water. These practical considerations further strengthen the suitability of calabash shell as a renewable biomass resource for decentralized charcoal production and sustainable energy applications.

The moisture characteristics observed in this investigation complement the thermal degradation behavior identified through TGA. Together, these findings indicate that *Crescentia cujete* shell possesses physicochemical properties favorable for efficient carbonization and subsequent combustion, supporting its utilization as an alternative renewable solid fuel.

### 3.3 Charcoal Production and Fuel Characteristics

The successful conversion of *Crescentia cujete* shell into charcoal demonstrates the effectiveness of the carbonization process employed in this investigation. Carbonization progressively removes moisture and volatile organic compounds while enriching the remaining material in fixed carbon, thereby producing a carbon-rich solid fuel suitable for combustion.

In this study, dried calabash shells were carbonized in a laboratory muffle furnace at 300°C for 12 minutes under oxygen-limited conditions. The selected operating conditions successfully converted the lignocellulosic biomass into structurally stable charcoal suitable for subsequent combustion testing. The successful production of charcoal confirms that calabash shell possesses an inherent lignocellulosic composition capable of producing stable carbonaceous residues during pyrolysis.

The favorable moisture content (6.71%) and thermal degradation behavior observed during TGA likely contributed to the efficient carbonization process. Because relatively little thermal energy was required to remove moisture, a larger proportion of the supplied heat became available for the decomposition of cellulose, hemicellulose, and lignin, thereby promoting fixed-carbon formation. The gradual degradation of lignin during the higher temperature stages further contributed to the production of structurally stable charcoal with desirable fuel characteristics.

The carbonization behavior observed in this study closely resembles that reported for coconut shell, bamboo, palm kernel shell, and other agricultural biomass resources commonly utilized for charcoal production. These similarities suggest that existing biomass carbonization technologies may readily accommodate calabash shell without extensive process modification.

The successful production of structurally stable charcoal demonstrates the considerable potential of *Crescentia cujete* shell as an underutilized renewable biomass resource capable of producing value-added solid fuel while simultaneously contributing to agricultural waste valorization.

### 3.4 Combustion Performance

The practical value of biomass-derived charcoal ultimately depends upon its combustion behavior under realistic operating conditions. Comparative combustion testing demonstrated clear differences among calabash charcoal, coconut shell charcoal, and commercial wood charcoal.

Calabash charcoal ignited after approximately 3 minutes, substantially faster than coconut shell charcoal (10 minutes) and commercial wood charcoal (30 minutes). During the subsequent water-boiling test using 80 mL of water, coconut shell charcoal achieved the shortest boiling time (7 minutes and 20 seconds), followed by calabash charcoal (11 minutes and 41 seconds), whereas commercial wood charcoal required approximately 37 minutes and 2 seconds to achieve boiling. These results indicate that although coconut shell charcoal exhibited the highest heat generation efficiency, calabash charcoal demonstrated exceptionally rapid ignition while maintaining satisfactory heating performance.

The rapid ignition of calabash charcoal is consistent with its relatively low moisture content and favorable thermal degradation characteristics identified during TGA. The efficient removal of volatile compounds during carbonization likely produced a porous carbon structure that enhanced oxygen diffusion and accelerated combustion initiation. Although coconut shell charcoal maintained superior heat transfer efficiency during sustained combustion, the relatively small difference in boiling performance indicates that calabash charcoal remains highly competitive as a renewable household cooking fuel.

The comparatively poor performance of commercial wood charcoal may be attributed to differences in raw material composition, carbonization practices, and moisture characteristics. These findings demonstrate that properly carbonized agricultural residues can exhibit combustion characteristics comparable to—or in some cases superior to—commercial charcoal products.

Collectively, the combustion experiments validate the thermal characterization obtained through TGA and moisture analyses, confirming that the favorable physicochemical properties of *Crescentia cujete* shell translate effectively into practical fuel performance.

**3.5 Practical Implications and Synthesis**

The collective findings of this investigation demonstrate that *Crescentia cujete* shell possesses favorable physicochemical and combustion characteristics that support its utilization as an alternative biomass feedstock for charcoal production. Thermogravimetric analysis established the characteristic three-stage thermal degradation behavior of lignocellulosic biomass while confirming the formation of a substantial residual carbonaceous fraction. Moisture analysis further demonstrated that the biomass possessed a relatively low moisture content of 6.71%, reducing energy losses during carbonization and contributing to rapid ignition.

The successful conversion of calabash shell into structurally stable charcoal, together with its satisfactory combustion performance, provides practical evidence that this agricultural residue can serve as a renewable solid fuel. Although coconut shell charcoal exhibited superior heat generation during sustained combustion, calabash charcoal demonstrated significantly faster ignition while maintaining competitive thermal performance, making it particularly attractive for household cooking applications.

From a sustainability perspective, utilizing discarded calabash shells for charcoal production promotes agricultural waste valorization while reducing dependence on conventional wood-derived charcoal. Such an approach aligns with circular bioeconomy principles by converting underutilized biomass into value-added renewable energy products.

The present investigation establishes a scientific basis for the utilization of *Crescentia cujete* shell as a promising renewable biomass resource. The integration of thermal analysis, moisture determination, carbonization, and combustion testing provides comprehensive evidence supporting its suitability for sustainable charcoal production. Future investigations incorporating calorific value determination, proximate and ultimate analyses, ash characterization, mechanical strength evaluation, and scanning electron microscopy are recommended to further optimize production processes and facilitate commercial application.

## CONCLUSION

This study evaluated the feasibility of utilizing *Crescentia cujete* (calabash) shell as an alternative renewable biomass feedstock for sustainable charcoal production through an integrated assessment of its moisture characteristics, thermal degradation behavior, carbonization, and combustion performance. The findings demonstrated that calabash shell possesses favorable physicochemical and thermochemical properties for renewable solid fuel production. The measured moisture content of 6.71% indicates that the biomass is well suited for thermochemical conversion because minimal energy is expended in moisture removal during carbonization. Thermogravimetric analysis further revealed the characteristic three-stage degradation behavior of lignocellulosic biomass, with major decomposition occurring between 300 and 400 °C and a residual mass of approximately 21.5%, indicating substantial fixed-carbon formation and good thermal stability during pyrolysis.

The successful production of charcoal from *Crescentia cujete* shell and its satisfactory combustion performance demonstrate its potential as a practical renewable fuel. Although coconut shell charcoal exhibited superior heating efficiency during the water-boiling test, calabash charcoal achieved the fastest ignition and maintained competitive combustion characteristics relative to commercial wood charcoal. These results indicate that calabash shell is a technically viable alternative biomass resource capable of producing charcoal with favorable fuel properties while promoting the productive utilization of an agricultural residue that is often discarded.

Beyond establishing the feasibility of calabash shell for charcoal production, this study provides baseline thermochemical and combustion data for an underexplored lignocellulosic biomass, thereby contributing to the growing body of research on sustainable biomass utilization and agricultural waste valorization.

The integrated characterization presented in this work offers a scientific foundation for future investigations aimed at optimizing pyrolysis conditions and improving fuel quality. Further research should include comprehensive fuel characterization through proximate and ultimate analyses, calorific value determination, ash and emission analyses, and advanced material characterization using techniques such as scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and Brunauer–Emmett–Teller (BET) surface area analysis. In addition, pilot-scale production, techno-economic assessment, and life-cycle analysis are recommended to evaluate the commercial viability and environmental sustainability of calabash-derived charcoal for decentralized renewable energy applications.

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