

The Proximate and Ultimate Composition of Pulverised Coconut Shell

Nurhazwani Hazman¹, Norasikin Mat Isa^{1*}, Nurul Fitriah Nasir¹, Mohamed Hussein², Adebayo, D.S.³

¹ Energy Technologies Research Group (EnRG), Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, MALAYSIA

² Faculty of Mechanical Engineering,

Universiti Teknologi Malaysia, 81310 Skudai, Johor, MALAYSIA

³ School of Engineering and Technology, College of Engineering and Physical Sciences, Aston University, Aston Triangle, Birmingham B4 7ET, UNITED KINGDOM

*Corresponding Author: sikin@uthm.edu.my

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Abstract

Biomass is gaining traction as a renewable energy source as it plays a significant role in global green transition. Authors believe coconut shells have a huge potential comparable to wood and sawdust in burning appliances. However, the use of coconut shells in the combustion industry is still limited due to limited studies and uncommon practices. Therefore, we expect the properties analysis of coconut shells to highlight their advantages as a fuel. The coconut shell residues were collected, dried, purified, crushed, and ground to obtain in pulverized form. Then, the sample of pulverized coconut shell underwent the proximate and ultimate analysis based on standard needs (ASTM E871, E872, and D1102). The results were compared with those of various other fuel types for a comprehensive analysis. This comparison found that coconut shells have significant potential as a fuel due to their low moisture and ash content, which contribute to higher heating values. Furthermore, Malaysia sustainably sources coconut shells.

1. Introduction

The world has taken essential steps to face the problem of limiting global warming to 1.5 °C above pre-industrial levels, which would require significant reductions in greenhouse gas emissions in all sectors. There has been a strict need for green energy in recent years, particularly renewable energy, to replace fossil fuels. Therefore, the authors chose biomass as one of the solutions to this issue because it is easy to obtain, abundant, and sustainable for power generation use. It has been used for thousands of years and is known as the oldest renewable energy source. Biomass may be thought of as a near-perfect coal replacement with the benefits of being carbon neutral and cost-efficient, as well as meeting energy demands [1], [2], [3]. The world interest in biomass resources is emerging because of its considerable potential to penetrate all energy sectorial markets, but economic restrictions also constrain it. Additionally, the simulation demonstrated that the right amount of excess air in the combustion of coconut shells can reduce carbon dioxide and carbon monoxide emissions [4].

In Malaysia, coconuts rank as the fourth largest industrial crop, behind oil palm, rubber, and rice, with most plantations located in Sabah and Sarawak. According to a report by the Malaysian Agricultural Research and

Development Institute (MARDI), although production fell between 2014 and 2016, Malaysia is still among the top 10 coconut producers in the world [5]. Owing to its peculiar qualities, coconut shells have a broader range of benefits than most crop and animal residues [6]. With their favorable qualities, researchers believe coconut shells could become a leading renewable energy source, comparable to other biomasses like wood and empty fruit bunches. As one of Malaysia's most critical resources, coconut shells hold significant potential in the renewable energy sector.

The composition of biomass is the unique basic codes that define and describe the characteristics, quality, possible use, and environmental outcome. Proximate analysis determines moisture, volatile matter, ash, and fixed carbon in a solid fuel [7]. The previous study by Akinrinola et al. showed that the chemical composition of biomass affects the ignition delay due to its moisture content [8]. Fuels with a high moisture content burn more slowly and produce less heat per unit mass. As a result, water contains very little energy, and fuel uses all its energy to heat and vaporize the water.

Meanwhile, the volatile content of biomass usually contributes about 70% of the heat of biomass combustion, which typically occurs at 160 – 250°C during devolatilization, compared to about 36% for coal volatile combustion [9]. Therefore, volatile combustion dominates the biomass combustion processes, while char combustion is less critical regarding thermal efficiency than coal combustion. Moreover, ash is also present in the biomass in the form of certain inorganic compounds like potassium, calcium, sodium, phosphorous, silicon, and chlorine. Chandrasekaran et al. [10] added that the increase in particulate matter (PM) emissions and operational issues such as fouling, slag, and corrosion are due to the very high concentration of fuel ash. As a result, disruptions can occur in the combustion process, leading to lower efficiency, unexpected shutdowns, and increased emissions of incomplete combustion. Additionally, understanding the fixed carbon content in biomass is crucial.

Fixed carbon is the solid carbon in the biomass that remains in the char after devolatilization. Indeed, the higher fixed carbon helps to maximize biochar yield and increase char production in the thermochemical conversion process [11]. The ultimate analysis is one of the crucial factors when evaluating biomass fuel properties. This analysis is a breakdown of the fuel into its elemental components. It relies on analyzing the leftover products after a small fuel sample has been completely burned [12]. It is crucial to identify the significant elemental composition of the solid fuel. Determining the percentages of sulfur and nitrogen may lead to an investigation of environmental impact.

2. Experimental Methodology

We collected the coconut shell residue from a nearby stall in Kulai, Johor. The residues were sun-dried for three weeks to remove moisture and impurities, such as leftover white kernel. After drying, the shells were broken into smaller pieces using a hammer. It is then crushed with a plastic granulator (SLM 50 FY) and ground using a grain grinding machine (BL-15B) to produce a pulverized form. The pulverized coconut shell was sieved for 10 minutes using a vibrator sieve shaker (Analysette 3 Pro) with sizes ranging from 1000 to 63 μm . The fraction retained in the pan below 63 μm was used for proximate and ultimate analysis, as shown in Fig. 1.



Fig. 1 Photographs of coconut shells (a) Undergo sundried; (b) After purification; (c) Broken pieces; (d) After crushed; (e) Pulverized form

The proximate analysis measured moisture levels, fixed carbon, volatile matter, and ash content, adhering to established standards (ASTM E871-2013, ASTM E872-82-2013, ASTM D1102-84-2013). In this study, a Carbolite PIF 120 (200) incubator is used to determine the moisture content of PCS, taking the final weight when the variation was less than 0.2%. Meanwhile, the volatile matter test is performed using a digital furnace shaker,

analyzing two replicates and achieving a repeatability of $\pm 1\%$ for volatiles. The ultimate analysis, conducted with a Perkin Elmer 2400 elemental analyzer, determined the chemical composition, including carbon, hydrogen, oxygen, nitrogen, and sulfur. The process flow of the sample preparation and experimentation can be represented in Fig. 2.

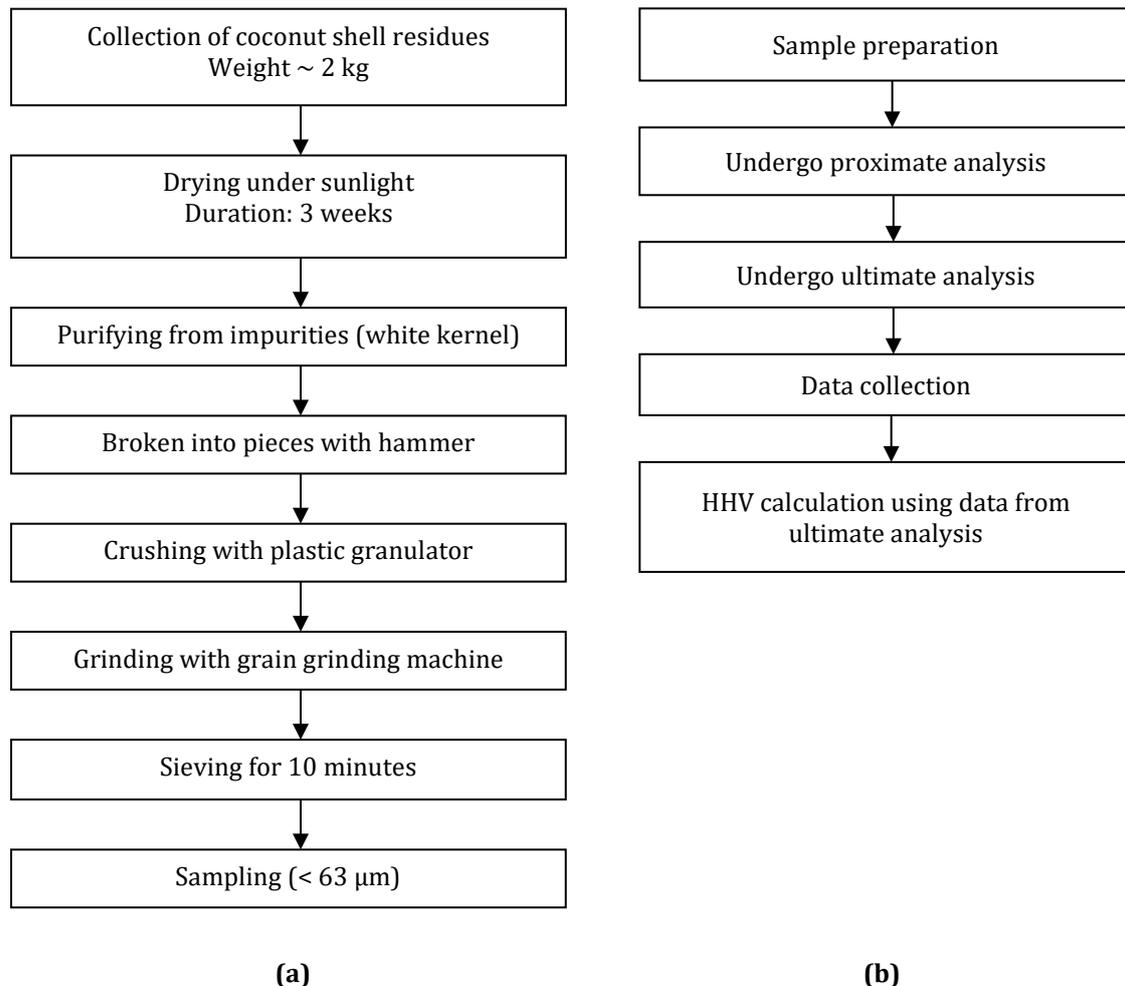


Fig. 2 Flowchart of (a) Sample preparation; (b) Experiment process

3. Results and Discussion

3.1 Proximate and Ultimate Composition

Table 1 presents the results of proximate and ultimate analyses for coconut shells and other types of fuels. The moisture content observed in this study and in other studies showed no significant difference. Table 1 indicates that the moisture content in this study, compared with that reported by another researcher [13], ranges from 9% to 11%, with a minimal difference of 0.84%. This slight variation is considered low, highlighting coconut shells' good fuel quality and desirability. Additionally, the practical permissible moisture level for fuel combustion is typically around 60% (on a wet basis), with most commercial combustion equipment operating effectively with fuels containing up to 40% moisture [17]. The ideal moisture content for solid fuels like wood or coal should be below 20% to ensure efficient combustion.

The mass fraction of coconut shells' incombustible material or ash content was below 1%, indicating low ash for solid biofuels. This lower ash content is crucial to prevent clogging in ash handling mechanisms and to improve combustion efficiency. It proved that coconut shells produce minimal ash, leading to a higher demand for ash removal. Slagging, a concern in boiler operation, occurs when biomass fuels contain more than 4% ash content [18]. Therefore, levels below this threshold reduce the likelihood of slagging issues.

The volatile content of coconut shells showed slight variation, approximately 71%, indicating a high volatile content within coconut shells. Biomass materials with high volatility offer favorable conditions, such as a low ignition temperature and sustained ignition over a more extended period. Furthermore, the heating value of biomass is determined by its fixed carbon and volatile matter content. Any increase in these elements also increases the heating value of the feedstock [19].

Table 1 Proximate and ultimate analyses of studied fuels

Fuel properties	Coconut Shell [13]	Wood Sawdust [14]	Empty Fruit Bunch [15]	Bituminous Coal [16]	Present work - CS
<i>Proximate analysis (wt%)</i>					
Moisture	10.5	3.07	2.44	13.2	9.66
Volatile matter	71.1	80.87	73.63	35.4	71.92
Fixed carbon	17.6	12.68	18.67	39.7	17.75
Ash	0.80	3.38	5.26	11.6	0.67
<i>Ultimate analysis (wt%)</i>					
Carbon	48.6	46.09	48.48	66.1	47.29
Hydrogen	5.97	6.62	7.14	4.6	4.91
Oxygen	43.8	47.19	43.74	9.9	47.24
Nitrogen	0.62	0.10	0.64	1.1	0.19
Sulfur	1.09	-	-	5.5	0.37

The ultimate analysis plays a significant role in evaluating the qualities of coconut shell biomass fuel, considering its carbon, hydrogen, oxygen, nitrogen, and sulfur content and their effects on combustion equipment and the environment. The analysis revealed that coconut shells possess a carbon content ranging between 47% and 48%, highlighting their high carbon concentration. This high carbon content is crucial for efficient combustion and results in a high calorific value, meaning coconut shells release substantial heat energy when burned.

The nitrogen (N) and sulfur (S) content in the current study were measured at 0.19% and 0.37%, respectively, while another researcher, Yahaya et al. [13] reported 0.62% and 1.1% for both nitrogen and sulfur. Both studies showed relatively low values of N and S, below and equal to 1%. In addition, most biomass materials contain less than 0.2% sulfur, with only a few exceeding 0.5%-0.7% [20], placing coconut shells within this lower sulfur content category. Biomass with higher nitrogen and sulfur content tends to produce harmful gases such as oxides of nitrogen (NO_x) and sulfur oxides (SO_x) when burned, contributing to acid rain and particle matter (PM) emissions [21]. Lower sulfur and nitrogen content, as found in coconut shells, indicates lower emissions of NO_x and SO₂.

Overall, the results of this study align closely with those of previous research, indicating the fundamental properties shared among coconut shell samples with minimal differences. These variations may be due to differences in coconut species, source locations, or analytical methods. The consistency between this study and previous research underscores the validity and reliability of both methodologies, contributing to a better understanding of coconut shell properties.

3.2 Comparison With Other Types of Biomasses

The sample of coconut shell was compared to wood sawdust and empty fruit bunch, as tabulated in Table 1. We chose these other biomasses to compare with coconut shells because they are commonly used as feedstock in Malaysia. The significant differences were that the coconut shell had the highest moisture content of about 10% but the lowest ash content below 1% compared to others. Meanwhile, the volatile matter content of coconut shells was lower than wood sawdust, resembling an empty fruit bunch. The lower the volatile matter, the lower the volume of bio-oil yield [17]. In this case, the volatile matter for all three biomasses is still considered higher, above 70%.

On the contrary, coconut shells had higher fixed carbon content than wood sawdust. At the same time, it is not much different from empty fruit bunches, which indicates that coconut shells might be the most suitable for biochar production. Notably, each biomass's moisture content had remarkable applications, especially in pellet production [18], [19]. Researchers believed that moisture content was related to the pellet density, heating value, and other aspects. Besides, each type of biomass had its optimum moisture content value after being manually adjusted during palletization. The increased moisture content for feedstock cases substantially increases the drying and ignition times. Plus, it had a negligible effect on the devolatilization rate and no impact on char burning. If the moisture content of the feedstock increases due to nature, the furnace temperature will decrease [20]. Hence, these studies imply that each biomass's moisture content varies and is best suited depending on its use.

Furthermore, the elemental composition of coconut shells is comparable to that of wood sawdust and empty fruit bunches, suggesting minimal differences when using coconut shells as fuel or feedstock. Specifically, carbon varies from 1.10% to 1.2%, hydrogen varies from 1.71% to 2.23%, oxygen varies from 0.05% to 3.5% and nitrogen

varies from 0.09% to 0.45%. Conclusively, these variations of elemental composition showed below 4% differences, which indicates that they are not too significant. Thus, coconut shells, like wood sawdust and empty fruit bunch, fuel Malaysia's boiler industries. To be highlighted, the carbon content of coconut shells exceeded 40%, which was 47.29%, clearly showing that they are almost comparable to both biomasses. It is higher than other biomass wastes, such as corn cobs and firewood, as reported by Gani et al. [21]. This result indicates that coconut shells, wood sawdust, and empty fruit bunches are good options for fuel utilization.

3.3 Comparison With Coal

In general, coconut shells are higher in volatility, lower in ash, have higher oxygen content, and are lower in nitrogen and sulfur than coal. The N and S content for coconut shell showed below 1% compared to coal, with 5.5% of S and 1.1% of N. The higher the N results, the higher the NO_x, and vice versa. Thus, coconut shells have low NO_x emissions, meaning they are better than coal in terms of emissions. In addition, the ashes from burning coconut shells will result in low alkaline and alumina constituents, unlike coal [22].

Coconut shells have a significantly higher volatile matter content of 71.92% compared to bituminous coal's 35.4%, classifying them as biomass with higher volatile matter. According to the reviewed article by Vassilev et al. [23], biomass with higher volatile matter (mainly woody biomass and agricultural and herbaceous biomass) had the advantages of low ignition temperature, easier burning, higher production of combustible gas, more flaming combustion, and less char; better and quicker burnout with lower unburned C in the ash when meets suitable particle size; provide more stable flame when co-fired. In addition, agricultural biomass fuels with high volatile matter may produce less NO_x than coals [24]. All of these compare the advantages of coconut shells over coal.

3.4 Estimation of HHV of Coconut Shell

The heat value of a fuel is the amount of heat released during its combustion. Higher heating value (HHV) or gross heating value refers to the total heat of combustion per unit mass measured using a bomb calorimeter. Due to the unavailability of a bomb calorimeter and limitations throughout this research, HHV is estimated empirically using the formulae below [25].

$$\begin{aligned} \text{HHV (MJ/kg)} &= 0.349 C + 1.1783 H + 0.1005 S - 0.1034 O - 0.0151 N - 0.0211 A & (1) \\ &= 0.349 (47.29) + 1.1783 (4.91) + 0.1005 (0.37) - 0.1034 (47.24) - 0.0151(0.19) - \\ &\quad 0.0211 (0.67) \\ &= 17.43 \text{ MJ/kg} \end{aligned}$$

The data obtained from the ultimate analysis were substituted into the correlation, resulting in the HHV of the coconut shell being 17.43 MJ/kg.

3.4.1 HHV Comparisons With Other Fuels

As can be seen in Table 2, three types of solid fuels were chosen to be compared explicitly with coconut shells in terms of HHV. Three variants listed every kind of solid fuel to see the typical range of the HHV's solid fuel presence. Insignificant differences in HHV values for the same type of fuel may be due to variations in biomass species, location of source crops, or errors during analysis methods. As expected, bituminous coal has the highest HHV, ranging from 28.32 to 26.90 MJ/kg, compared to other biomass solid fuels. The heat content of coals may vary depending on their rank, but in this case, the amount of heat content of bituminous, as predicted, was higher than the coconut shells, about 6.37 to 10.89 MJ//kg difference.

Furthermore, the coconut shell recorded a difference of about 0.4 to 2.3 MJ/kg and 0.47 to 3.67 MJ/kg compared to wood sawdust and empty fruit bunch, respectively. In the highest to lowest HHV sequence, the fuels are arranged as follows: bituminous coal > wood sawdust > coconut shell > empty fruit bunch. It means coconut shells also have high energy potential and can go further than the utilization of wood sawdust and empty fruit bunches in Malaysia's biomass industry.

4. Conclusions

This study examined the properties of coconut shells using proximate and ultimate analysis. When compared with similar biomass types, it becomes evident that the moisture content of coconut shell ranges from 9% to 11%, with a mere 0.84% difference, suggesting it is a potentially excellent and preferred fuel option due to its lower moisture content. The ash content of coconut shells is below 1%, indicating minimal ash compared to other solid biofuels. The volatility of coconut shell is approximately 71%, signifying a high volatile content. Its carbon content falls between 47% and 48%, indicating a high carbon content essential for efficient combustion. Nitrogen (N) and

sulfur (S) content in coconut shells are at 0.19% and 0.37%, respectively, slightly lower than those found by other researchers. Both studies reveal low N and S content, suggesting reduced emissions of NO_x and SO₂.

Overall, the results of this study and previous research indicate that coconut shell samples share fundamental properties with minimal differences, likely influenced by coconut species, source locations, or analytical methods. Moreover, the consistency between findings from different studies underscores the validity and reliability of the methodologies, enhancing the understanding of coconut shell properties.

Significant differences can be observed compared to other biomass types, such as wood sawdust and empty fruit bunch. Coconut shells exhibit the highest moisture content at approximately 10% but the lowest ash content, below 1%, compared to the others. Volatile matter content in coconut shells is lower than that of wood sawdust but similar to that of empty fruit bunch, remaining above 70%. Coconut shell also has higher fixed carbon content than wood sawdust, suggesting its potential for bio-char production. The elemental composition of coconut shell closely resembles that of wood sawdust and empty fruit bunch, indicating its suitability as a fuel or feedstock with minimal differences.

Compared with coal, coconut shells have higher volatility, lower ash content, higher oxygen content, and lower nitrogen and sulfur content. The N and S content in coconut shells is below 1% compared to coal, resulting in lower NO_x emissions, making coconut shells a preferable option over coal in terms of emissions. Coconut shell's volatile matter content is significantly higher at 71.92% compared to bituminous coal at 35.4%, placing it in the category of biomass with high volatile matter.

Finally, the higher heating value (HHV) of coconut shell is measured at 17.43 MJ/kg, ranking it third in the sequence of HHV from highest to lowest, after bituminous coal and wood sawdust but ahead of empty fruit bunch. The result indicates a high energy potential for coconut shells, suggesting its potential utilization in Malaysia's biomass industry akin to wood sawdust and empty fruit bunch.

Table 2 HHV of selected fuels

Types of fuels	HHV (MJ/kg)	Authors
Coconut shell	17.43	Present work
Coconut shell	20.53	[26]
Coconut shell	18.80	[13]
Wood sawdust	18.40	[27]
Wood sawdust	18.34	[14]
Wood sawdust	18.23	[28]
Empty Fruit Bunch	16.86	[29]
Empty Fruit Bunch	16.96	[26]
Empty Fruit Bunch	17.97	[30]
Bituminous coal	28.32	[31]
Bituminous coal	28.20	[16]
Bituminous coal	26.90	[32]

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** Nurhazwani Hazman, Norasikin Mat Isa; **data collection:** Nurhazwani Hazman; **analysis and interpretation of results:** Nurhazwani Hazman, Norasikin Mat Isa, Nurul Fariah Nasir, Mohamed Hussein; **draft manuscript preparation:** Nurhazwani Hazman, Norasikin Mat Isa, Adebayo, D.S. All authors reviewed the results and approved the final version of the manuscript.

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