Article

Improving the Combustion Properties of Corncob Biomass via Torrefaction for Solid Fuel Applications

Segun Emmanuel Ibitoye [1,2,*], Tien-Chien Jen [1], Rasheedat Modupe Mahamood [1,3] and Esther Titilayo Akinlabi [1,4]

1 Department of Mechanical Engineering Science, Faculty of Engineering and the Built Environment, University of Johannesburg, P.O. Box 524, Auckland Park 2006, South Africa; tjen@uj.ac.za (T.-C.J.); mahamoodmr@unilorin.edu.ng (R.M.M.); etakinlabi@gmail.com (E.T.A.)
2 Department of Mechanical Engineering, Faculty of Engineering and Technology, University of Ilorin, P.M.B. 1515, Ilorin 240003, Nigeria
3 Department of Materials and Metallurgical Engineering, Faculty of Engineering and Technology, University of Ilorin, P.M.B. 1515, Ilorin 240003, Nigeria
4 Directorate of Pan African University for Life and Earth Science Institute, Ibadan 200005, Nigeria
* Correspondence: ibitoye.s@unilorin.edu.ng

Abstract: The overdependence on fossils as the primary energy source has led to climate change, global warming, and the emission of greenhouse gas. As a result, the United Nations, while setting the goals for the year 2030, has made the provision of a green environment and energy one of the top priorities. In this study, the suitability of corncob for green energy production was investigated. The improvement of corncob's thermal and combustion properties via the torrefaction process was considered for solid fuel applications. The raw corncob was collected, sorted, and dried for seven days before being used for the torrefaction experiment. Different torrefaction temperatures (200, 240, and 260 °C) and residence times (20, 40, 60 min) were studied. There was no particle reduction—samples were torrefied as collected (whole corncob). The results show that torrefaction temperature and residence time affect the torrefaction products yields along with their properties. Thermal and combustion properties were improved with an increase in torrefaction temperature and residence time. The higher heating value and energy density of the torrefied corncob varied between 17.26 and 18.89 MJ/kg, and 3.23 and 5.66 GJ/m^3, respectively. High torrefaction temperature and residence time lead to low solid yield; however, liquid and gas yields increase with torrefaction temperature and residence time. The solid yields varied from 27.57 to 52.23%, while the liquid and gas yields varied from 31.56 to 44.78% and 16.21 to 27.65%, respectively. The properties of corncob improve after torrefaction and are suitable for solid fuel application.

Keywords: combustion property; corncob; energy density; thermal property; torrefaction process

1. Introduction

The impact of the combustion of fossil fuels on human health, environment, and climatic conditions cannot be overemphasized; the rise in the global mean temperature, global warming, and greenhouse gas emissions [1,2]. This is due to overdependence on fossil fuels as the primary source of energy. As a result, the United Nations, while setting the goals for the year 2030, has made the provision of a green environment and energy one of the top priorities [3]. The utilization of green energy would help reduce the overdependence on fossil fuel and create an eco-friendly environment. Furthermore, research has shown that conventional sources (fossil, coal, etc.) of energy tend to go extinct; therefore, there is a need to seek an alternative to ensure the continuous supply of energy to the consumers [2,4,5]. The available renewable energy options include hydro, geothermal, tidal, solar, wind, and biomass energy [2]. Out of the renewable energy options, biomass exhibited sustainable and promising characteristics. This is because biomasses are abundant in different

forms—woody (forest wood) and non-woody (agricultural). Agricultural biomass is available as virgin material (cultivated energy crops) and residues/wastes.

Residues generated from agricultural activities are likely to be one of the major favorable energy sources soon [6]. Literature has shown that the annual agricultural residues generated globally are approximately 2000 billion tons [7]. These residues/wastes are generated mostly in remote areas, where there are intensive agricultural activities. Majorly, these residues are dumped in fields or set on open fire. This has led to environmental degradation, such as the emission of greenhouse gas. Converting these residues to usable energy will serve as mitigation to these problems.

Traditionally, woody biomass accounted for 85 per cent of the overall energy consumption, contributing substantially to environmental degradation in the country [8]. The percentage is associated with the people living in remote areas and some urban poor, mainly for domestic cooking and heating. This is responsible for the high level of deforestation in these areas [9].

For agro-residue to be effectively and efficiently utilized for energy generation, it must be adequately processed. This is to mitigate some of the limitations associated with raw biomass—poor thermal efficiency, low energy and bulk densities, high moisture contents, environmental challenge, transportation, storage, etc. [6,10,11]. Several solutions have been proffered to eliminate biomass challenges for energy applications. These include thermal, physical, biological, and mechanical treatments [6,12–14]. The thermal treatment is the process of heating biomass in an inert or oxygen-deficient environment. Examples of thermal treatment are gasification, pyrolysis, carbonization, and torrefaction [6]. These treatment methods differ by their operating temperatures. Torrefaction is the process of heating biomass (200–300 °C) in an oxygen-deficient atmosphere [15,16]. The thermal treatment improves the combustion properties of the biomass. Quite a few factors have been reported to affect the product of torrefaction—temperature, residence or dwelling time, and particle sizes. However, the most significant factors are temperature and residence time [11,17,18].

Several investigation efforts on biomass torrefaction have been testified in the literature. Severy et al. [19] carried out torrefaction and briquetting on a pilot-scale plant. The optimal torrefaction conditions were obtained at residence time, moisture content, and temperature range of 10 min, <11%, and 267–275 °C, respectively. The results showed that high-standard torrefied briquettes could be produced on a commercial scale. The effect of torrefaction temperature on thermal degradation of woody biomass (beech wood) and non-woody biomass (miscanthus) of northern Germany origin was investigated by Pielsticker et al. [17]. Fuel basic properties such as proximate, particle size, ultimate analyses, char yields, and HHV were investigated. Analyses of results revealed that char yield and HHV increase with torrefaction temperature while the volatile product decreases. It was also reported that the effect of torrefaction temperature on char composition was pronounced. Further investigation is required to determine the impact of other torrefaction process parameters on product yields and compositions. Research should also be carried out by varying different parameters at a constant temperature.

Moisture absorption and self-ignition characteristics of biomass were investigated through thermal and degradative solvent extraction pretreatments by Liu et al. [20]. It was reported that the moisture absorption characteristics of the pretreatment products were lower than the raw biomass. In addition, biochar and hydrochar display better self-ignition compare to the raw sample, while the extract was lower than the raw sample.

Studies on the ignitability, ash fusion temperatures, and fuel ratio of torrefied woody biomass (Melina and Teak) have been carried out [21]. The results revealed that torrefaction improved the heating value, grindability, and fuel ratio of biomass investigated. A temperature range of 220–320 °C was recommended for desirable fuel properties. Andini et al. [22] carried out torrefaction studies on a corncob, rice straw, and cassava stalk of Indonesian origin. It was discovered that the blending ratio does not significantly influence the torrefaction product properties.

Oxidative torrefaction of biomass for soil amendment was carried out by Thengane et al. using rice husk and pinewood as feedstock [23]. The results showed a linear relationship between the properties of the biochar produced. Utilization of the biochar for soil treatment reduced the PH of the soil by 0.2–0.3. However, the treatment had no significant influence on the seed germination and the number of shoots. Furthermore, the height of the shoot and crop yields increase with the degree of torrefaction.

Odusote et al. [11] investigated torrefied Tectona grandis in a tubular furnace at 240–300 °C, 30–60 min, and 2–6 mm temperature, residence time, and particle sizes, respectively. Analyses of the results showed that torrefaction temperature had the most significant influence on the biomass properties (mass yield, energy yield, and heating value) compared to other factors (residence time and particle size) considered in the study. The maximum mass yield, heating value, and energy yield were obtained at optimized torrefaction conditions of 260 °C, 60 min, and <2 mm temperature, residence time, and particle sizes.

Torrefaction after pelletization was performed by Manuuchehrinejad and Mani [24]. It was discovered that the solid yields decrease with an increase in torrefaction temperature during the condensable liquid increase with torrefaction temperature. The results of HHV, the energy density at 270 °C, were found comparable with coal for industrial applications. The physico-mechanical properties of the pellets were found to decrease with an increase in torrefaction severity; however, the grindability property was enhanced with an increase in torrefaction severity.

The combustion properties of terrified Camellia shell pellet were studied via dry and hydrothermal torrefaction [25]. Products analyses revealed that properties of bio-char from hydrothermal processes are closer to sub-bituminous coal, while the dry torrefaction compared favorably with anthracite coal.

Studies have been carried out on investigating combustion properties of corncob biomass from different origins via torrefaction, pyrolysis, and gasification for energy application. These include corncob of China [26–30], Taiwan [31], South Africa [32], Canada [33], Malaysia [34] and Nigeria [35–37] origins. However, there is still a need for further studies on the torrefaction of corncob for energy applications. Therefore, this study seeks to improve corncob's combustion and thermal properties through torrefaction for solid fuel application. In the previous studies, it was reported that pulverization of corncob is time and energy-consuming, resulting in higher production costs [31,35,38]. Herein, torrefaction was carried out without pulverizing the raw corncob. HHV, proximate, ultimate, and thermogravimetric investigations were carried out. The torrefaction yields (mass and energy), energy density, and enhancement factors were also investigated to ascertain the feasibility and viability of the torrefied corncob for energy applications.

2. Methodology

The materials, methods, and equipment used for this study are discussed in this section.

2.1. Material Preparation

The feedstock used for this study is the corncob. The corncob was collected from a maize farm located at Oro town, Kwara State, Nigeria. The collected sample was sorted to remove foreign material such as sand, grasses, stones, etc. This was followed by sun-drying for 7 days to eliminate the apparent moisture. The dried feedstock was stored in a zip-lock back to prevent further uptake of moisture from the surrounding.

2.2. Methods

The step-by-step methods adopted in this study are presented in this section.

2.2.1. Thermogravimetric Analysis (TGA)

A thermogravimetric study was conducted on the raw corncob using a thermogravimetric analyzer (TA instrument, Model: TGA 55). The corncob (5 mg) was analyzed using

a Nitrogen purge gas (120 mL/min) and a heating rate of 5 °C/min. The analyzer measures the change in weight of the sample with a temperature between 0 and 1000 °C [26].

2.2.2. Torrefaction Experiment

Based on the results of the TGA, the torrefaction was conducted between 200 and 300 °C. Previous torrefaction studies on corncob performed particle reduction before torrefaction [26–32,34,36,37], and reports have shown that particle size does not significantly affect the torrefaction process; therefore, the corncob was torrefied as received [11]. Therefore, in this study, the corncob was torrefied without performing particle reduction. This was carried out to save cost, time, and energy due to pulverization [35,38]. Torrefaction experiment was carried out at three temperatures (200, 240, and 260 °C) and residence (20, 40, and 60 min). An amount of 50 g of the corncob was utilized for every torrefaction. The corncob heating in the torrefaction reactor was by conduction—the heat source was in direct contact with the corncob chamber. Some previous studies achieved feedstock heating during thermal treatment by convection using a carrier gas [33]. Nitrogen gas was used to create an inert environment. The gas flow was monitored through the water bath placed at the outlet of the reactor's exhaust. After the torrefaction temperature was reached, the residence time was observed. The solid products were collected from the reactor chamber immediately after observing the residence time and transferred into a desiccator to cool to room temperature. Condensable gases were received using the collection bottles connected to the ports created on the exhaust of the torrefaction reactor. The collection bottles are cooled by ambient air. After sufficient cooling, the weight of the torrefaction products (solid, liquid, and gas) yields was calculated using Equations (1)–(3) [18]. The experiment was repeated, and the average is reported. Figure 1 shows the sample solid and liquid products obtained after the torrefaction process, while the schematic of the experimental setup is shown in Figure 2.

$$S_y = \frac{W_s}{W_r} \times 100\% \tag{1}$$

$$L_y = \frac{W_l}{W_r} \times 100\% \tag{2}$$

$$G_y = 100 - (S_y + l_y)\% \tag{3}$$

where are the solid, liquid, and gas yields, respectively, S_y, L_y, and G_y, W_s, and W_l, is the weight solid and liquid products, and W_r is the weight of the raw sample.
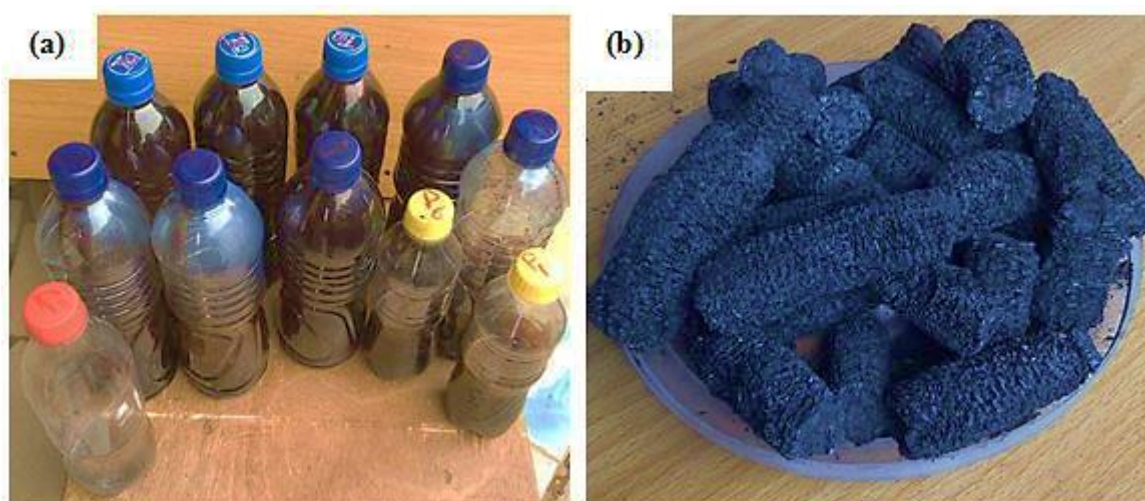

Figure 1. Samples of torrefaction products—(**a**) liquid yield and (**b**) solid yield.
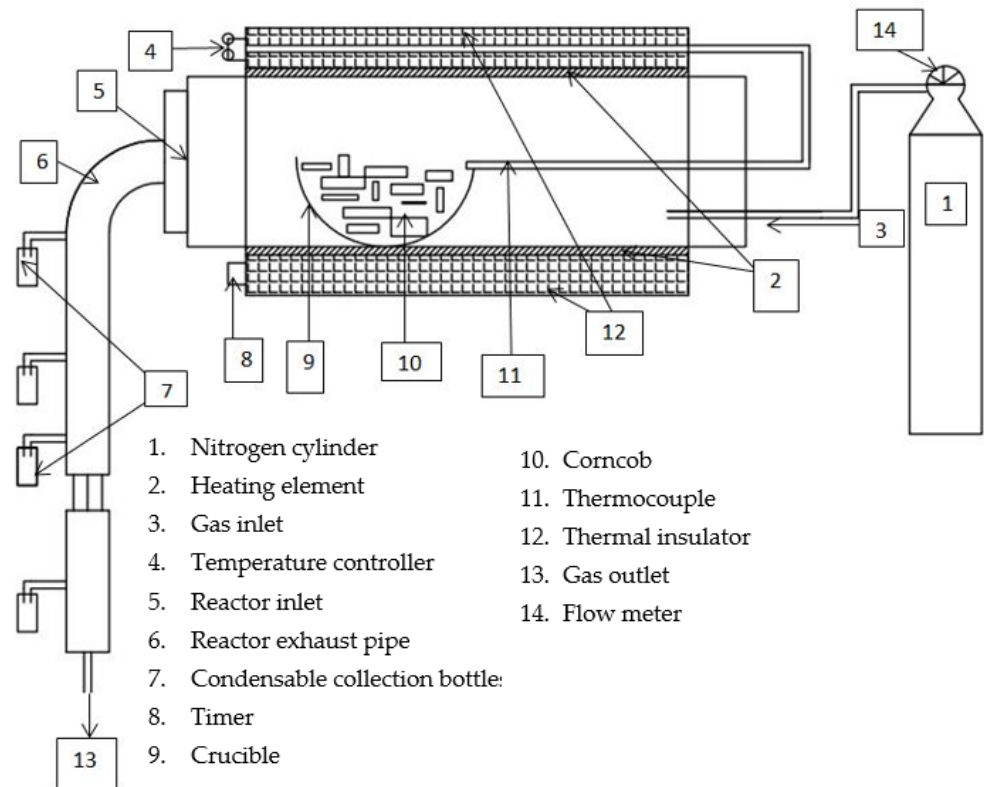
Figure 2. Schematic of the experimental setup.

2.2.3. Characterization of the Torrefied and Raw Corncob

Higher heating values: The raw and torrefied corncob's higher heating values were determined using Parr 6400 oxygen bomb calorimeter following the ASTM D5865-04 standard [39].

Proximate analysis: The proximate constituent of the raw and torrefied corncob was examined in accordance with the established standards. The fixed carbon (FC), ash (AC), volatile matter (VM), and moisture (MC) contents were determined following the ASTM E1756-08, E1755-01, E872-82, and E1871-82 standards, respectively [40–43].

Ultimate analysis: The elemental composition (Nitrogen, Hydrogen, Sulphur, and Carbon) of the raw and torrefied corncob was determined using a CHNS analyzer following ASTM D5373 standard [44]. The percentage of oxygen was determined by estimating the difference using Equation (4) [18,21].

$$O = 100 - (H + N + C + S)\% \tag{4}$$

Fuel ratio and degree of torrefaction: The fuel ratio and degree of torrefaction were calculated using Equations (5) and (6), respectively.

$$f_r = \frac{FC}{VM} \tag{5}$$

$$d_t = \frac{VM_{torrefied\ corncob}}{VM_{raw\ corcob}} \tag{6}$$

where HHV, d_t, i_d, f_r, FC, MC, and VM are the higher heating value, degree of torrefaction, ignitability index, fuel ratio, fixed carbon, moisture content, and volatile matter.

Enhancement factor, energy density, and yield: The enhancement factor, energy yield, and density of the torrefied corncob were estimated using Equations (7)–(9) [16,18,45].

$$E_d = HHV \times bulk\ density;\ bulk\ density = \frac{weight\ of\ sample}{volume\ of\ the\ container} \tag{7}$$

$$E_f = \frac{HHV_{torrefied\ corncob}}{HHV_{raw\ corncob}} \tag{8}$$

$$E_f = \frac{HHV_{torrefied\ corncob}}{HHV_{raw\ corncob}} \tag{9}$$

where E_y, E_f, E_d, and HHV are the energy yields, enhancement factor, energy density, and higher heating value, respectively.

3. Results and Discussion

The results of thermal and combustion characterization are presented and discussed in this section.

3.1. Thermogravimetric Analysis

The result of the thermal decomposition of raw corncob is shown in Figure 3. The onset temperature measures the point at which the thermal breakdown begins. It is an indication of the thermal stability of a substance. The higher the onset temperature, the more stable the material. The onset temperature of the corncob used in this study is approximately 389 °C. This implies that beyond this temperature, the corncob becomes thermally unstable. The initial mass loss might be due to the liberation of surface moisture and volatile matter contents of the corncob.
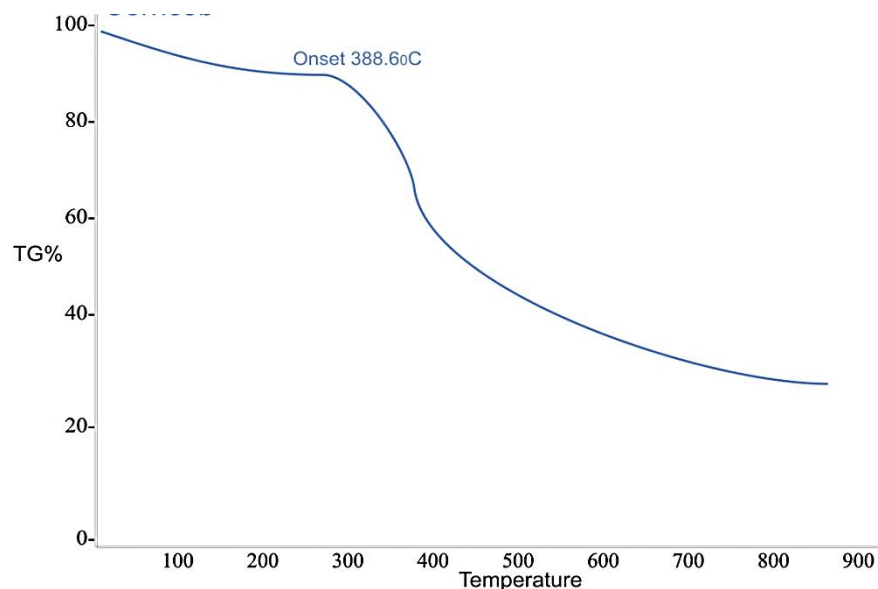

Figure 3. Thermogravimetric analysis of the raw corncob.

Thermogravimetric analysis (TGA) guides the setting of temperature for the corncob thermal pretreatment processes. Fortunately, the onset temperature of the corncob was higher than the torrefaction temperature range (200–300 °C). Figure 3 shows that there was no significant mass loss up to about 200 °C [46]. It has been reported that biomass thermal decomposition begins around this temperature. A substantial mass was recorded between 300 and 600 °C. Beyond 600 °C, the mass loss was no longer significant. This study aims to investigate the suitability of corncob for solid fuel applications; hence, the main focus is

on solid yields. Therefore, a 200–300 °C temperature range was adopted in this study to achieve high solid yields.

3.2. Proximate and Ultimate Analyses

The result of proximate and ultimate analyses and the atomic ratio of the raw and torrefied corncob is shown in Table 1. The raw corncob's C, S, O, N, and H compositions were 41.24, 1.56, 35.87, 0.12, and 6.10%, respectively. After torrefaction, the elemental composition was in the range of 44.43–67.15, 0.02–0.05, 22.11–38.89, 0.11–0.27, and 4.10–5.59% for C, S, O, N, and H, respectively. It was observed that torrefaction temperature significantly affects the ultimate analysis results, while the effect of residence time was not pronounced. At lower temperatures (200 °C), the constituents of the torrefied corncob were still close to the raw corncob. However, at higher temperatures, a significant difference was observed between the torrefied and raw corncob. The C and N contents increased with torrefaction temperature for the ultimate analysis, while S, O, and H contents decreased. This might result from the thermal decomposition of the structural component (cellulose and hemicellulose) of the corncob, which gives rise to the emission of the volatile matters (such as S elements), leading to the high carbon content in the torrefied products. The slight increase in N might be due to the heat resistance of N-bonds because of the presence of N in the corncob. This makes the N constituent increase at a higher torrefaction temperature. The constituent of S and N in solid fuel should be minor for satisfactory energy application. It could also be observed that the atomic ratios decrease with torrefaction conditions. This implies that the resulting torrefied corncob contains more aromatic compounds than the carboxyl and hydroxyl group, hence; enhance the energy yields and densities with an increase in torrefaction condition.

Table 1. The result of proximate and ultimate analyses of the raw and torrefied corncob.

Process Parameters		Ultimate Analysis (%)					Proximate Analysis (%)				Atomic Ratio	
Temperature (°C)	Time (min)	C	S	O	N	H	MC	AC	VM	FC	H/C	O/C
200	20	44.43	0.05	38.89	0.13	5.59	1.56	3.10	60.34	35.09	0.13	0.88
	40	45.21	0.05	38.66	0.11	5.55	1.4	3.32	59.45	35.83	0.12	0.86
	60	45.22	0.04	37.90	0.15	5.53	1.34	4.23	58.43	36.00	0.12	0.84
240	20	54.10	0.03	33.32	0.21	5.56	1.12	4.55	56.78	37.55	0.10	0.62
	40	56.23	0.03	33.11	0.22	5.44	0.98	4.66	50.32	39.07	0.10	0.59
	60	62.44	0.02	26.71	0.23	5.32	0.87	5.23	47.10	41.52	0.09	0.43
260	20	65.54	0.02	24.64	0.26	4.12	0.75	5.45	45.01	44.37	0.08	0.38
	40	67.71	0.02	22.21	0.27	4.11	0.69	5.78	40.23	49.42	0.08	0.33
	60	67.15	0.02	22.11	0.27	4.10	0.56	5.80	38.41	49.56	0.08	0.33
Raw corncob		41.24	1.56	35.87	0.12	6.10	8.7	10.12	71.12	10.60	0.15	0.87

For the proximate analysis, on the other hand, the MC, AC, VM, and FC of the raw corncob are 8.7, 10.12, 71.12, and 10.60%, respectively, while that of the torrefied corncob, following the same order, and are in the range of 0.56–1.56, 3.1–5.80, 38.41–60.34, and 35.09–49.56%, respectively. The results revealed that temperature affects the proximate analysis component more than residence time. This observation was in line with the results of the ultimate analysis. The combustion properties of the torrefied corncob were found to increase with temperature. The MC and VM decrease as torrefaction conditions increase, even though the AC and FC increase. The AC of the entire torrefied corncob was lower than the raw. Nevertheless, the FC of the torrefied was significantly higher than the raw corncob. An increase in FC was mainly because of the increase in treatment temperature against the minor effect of the residence time. This could result from the emission of the volatile matters during torrefaction at a higher temperature. The lowest and the highest FC obtained were 49.56 and 35.09%, which are related to the highest and lowest VM (Table 1). The corncob is more thermally stable at lower treatment temperatures, as revealed by the TGA (Figure 3). The breakdown of the hemicellulose and cellulose contents begins at a temperature above 230 °C. This may account for the high VM in the samples treated at 200 °C.

3.3. Energy Density and HHV

The effect of torrefaction conditions on the energy density and HHV is shown in Figure 4. The HHV and energy density of the torrefed corncob varied between 17.26 and 18.89 MJ/kg, and 3.23 and 5.66 GJ/m^3, respectively. The energy density and HHV of the raw corncob are 3.25 GJ/m^3 and 14.1 MJ/kg, respectively. It was discovered that the highest and lowest energy density and HHV correspond to the highest and the lowest torrefaction temperature. The HHV and energy density increase with torrefaction temperature and residence time. This result was corroborated by the report of Ren et al. [25]. In their study using Camellia shell pellet as feedstock, energy density was reported to increase with torrefaction temperature. The result of HHV is traceable to the component of the proximate analysis. It was observed that higher FC gave higher HHV. This is because HHV depends on the amount of carbon available for combustion for heat to be released. The HHV recorded in this study is higher than 18.4 MJ/kg reported by Klass et al. [33] (at 300 °C) using corncob of Canadian origin. However, lower than the 23.3 MJ/kg (at 250 °C) by Lu and Chen [31] using corncob of Taiwan origin, 28.85 MJ/kg (at 270 °C) by Brigagao [29] using corncob of China origin. The variation in the results might be due to composition and structural differences associated with the corncob or the methods of torrefaction adopted. Energy density is also a function of HHV and bulk density; therefore, the higher the HHV, the higher the energy density. The torrefaction process was observed to enhance the energy density of the corncob, though energy density was observed to decrease with increasing temperature and residence time. More so, the effect of residence time was not as pronounced as that of torrefaction temperature [10,18]. When linked with the ultimate analysis results, it was discovered that the HHV increase after torrefaction due to the reduction in H and O elements in the torrefied products. C-C and C-H bonds increase after torrefaction, while O-H and O-C bonds decrease. The C-C and C-H bonds account for the energy released during combustion. Generally, HHV increases with an increase in the treatment condition, while energy density decreases. The HHV and energy density of the torrefied corncob was more than the raw corncob.
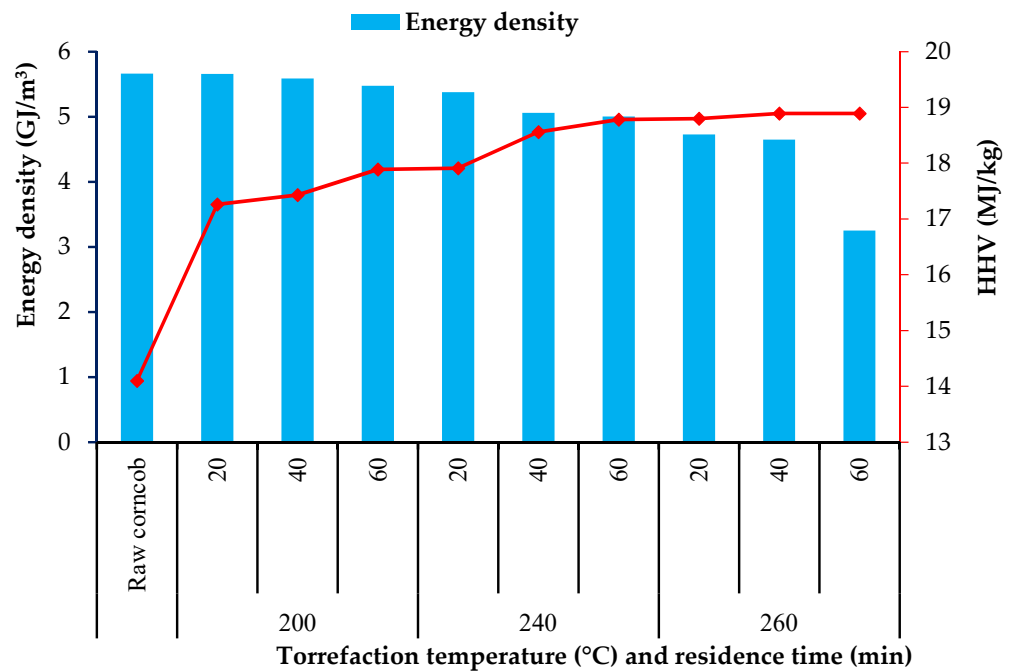

Figure 4. Effect of torrefaction conditions on the energy density and HHV.

3.4. Fuel Ratio and Degree of Torrefaction

The ratio of FC to VM (fuel ratio) and degree of torrefaction are essential parameters used to investigate the combustion characteristics of biomass. Figure 5 shows the variation of temperature and residence time with the degree of torrefaction and fuel ratio. The fuel ratio and degree of torrefaction range from 0.18 to 1.29 and 0.46 to 0.88, respectively. It can be seen from Figure 5 that the fuel ratio of the torrefied corncob is higher than the raw corncob. This is because of the liberation of volatile content in the raw corncob, which led to an increase in FC with reduced VM in torrefied corncob. The results show that the fuel ratio increases significantly with torrefaction conditions, while the degree of torrefaction decreases. This was in agreement with the report of Adeleke et al. [21] using Melina and Teak as feedstock. They reported an increase in fuel ratio with an increase in torrefaction temperature. A small fuel ratio indicates combustion with larger flam, fast burnout, and low char generation. Pretreatment via the torrefaction process produced a fuel ratio with steady and long-lasting combustion, making the fuel suitable for energy applications. Similarly, a smaller degree of torrefaction values indicated fuel with stable combustion properties. Analyses of the results show that torrefied corncob is more stable than raw corncob, especially at higher treatment conditions.
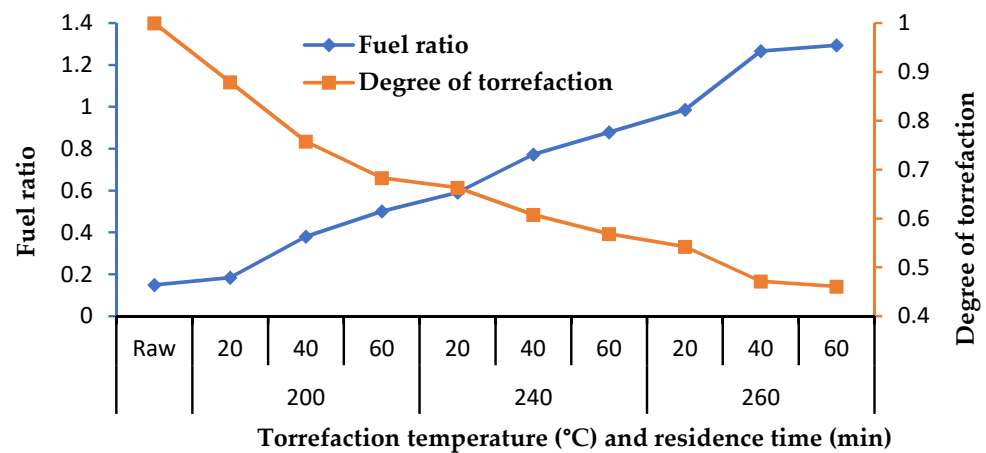

Figure 5. Variation of temperature and residence time with the degree of torrefaction and fuel ratio.

3.5. Torrefaction Product Yield

For the purpose of solid fuel application, solid yield is an essential element of determination. On the contrary, liquid and gas yield is the primary determinant factors for biodiesel or biogas production. The variation of solid yield, liquid yield, and gas yield with temperature and residence time is shown in Figure 6. The solid yield varied from 27.57 to 52.23%, while the liquid yield and gas yield varied from 31.56 to 44.78% and 16.21 to 27.65%, respectively. Figure 6 also shows that the solid yield decreases with an increase in temperature and residence time. Conversely, liquid yield and gas yield increases with temperature and residence time. Furthermore, temperature and residence time affect torrefaction yields, though the effect of temperature on torrefaction yields was more pronounced than residence time. The observation made in this study was in line with literature that revealed that solid yields decrease as the torrefaction temperature increase [11,24]. However, a contrary observation was made by Zheng et al. [26], as they reported that solid increases with temperature, while liquid and gas yields decrease. The significant reduction in the solid yield is traceable to the high VM contents of the raw corncob. During the torrefaction process, the thermal disintegration of the feedstock leads to the release of VM, which evolved as condensable and non-condensable products. The low solid yield at higher temperatures was due to the thermal breakdown of the corncob's structural components. A small solid yield was linked to high liquid yield and gas yield. The percentage of liquid collected in this study is substantial compared to gas, which revealed the potential of corncob for biodiesel production. This was in agreement with the

report of Ogunjobi and Lajide [37], who concluded that liquid fuel could be produced from corncob. The liquid collected in their study contains bio-oil and a higher percentage of polar liquid; however, the liquid received in this study contains high bio-oil with a smaller amount of polar liquid. In another study, the liquid collected ranges from 12.4 to 24.2% and 12.4 to 18.7% at 250 and 300 °C, respectively [31], which is lower than the percentage collected in this study. The variation in the product's yield could be due to methods of torrefaction and the properties of the feedstock. The liquid yield collected in this study was characterized by dark brown color and a choking smell by physical inspection.
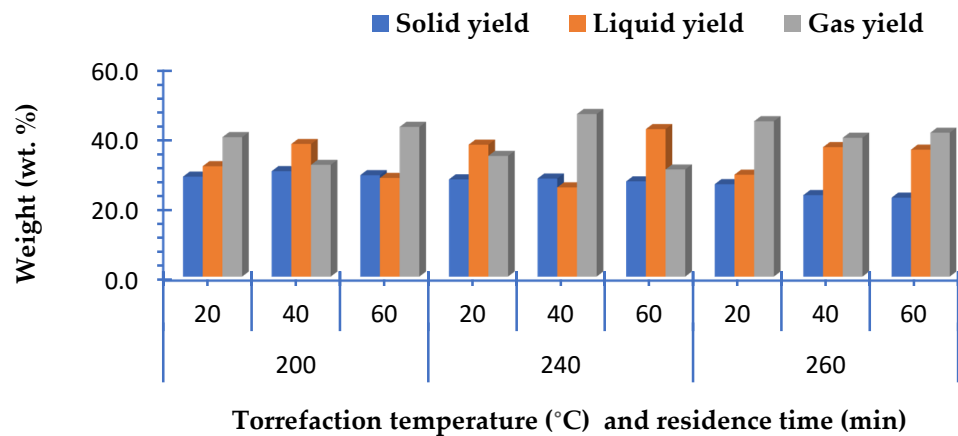

Figure 6. Variation of solid, liquid, and gas yields with temperature and residence time.

3.6. Enhancement Factor and Energy Yield

The effect of temperature and residence time on the enhancement factor and energy yield is shown in Figure 7. The highest (1.34) and the lowest (1.22) enhancement factors were achieved at 260 °C (60 min) and 200 °C (20 min), respectively. The enhancement factors increase with an increase in torrefaction temperature and residence time. Quite the reverse, the energy yields decrease with torrefaction temperature and residence time. This is because energy yield is a function of solid yield (mass yield), decreasing with increasing temperature and residence time (Figure 6). Similarly, the enhancement factor values depend on the HHV of the torrefied products, which is responsible for the observed increasing trends—HHV increases with torrefaction temperature and residence time (Figure 4). The effect of torrefaction temperature on energy yield and enhancement factor was more significant than residence time.
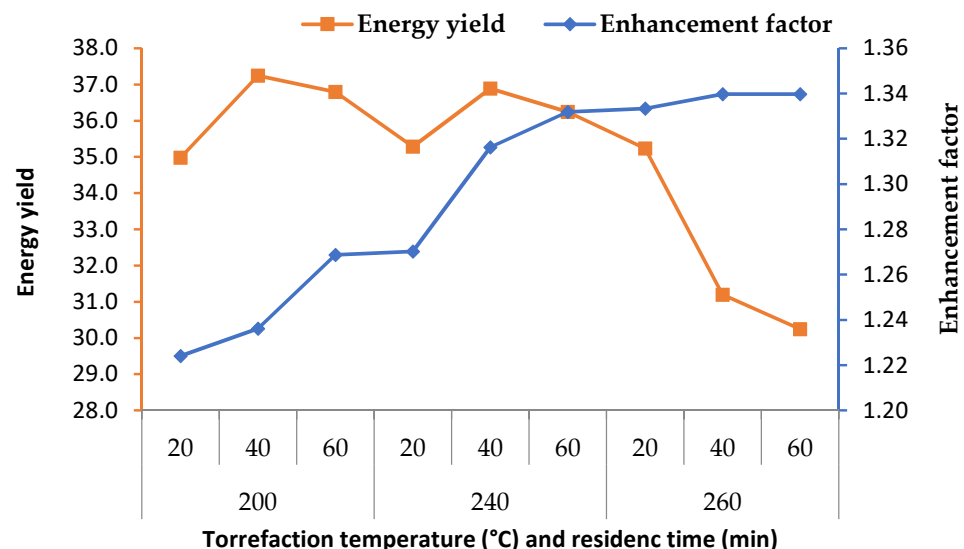

Figure 7. Effect of temperature and residence time on the enhancement factor and energy yield.

4. Conclusions

Torrefaction of corncob was carried out in this study by varying the process conditions (torrefaction temperature and residence time). The thermal and combustion characteristics of the torrefied product were investigated to determine its suitability for solid fuel applications. The torrefaction process significantly improves the thermal and combustion properties of the corncob. High torrefaction conditions lead to low solid yield; conversely, liquid and gas yields increase with torrefaction conditions. The corncob torrefied at 260 °C (60 min) displayed the best thermal and combustion characteristics. The product yields, along with their combustion properties, are significantly affected by torrefaction temperature, while the effect of residence time is negligible. The energy yield was improved due to the enhancement of higher heating properties after torrefaction. The liquid yield generated via the torrefaction process revealed that corncob could also be utilized for biodiesel production. However, the fuel properties must be investigated for liquid fuel applications. Overall, the properties of the corncob were improved after torrefaction; consequently, it can be utilized for solid fuel applications.

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