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Effect of Temperature and Residence Time on Torrefaction Characteristics of African Birch (*Anogeissus leiocarpa*)

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Abstract- In this study, the effect of temperature and residence time on African birch (*Anogeissus leiocarpa*) torrefaction characteristics was investigated. African birch trunk was procured from Aanu-Oluwapo Sawmill in Ogbomoso, South-Western Nigeria. The trunk was sawn into pieces. The pieces were machined into cylindrical samples of 40 mm diameter and 65 mm length using a wood lathe machine (Powermatic 3520B). Prepared samples were torrefied, one at a time, in an electrically heated fixed bed reactor at different torrefaction temperatures (200, 230, 260, and 290 ºC) and residence times (10, 20, 30, and 40 min). The proximate analysis of both the raw sample and solid torrefaction products was done according to the ASTM D3174-76 standard. The mass and energy yields, Higher Heating Value (HHV), and water absorption characteristic of the solid torrefaction products were then determined. Findings revealed mass and energy yields of the torrefied solid products decreased with an increase in both temperature and residence time. HHV increased with temperature but did not show any consistent pattern with residence time. The water affinity of the torrefied biomass decreased with both temperature and residence time. Torrefaction inhibits biomass moisture uptake during storage while increasing its heating value.
Keywords: Torrefaction, temperature, residence time, HHV, water absorption.

1. INTRODUCTION

The acceptance of biomass energy as a promising alternative to fossil fuels has resulted in many advancements regarding biomass conversion technologies. Aside from being available on a renewable basis, biomass is almost evenly spread across the globe, and is suitable for many biochemical and thermo-chemical conversion processes. The by-products from its conversion processes do not also threaten environmental health as those from fossil fuels. However, raw biomass possesses low bulk energy density, high moisture content, poor grindability, susceptibility to deterioration, and microbial and fungal attacks during storage. In order to extenuate these defects, thermal pretreatment of raw biomass, referred to as torrefaction, is being practiced. Torrefaction is a mild pyrolysis process within a temperature range of 200 – 300 ºC over a residence time of several minutes to few hours [1, 2].

Previous studies have shown that torrefied biomass has reduced moisture content, increased energy density, improved hydrophobicity, better resistance to microbial attacks during storage [3-6] and closely resembles coal in quality [7]. During torrefaction, parameters influencing product characteristics include temperature, heating rate, reaction time, particle size, and feedstock type [8]. Many experimental studies have investigated the effect of these parameters on biomass torrefaction [9,10,11,12]. Modelling and simulation of torrefaction have also been attempted to understand the kinetics and transport interactions during the process [1,7,13,15,16].

In most of these studies, temperature and residence time effects on the water absorption characteristic of the torrefied sample was not reported. The wood samples used were not also typical of West Africa.

Therefore, in this study, the effects of torrefaction temperature and residence time on mass and energy yield, Higher Heating Value (HHV), and water absorption characteristics of African birch (*Anogeissus leiocarpa*) were investigated.

2. MATERIALS AND METHODS

2.1 Sample procurement and processing

African birch trunk was obtained from Aanu-Oluwapo Sawmill in Ogbomoso, South-Western Nigeria. The trunk was sawn into pieces. The pieces were machined into cylindrical samples of 40 mm diameter and 65 mm length by using a wood lathe machine (Powermatic 3520B) at the sawmill.

2.2 Experimental set-up

A fixed bed reactor, electrically heated, was set up for the experiments. The reactor consists of a furnace chamber, which houses a cylindrical retort, charged with the raw sample to be torrefied. A temperature controller, fed by signals from a thermocouple buried in the reactor, controls the bed's temperature. Two traps were used to trap the released condensable volatiles during the process. Figure 1 shows the exploded view of the reactor for the torrefaction process.

2.3 Experimental procedure

The biomass samples prepared were placed, one at a time, inside the retort in preparation for a run. The reactor was connected to the mains and set at an initial temperature value of 230 ^oC (30 ^oC higher than the desired temperature) in compensation for the heat loss due to retort insertion. When the reactor temperature attained the preset temperature of 230 ^oC, the reactor was opened. The retort was then placed in it. The reactor temperature then fell steadily towards 200 ^oC due to the heat absorbed by the retort and heat loss by convection. The reactor temperature was then set to 200 ^oC, and the sample was heated steadily for 10 min. The torrefied sample was taken out of the reactor after the specified time and cooled before its mass was measured. This procedure was repeated for other biomass samples at 20, 30, and 40 min. The entire process was followed for torrefaction temperatures of 230, 260, and 290 ^oC.

2.4 Proximate analysis

The proximate analysis of the raw sample and torrefied solid products was carried out according to the ASTM D3174-76 standard. The HHV of the raw sample and torrefied solid products were estimated according to [17] as expressed by equations 1 and 2, respectively.

$$HHV_{\text{raw}} = 0.1708\,VM + 0.3543FC \qquad (1)$$

$$HHV_{\text{torrefied}} = 0.1846\,VM + 0.3525FC \qquad (2)$$

Where *VM* and *FC* are the volatile matter and fixed carbon, respectively.

2.5 Determination of Mass and Energy Yield

Mass and energy yield after torrefaction were determined on a Dry Ash-Free (DAF) basis according to equations 3 and 4, respectively [18].

$$Mass\ yield = \frac{Mass\ of\ torre.\ biomass\ on\ DAF\ basis}{Mass\ of\ dried\ biomass\ on\ DAF\ basis} \times 100\% \qquad (3)$$

$$Energy\ yield = \frac{Product\ mass \times HHV_{product}}{Raw\ feed\ mass \times HHV_{raw}} \times 100\% \qquad (4)$$

2.6 Water absorption

To study the effect of torrefaction on biomass water absorption characteristic, the weight of selected raw samples, and their corresponding torrefied solid products were measured. These were then submerged simultaneously to the same depth in 5 liters of water for 24 hours. The samples were then taken out of the water, and their weight was measured and recorded. The weight of water absorbed was determined according to equation 5, given as

$$Weight\ of\ water = Ws2 - Ws1 \qquad (5)$$

Where $Ws1$ and $Ws2$ are the weight of the sample before and after immersion, respectively.

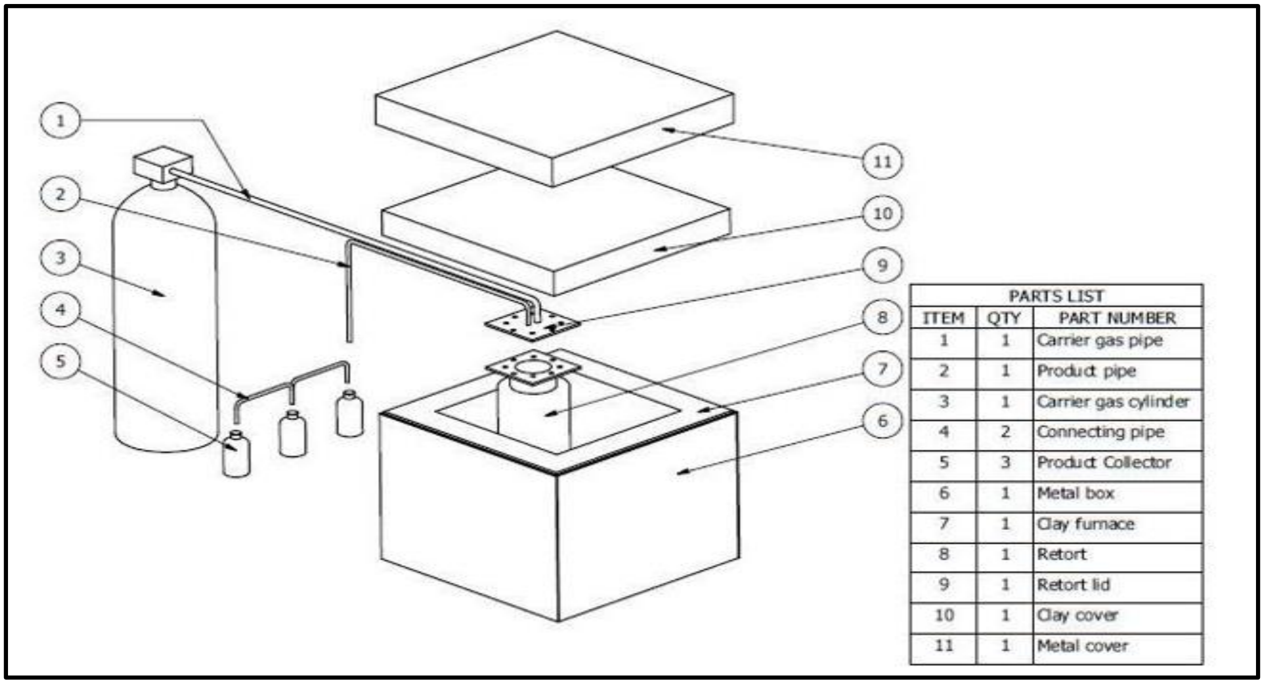

Figure 1: Exploded view of torrefaction fixed bed reactor

3. RESULTS AND DISCUSSION

3.1 Proximate analysis

Table 1 shows the proximate analysis of both the raw sample and torrefaction solid products. From the table, it can be seen that at 200 ^{o}C, percentage moisture content decreased with increase in residence time. However, this decrease did not follow any definite pattern. Also, at 200 and 230 ^{o}C, the percentages of fixed carbon and volatile matter at all residence times are not significantly different from those of the raw sample. However, as expected, the percentage moisture content decreased in compared to that of the raw sample. For 260 and 290 ^{o}C, the percentage of fixed carbon and ash increased while volatile matter decreased. At all temperatures and residence times considered, the ash content in the torrefaction products was higher than that of the raw sample. These results are in agreement with the findings of [19]. Figure 2 shows the variation of HHV of torrefied biomass at different temperatures and residence times. As shown in Figure 2, HHV generally increased with temperature [19] but did not show any definite pattern with change

in residence time. This may be due to not too distant residence times used.

Other researchers have reported some slight increase in HHV with residence time [19]. However, at 260 ^{o}C, HHV does not show any appreciable response to increased residence time.

3.2 Effect of temperature and residence time on mass and energy yield

Figure 3 shows the mass yield of solid torrefaction products at different temperatures and residence times. As shown in Figure 3, mass yield decreased with both temperature and residence time. An increase in temperature and residence time implies a higher degradation, which is usually associated with a greater release of biomass organics containing water, acetic acid, lactic acid, formic acid and furfural [18], hence the decrease in mass yield. These findings are in agreement with [19] and [20]. Figure 4 shows the energy yield of solid torrefaction products at different temperatures and residence times. From Figure 4, although no definite pattern at residence time of 10 min, energy yield generally decreased with temperature and residence time.

Table 1: Proximate analysis of the raw sample and torrefaction solid products

Temperature (ºC)	Time (min)	FC (%)	VM (%)	Ash (%)	Moisture content (%)
200	10	18.92	72.46	0.78	7.59
	20	25.54	69.58	1.06	3.82
	30	19.12	71.04	0.84	3.94
	40	18.24	70.69	0.67	4.11
230	10	25.19	70.25	0.85	3.71
	20	17.88	70.18	0.87	3.71
	30	24.15	71.47	0.33	3.75
	40	28.15	67.05	1.01	3.79
260	10	71.73	22.85	2.21	3.21
	20	70.60	23.65	2.31	3.44
	30	70.78	23.64	2.23	3.35
	40	70.43	23.76	2.42	3.36
290	10	71.65	22.78	2.26	3.39
	20	25.27	69.84	0.92	3.97
	30	69.81	24.56	2.34	3.29
	40	69.65	24.56	2.37	3.42
Raw sample		24.35	70.18	0.45	5.02

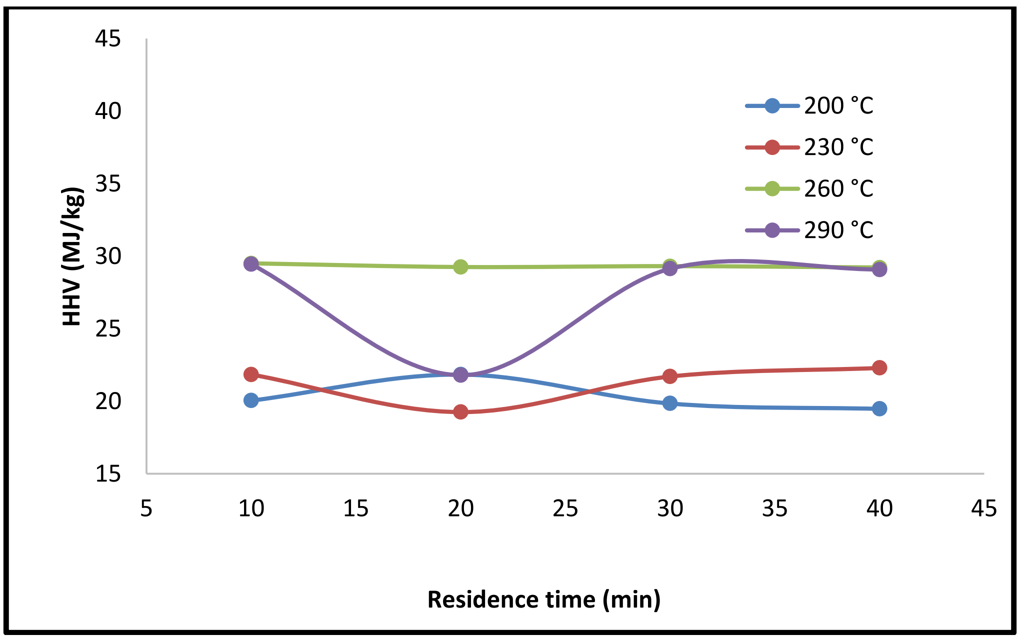

Figure 2: HHV at different torrefaction temperatures and residence times

The decrease in energy yield with temperature is in agreement with the findings of [1] and [20]. The decrease in energy yield with residence time agrees with the findings of [23], who reported that mass and energy yields of biomass decreased with operating temperature and torrefaction residence time.

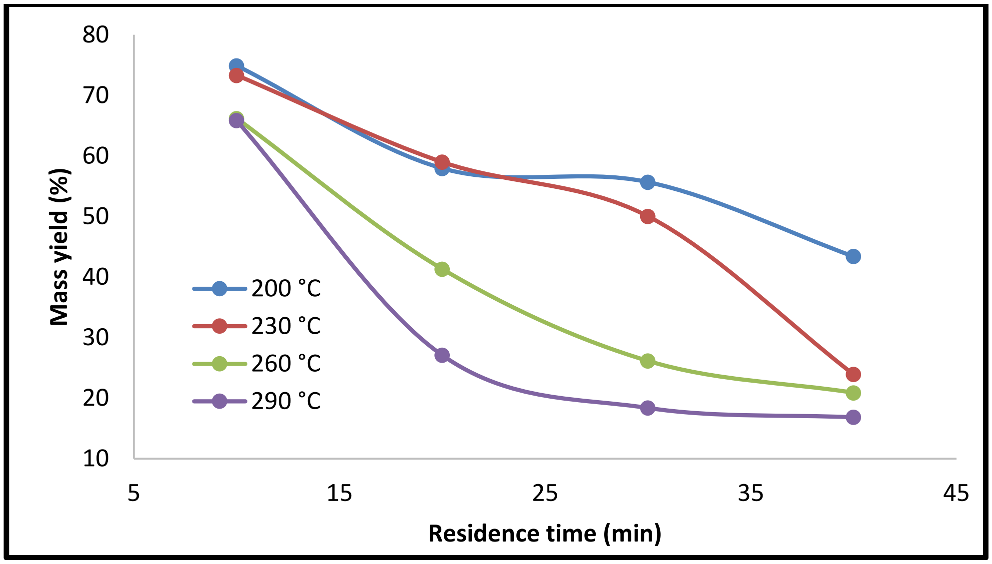

Figure 3: Mass yield at different torrefaction temperatures and residence times

3.3 Effect of temperature and residence time on water absorption

Figure 5 shows the effect of temperature and residence time on the solid torrefaction products water absorption characteristics. From Figure 5, it can be seen that the weight of water absorbed by the torrefied solid

decreased with both temperature and residence time. This implies wood, which is naturally hydrophilic, becomes hydrophobic, and the degree of hydrophobicity increases with torrefaction temperature and residence

time. This is in agreement with the findings of [21], who reported that wood wettability change during heat treatment is more probably due to the plasticization of the lignocellulosic polymeric components of wood. Although the relation between hydrophobicity and fungi growth cannot be established, the chemical modification and degradation during torrefaction have been responsible for improved durability of torrefied solid products [22].

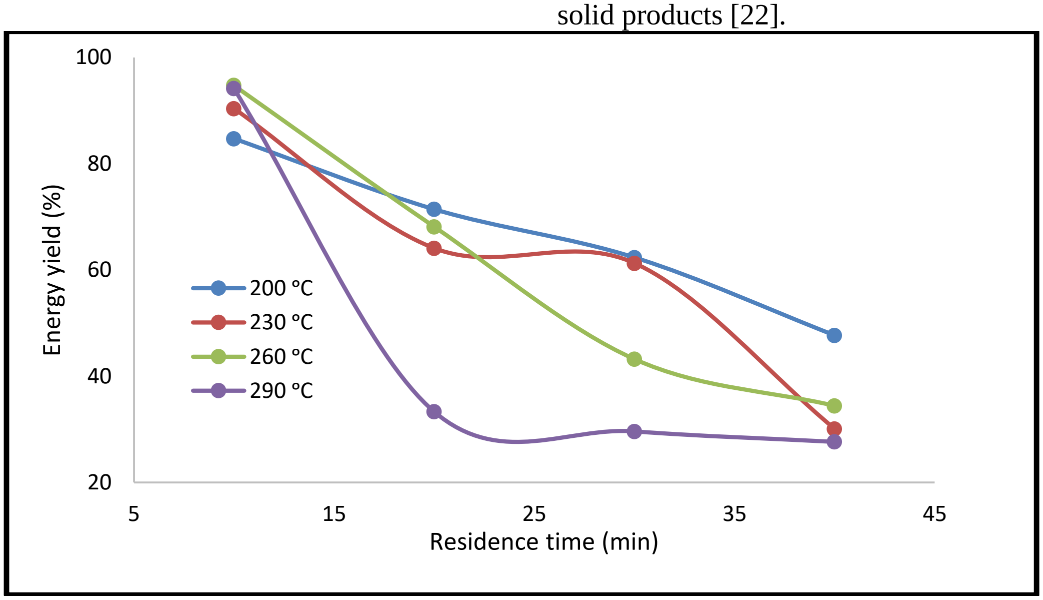

Figure 4: Energy yield at different torrefaction temperatures and residence times

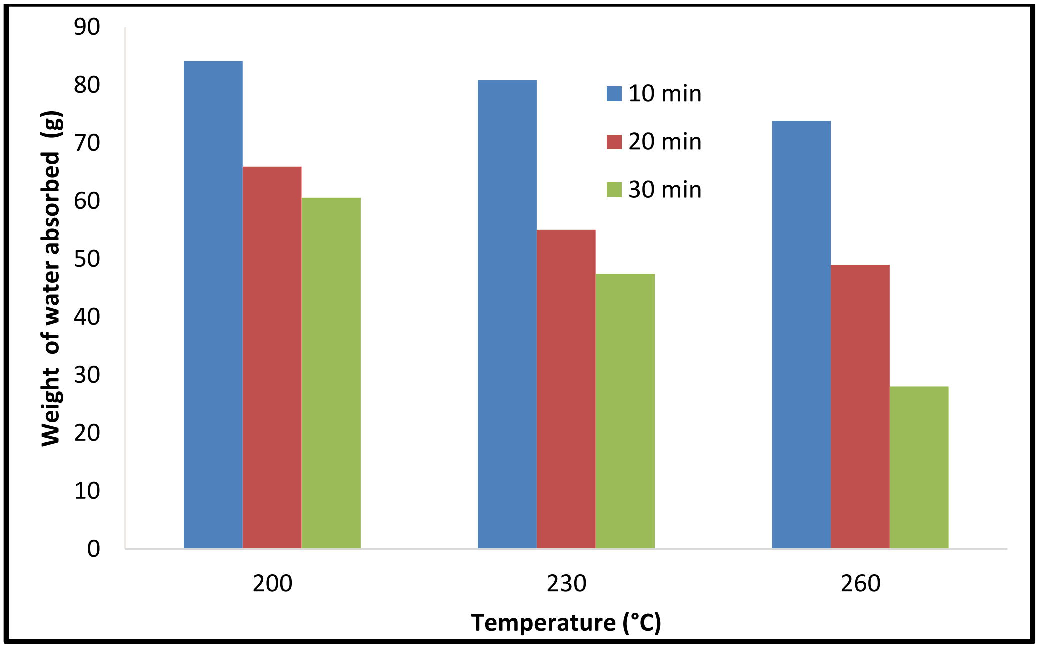

Figure 5: Water absorption of solid torrefaction products

4. CONCLUSION

Effects of temperature and residence time on torrefaction characteristics of African birch were investigated. Mass and energy yields decreased with increase in temperature and residence time. On the other hand, HHV increased with temperature but did not show any definite pattern with residence time. Results also showed that torrefaction limits water absorption in the solid torrefaction products. The degree of hydrophobicity increased with temperature and residence time. In all, the effect of temperature on the torrefaction characteristics of the woody biomass used was higher than that of residence time.

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