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Torrefaction of non - oil *Jatropha curcas L.* (*Jatropha*) biomass for solid fuel

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ABSTRACT

The use of non-oil *Jatropha* biomass in the energy mix as a solid fuel offers the most effective ways of utilising such resource. However, available information indicates that biomass has negative inherent properties which lower its fuel value. This negative effect can be improved by slow pyrolysis process called torrefaction where the biomass is heated in the range of 200 °C to 300 °C. In the present investigation the effects of torrefaction temperature on the solid fuel value of different *Jatropha* biomass materials were determined. Consequently, three types of *Jatropha* biomass namely; seed cake, stem and fruit cover were considered under five temperature levels (200 °C, 225 °C, 250 °C, 275 °C, 300 °C). Analysis of Variance (ANOVA) revealed that there were significant differences ($P > 0.05$) in bulk density, hygroscopicity, energy content and ultimate etc. The statistical analysis results indicated that there was biomass type and torrefaction temperature interaction effects on the ultimate analysis, bulk density, hygroscopicity, energy content and energy yield. The interaction effects of the factors under investigation were not observed in mass yield. Increase in torrefaction temperature generally reduced the equilibrium moisture content and volatile matters across the biomass types. However fixed carbon, carbon content, ash content and energy density were increased across the biomass types as the temperature was increased from 200 °C to 300 °C. The torrefied *Jatropha* seed cake biomass showed relatively enhanced fuel characteristics than the torrefied stem and the torrefied fruit husk when considering the properties under investigation.

1. Introduction

Jatropha curcas L. (*Jatropha*) plant is a drought tolerant shrub that thrives under various soil and climatic conditions [1, 2]. It is native to Mexico and Central America, but now grows widely throughout the tropics and other areas in Latin America, Africa, India and South-East Asia [3, 4]. It is globally gaining recognition as intensive research is being undertaken on its potential as a feedstock for biodiesel production [5]. In addition, the species is non - edible. Consequently, its use in biodiesel production would not compete directly with food production [1, 6]. Based on this observation Botswana government started a *Jatropha* plant research project in 2011. This was a collaborative effort between Japanese and Botswana governments [7]. This was considered vital because Botswana does not have sufficient petroleum deposits to satisfy her energy demand. The use of oil from the *Jatropha* plant for biodiesel production in Botswana is expected to generate huge non-oil biomass waste, posing disposal problem.

An alternative and effective way of sustainably use of non-oil biomass material is to use it as a solid fuel [8, 9]. The non-oil *Jatropha* biomass waste comprises of seed cake, stems and branches, fruit shell and seed cover which could be recovered during *Jatropha* biodiesel processing. The non-oil biomass has inherent properties which lower its fuel value. Such properties include hydrophilic, high moisture content, low bulk density, low carbon content, high volatile matter and low calorific value [10, 11, 12, 13]. The torrefaction processes, involve heating biomass from 200 °C to 300 °C [5, 6, 14]. The torrefaction processes mainly produce the solid product of torrefied biochar which is suitable for use at household level and public institutions for thermal energy. The approach has huge potential for replacing non-renewable fuels such as coal. Available information indicates that torrefaction processes improve energy density, grindability, hydrophobicity of a solid fuel [6, 17, 18]. The hydrophophic characteristics of the torrefied biomass are influenced by loss of hydroxyl groups (OH) [11, 18]. Available information also indicates that transportation of torrefied solids is relatively less expensive due to the reduction in moisture content [17]. Biomass fuel is highly heterogeneous and its quality depends on the types of feedstock, climatic variation, harvest season, and storage condition [18, 19, 20]. These variability in biomass affects its fuel value due to its non-uniform

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properties. The torrefaction processes therefore improve the uniformity of biomass by removing moisture and volatile matters resulting in a more uniform fixed matter of stable quality [13, 20, 21].

The conditions of biomass and torrefaction processes influence the quality of the torrefied biochar. The advantage of treated and characteristics of torrefied biomass were emphasized by Medic et al [22] who worked with different maize stalk parts. This was also emphasised by Zanzi et al. [23] who echoed that torrefaction conditions strongly determine the char yield and its reactivity in combustion. Several authors also reported that the torrefied biochar yield and quality are highly affected by the biomass feedstock and the torrefaction temperature. For all the torrefaction conditions, the torrefaction temperature level has relatively more influence on the products as low final temperature maximizes the torrefied biochar yield while high temperature conditions enhances gas yield [29]. Generally torrefaction of biomass results in reduction of mass and energy yield and increased energy density of solid fuel [18, 21, 30]. The reduction in mass and energy yield is associated with relative oxygen and hydrogen loss as compared to carbon [6]. The situation then results in increased heating value of the solid fuel. The biomass type also have influence on the torrefaction products. This was emphasised by Deng et al. [30] who carried out torrefaction of rape stalk and rice straw at 250 °C and reported difference in mass yields. The authors concluded that the difference was due to their difference in lignocellulose composition. Chen et al. [21] torrefied bamboo, willow, coconut shell and *Ficus benjamina L* wood at 240 °C and 270 °C and found out that the feedstock materials responded differently across the torrefaction temperature levels. Medic et al. [22] demonstrated that biomass from different parts of a plant can respond differently under torrefaction processes. The authors further reported that at torrefaction temperature of 250 °C the dry matter loss of corn stalk pith and corn cob were significantly different from corn stalk shell sample. They concluded that the differences could be due to difference in hemicellulose content and particle density.

The information on the torrefaction of *Jatropha* biomass is limited [6, 34]. Most available information appears to be on de-oiled seed cake. The situation therefore stimulated the present investigations on torrefaction of *Jatropha* biomass such as the fruit husk and the stem. The main objective of the present study was to investigate the effects of torrefaction temperature levels and biomass type on the fuel characteristics of non-oil *Jatropha* biomass.

2. Materials and methods

2.1. Sample material source and preparation

The sample preparations were similar to the ones described by Kethobile et al. [31]. Consequently, sample preparations will not be presented in details in this section. However, the geographical coordinates of the plantation where sample materials were sourced are 24°34′25″ S and 25°58′0″ E [31]. The *Jatropha* material planted in the plantation was initially collected from the homesteads in Botswana and the origins of the plant species are not known. The germplasm is therefore loosely called Botswana's variety. The jatropha stem sample were products of pruning which were collected before 2018 winter season (May–August). This was undertaken as one of the measures to avoid cold season. The stems pruned were about a year old and 1–3 cm thickness. The fruit husk and seed cake samples were byproducts of oil extraction. The biomass were then individually prepared as described by [31].

2.2. Torrefaction of biomass

The non-oil *Jatropha* biomass samples were torrefied using a Yamoto Electric furnace FO310. The furnace was purged with nitrogen gas for 2 min prior to test run to ensure oxygen free environment. This was then followed by heating the furnace to 25 °C for settling purposes. About 2.0 g of each samples were put inside a crucibles before placing them in the middle of a furnace. A nitrogen gas flowing at 2 mL/min was then supplied to the furnace during the experimental runs in order to maintain an inert atmosphere. The samples were then heat-treated at 5 °C/min starting from 25 °C up a predetermined torrefaction temperature from 200 to 300 °C at a small incremental of 50 °C. When the target temperature was reached, the experimental conditions were maintained according to Peng et al. [33]. The experimental runs were set to run for 1 h in order to limit de-volatilization of biomass and maximize torrefied charcoal yield [25, 34]. However, nitrogen gas was supplied to the furnace until the temperature dropped to about 100 °C. The furnace was then opened at the end of each experimental run in order to speed up the cooling processes. The samples were then removed from the furnace and allowed to cool to room temperature before their mass was recorded. The torrefied samples were then transferred to airtight container until subsequent analysis were carried out. The pre and post torrefaction weights were recorded in order to determine mass yield according to Bergman

Table 1. Properties of different *Jatropha* biomass material [31].

Properties		Biomass types		
		Seed Cake	*Jatropha* stem	*Jatropha* fruit husk
Lignocellulose (%)	extractives	6.41	0.65	1.40
	hemicellulose	7.99	16.83	6.26
	Lignin (ADL)	18.08	19.72	4.63
	cellulose	26.21	40.09	47.70
Proximate (%)	Moisture content	4.56	8.09	6.98
	Volatiles	65.47	64.93	57.12
	Fixed carbon	24.88	19.65	17.41
	Ash	5.04	7.29	18.33
Ultimate (%)	Carbon	46.15	43.68	36.05
	Hydrogen	6.47	6.32	5.37
	Nitrogen	4.48	1.33	1.07
	Sulphur	0.20	0.21	0.37
	Oxygen	42.71	48.46	57.15
Bulk density (g/cm^3)		0.75	0.20	0.37
Hygroscopicity		34 .92	60.13	47.59
Energy (MJ/kg)		19.28	18.39	13.57

et al. [18]. The furnace was then left to cool down to 25 °C before prior to subsequent test run. This was done to assure repeatability of tests run. The same experimental procedures were repeated three types by charging the furnace with a new batch at a time. Enough torrefied samples were produced in order to investigate other fuel characteristics including proximate analysis, ultimate analysis, energy content, bulk density and hygroscopicity analysis.

2.3. Characteristics of the torrefied Jatropha biomass material

Factors which influence fuel characteristics covered in this investigation were proximate components, elemental composition, bulk density, hygroscopicity and higher heating value (HHV). Methods and procedures similar to the one described by Kethobile et al. [31], were followed. Consequently, the determination of these factors will not be presented in details in this section. However, for energy analysis the gelatine capsules were used to hold the biomass samples because they were light and powdery after torrefaction. They also showed signs of explosive behaviour when combusted without gelatine capsules. The spike mass and value were therefore determined first to correct for the mass and energy value emanating from the combustion of the gelatine capsules. This was done by recording the mass and the HHV of an empty gelatine capsules before filling them with the sample material. The estimation of the spike value and mass were repeated three times in order to obtain average values which were used throughout the experiment. The spike mass was then recorded as 0.1214g while the spike value was 17.97 kJ which were the correction values for mass and energy due to the combustion of the capsules. The measurements were repeated three times and the IBM SPSS 24 [45] statistical software was used for analysis of variance (ANOVA) for the data generated and the means were compared using the Least Significant Difference (LSD).

3. Results and discussion

3.1. Fuel properties of torrefied Jatropha biomass

The characteristics of the raw *Jatropha* biomass samples under investigation from our previous investigation [31] are summarised in Table 1. The results were compared with the results in Table 2 and Figures 1, 2, 3, and 4 to show how torrefaction at different temperature levels influenced the fuel value of the *Jatropha* biomass samples under investigation.

The analysis of variance revealed that the effects of biomass type was significant (P < 0.05) on the proximate analysis, ultimate analysis, bulk density, energy content and hygroscopicity of the torrefied *Jatropha* biomass samples under study except the mass yield. The effect of the torrefaction temperature level in all the parameters under investigation was significantly different (P < 0.5) amongst all the biomass types under study. It also showed that there was biomass type - torrefaction temperature interaction effect in all the parameters under investigation except mass yield. The separation of means which showed no significant difference (P > 0.05) are shown by the same symbol in Table 2 as indicated by footnote 2 below Table 2. This was done in order to minimise the size of the table and also make the presentation less complex.

3.1.1. Proximate analysis

The proximate analysis of a solid fuel is important for prediction of its combustion properties such as burning patterns, ash load and emissions. The results on proximate analysis are summarised in Table 2. The results show that the equilibrium moisture content (EMC) of the torrefied fruit husk (3.1%) was significantly higher (P < 0.05) than of the torrefied seed cake (1.9%) but significantly similar (P > 0.05) to the equilibrium moisture content of the torrefied stem (2.3%). The difference in

Table 2. Effect of biomass type and torrefaction temperature on the fuel properties of non-oil *Jatropha* biomass.

Biomass Sample		Proximate (%)				Ultimate (%)				Energy parameters				Bulk density (g/cm³)	Hygroscopicity (%)
Biomass type	Temp (°C)	[1]EMC	VM	FC	Ash	C	H	N	O	Energy (kJ/g)	Energy ratio	Mass yield (%)	Energy yield (%)		
Seed cake	200	2.7	63.4	23.1	10.9	49.9	6.8	4.7	38.5	19.9	1.03	96.0	99.1	0.63	26.20
	225	2.5	61.8	24.5	11.3	51.7	6.7	4.9	36.6	20.5	1.07	94.0	100.1	0.62	26.10
	250	2.1	58.4	26.1	13.5	53.7	6.7	5.1	34.6	21.0	1.09	89.3	97.1	0.59	22.56
	275	1.2	45.1	33.3	20.5	56.3	6.4	5.1	32.2	21.7	1.12	68.5	77.0	0.44	18.23
	300	1.2	38.4	39.6	20.8	60.8	6.2	4.6	26.5	25.0	1.30	62.6	81.2	0.55	15.36
	Average	1.9*[2]	53.4	29.3	15.4 *	54.5	6.6	4.9	34.1	21.6		82.6*	90.9*	0.56	21.69
Stem	200	3.7	66.5	16.5	13.3	47.2	6.4	1.3	45.1	17.4	0.94	95.4	75.2	0.16	64.11
	225	2.6	66.2	17.1	14.2	48.5	6.3	1.4	43.9	18.6	1.01	86.8	79.2	0.15	61.56
	250	1.9	65.4	18.3	14.5	50.6	6.2	1.4	41.8	18.7	1.02	72.1	73.4	0.15	55.03
	275	1.8	52.6	28.9	16.7	54.9	5.6	1.9	37.6	18.9	1.03	77.0	87.7	0.14	41.22
	300	2.0	45.5	34.9	17.6	54.1	5.4	2.4	38.1	21.1	1.15	65.5	90.1	0.14	26.20
	Average	2.3	59.2	22.8	15.3*	51.0	6.0	1.7	41.3	18.9		79.5*	81.1	0.15	49.62
Fruit husk	200	4.4	56.0	19.1	20.4	39.1	5.6	0.9	54.3	13.5	1.00	92.7	92.4	0.31	48.06
	225	3.4	53.7	20.9	22.0	40.6	5.5	1.1	52.8	13.6	1.00	82,7	83.2	0.29	44.88
	250	2.8	48.7	24.0	24.5	42.4	5.4	1.1	51.0	13.8	1.01	83.0	84.4	0.27	39.26
	275	2.5	37.7	33.5	26.3	46.0	4.8	1.3	47.9	20.1	1.48	72.5	107.4	0.36	31.17
	300	2.3	35.0	36.9	26.6	47.9	5.0	1.3	45.8	24.8	1.83	65.3	107.9	0.24	25.52
	Average	3.1*	46.2	24.8	24.5	43.2	5.3	1.1	50.4	17.2		79.3*	89.0*	0.29	37.78
Temperature averages (°C)															
200		3.6	62.0	19.2	14.9 *	45.4	6.3	2.3	46.0	16.9		93.9	94.7	0.37	46.12*
225		2.8	60.6	20.6	15.8 *	46.9	6.2	2.5	44.5	17.6		90.3	87.9	0.35	44.18*
250		2.3	57.6	21.6	18.4	48.9	6.1	2.5	2.5	17.8		85.0	83.7	0.33	38.95
275		1.8*	45.2	30.9	21.2 #	53.3	5.6	2.7	39.3	20.2		87.9	70.7	0.31*	30.30
300		1.7*	29.6	35.7	21.7 #	54.4	5.5	2.7	37.5	23.7		70.7	64.4	0.31*	22.36

[2,*,#] The means with the same symbol were not significantly different (P > 0.05).
[1] EMC stands for Equilibrium Moisture content, VM stands for Volatile Matter, FC stands for Fixed Carbon.

equilibrium moisture content of the torrefied stem and the torrefied seed cake were insignificant (P > 0.05). This demonstrates that the torrefaction process brought the equilibrium moisture content of the seed cake closer to of the stem. It also reduced the gap between the equilibrium moisture content of the fruit husk and stem when compared to the results in Table 1. The results in Table 2, in comparison to the results of raw biomass in Table 1 show that the torrefaction processes reduced the equilibrium moisture content by 56%, 71% and 32% for the fruit husk, stem and seed cake respectively. The reduction in EMC is credited to the devolatisation, depolymerisation and dehydration process which liberated moisture and volatile matter from the biomass [46]. The reduction in equilibrium moisture content is consistent with the findings by Tumuluru et al. [19] who reported that the torrefaction process reduces the equilibrium moisture content of the biomass to 1–3%. The decrease in EMC during torrefaction processes results in relatively high calorific value of the biomass fuel when compared to its raw form. The fuel value of the torrefied biomass is also elevated as the emissions are reduced during combustion [14]. The reduction in moisture content in all the biomass types is specifically attributed to hydroxyl groups (OH) destruction during homocellulose decomposition [11, 21, 47]. This inhibits hydrogen bonding with water molecules, so that the torrefied biomass tends to be more hydrophobic [18, 47]. It could therefore be presumed that the torrefaction process considerably reduced the ability of biomass samples to absorb moisture from the surroundings. The reduced moisture levels in torrefied biomass samples make it suitable for energy conversion processes such as gasification and pyrolysis [48]. The results in Table 1 also indicate that the stem (8.1%) had the highest equilibrium moisture content followed by fruit husk (7.0%) and the seed cake (4.6%). However, after the biomass materials underwent torrefaction processes the order changed. The torrefied fruit husk recorded relatively high equilibrium moisture content followed by the torrefied

stem and the torrefied seed cake as presented in Table 2. This could be attributed to the loss of extractives in the fruit husk during torrefaction. The extractives are reported to reduce the equilibrium moisture content in biomass material [49, 50] and therefore once they are destroyed, the plant biomass material easily absorbs moisture from the soundings.

The results in Table 2 also show some torrefaction temperature effects irrespective of biomass type. The results show that there was a significant difference (P < 0.05) in the levels of moisture in the biomass sample at different torrefaction temperature levels. However there was no significant difference (P > 0.05) in equilibrium moisture content between 275 °C and 300 °C torrefaction temperature levels. This might indicates that the torrefaction of the *Jatropha* biomass samples under investigation at temperature above 275 °C did not results in the reduction of equilibrium moisture content, even though the moisture content in the plant sample materials decreased with an increase in the torrefaction temperature levels.

The results in Figure 1(a) illustrate the effects of biomass type - torrefaction temperature on the equilibrium moisture content. The Figure shows that the profiles of the torrefied biomass types were not parallel to each other. This indicates that there was a biomass type - torrefaction temperature effects on the equilibrium moisture content. However, the interaction effect is more pronounced in the torrefied seed cake and torrefied stem. Their profiles intersected at around 225 °C and around 255 °C suggesting that they behaved differently at torrefaction temperature levels. This is also demonstrated by results in Table 2 which displays that the equilibrium moisture content values at 225 °C for stem (2.6%) and seed cake (2.5%) were almost the same. A similar deduction could be made about their values at 255 °C as they were approximately 2.0%. The equilibrium moisture content profile in Figure 1 (a) also show that at low torrefaction temperatures (<250 °C), the equilibrium moisture content gradually reduced at faster rate in the stem and the fruit husk
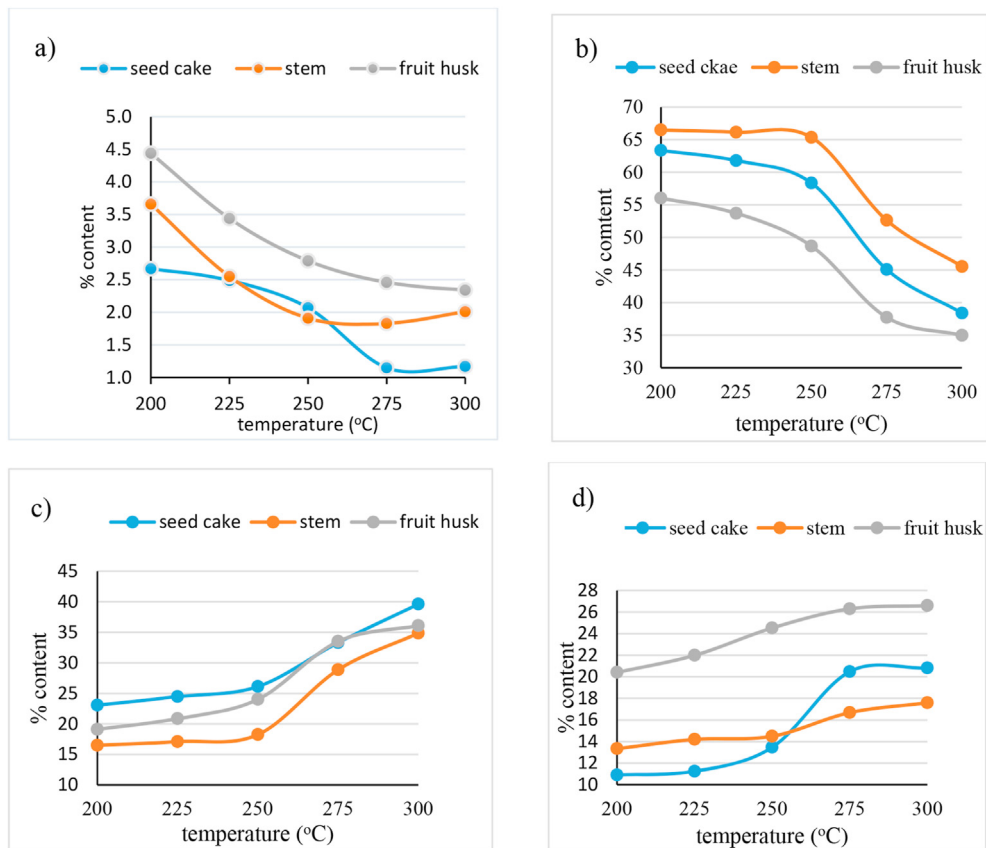
Figure 1. Biomass type - torrefacftion temperature interaction effects on a) equilibrium moisture content b), volatile matter content, c) fixed carbon content, d) ash content of seed cake, stem and fruit husk.
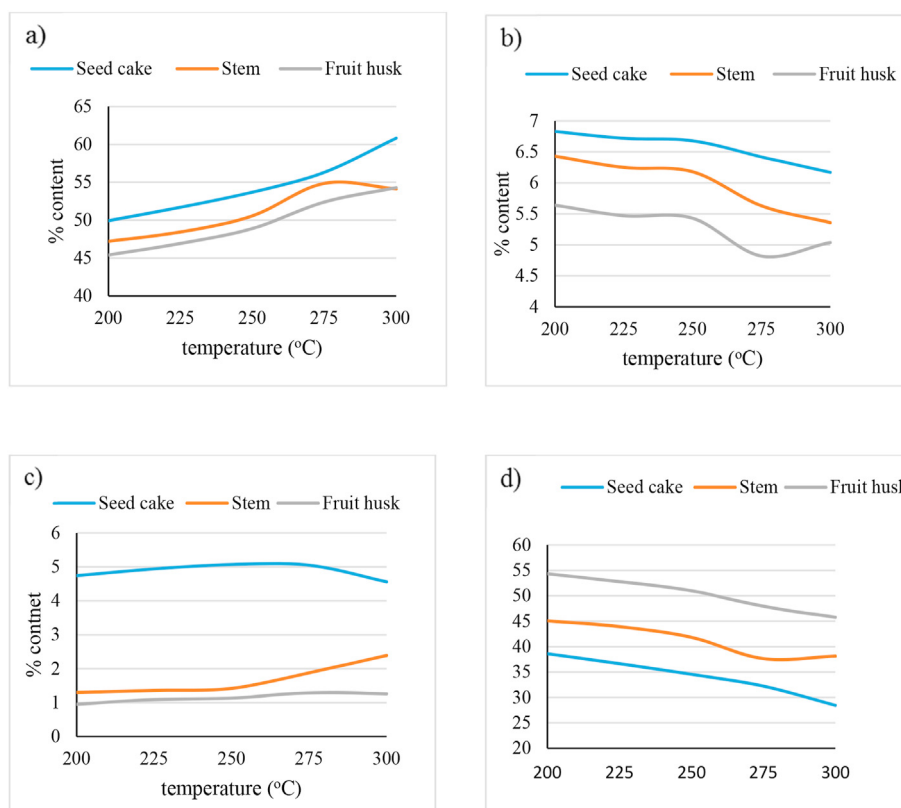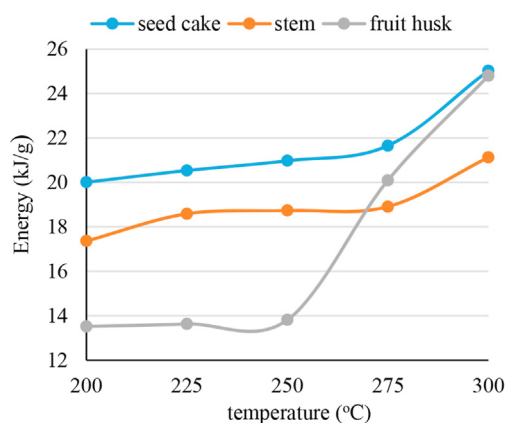
Figure 2. Effects of biomass type - torrefaction temperature on the a) carbon, b) hydrogen, c) nitrogen and d) oxygen composition of torrefied *Jatropha* seed cake, stem and fruit husk.
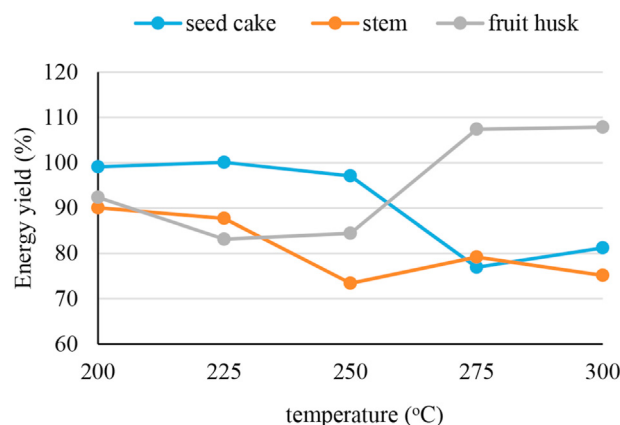
than the seed cake. However, at temperature range from 250 °C to 275 °C the equilibrium moisture content in the seed cake reduced at faster rate while the equilibrium moisture content for the stem and the fruit husk became relatively constant. This indicates that torrefaction processes were more effective in seed cake at the same temperature range. This is likely to be due to the differences in bulk density as illustrated by Figure 4 in Section 3.1.4. It seems that above 275 °C the stem's equilibrium moisture content increased whereas in the fruit husk the moisture content remained constant. This could be attributed to an increase in porosity and hygroscopic characteristic of biomass as torrefaction temperature was raised [51]. The equilibrium moisture content profiles appears to suggest that the ideal torrefaction temperature to reduce the equilibrium moisture content from the seed cake was 275 °C and 250 °C for both stem and fruit husk. Overall the results suggest that these were

the temperatures at which the profiles started to become constant indicating that torrefied biochar contained relatively small amount of moisture.

The results in Table 2 also indicate that the volatile matter (VM) in the torrefied stem was highest (59.2%) followed by the seed cake (53.4%) and the fruit husk (46.2%). This shows a reduction in volatility of 18.4%, 8.8% and 19.0% for seed cake, the stem and the fruit husk respectively in contrast to the values of raw biomass samples presented in Table 1. This could also be due to the devolutisation and depolymerisation processes as stated earlier in this section. The reduction in VM in torrefied biochar could also be due to the loss of the extractives and decomposition of hemicellulose during torrefaction process. The volatile matter in torrefied biomass shows some change in trend when compared to results presented in Table 1. In fact in Table 1, the difference in volatiles

Figure 3. Effects of biomass type – torrefaction temperature on the energy content of *Jatropha* seed cake, stem and fruit husk.

Figure 4. Effects of biomass type - torrefaction temperature on the energy yield of *Jatropha* seed cake, stem and fruit husk.

between the seed cake (65.47%) and the stem (64.93%) were insignificant (P > 0.05). However the volatile matter in seed cake (53.4%) reduced significantly after torrefaction as it was now statistically different (P < 0.05) from both the stem (59.2%) and the fruit husk (46.2%). This could be attributed to the loss of extractives in seed cake during torrefaction as they largely contributed to its volatility in its raw form. The volatile matter was also significantly different (P < 0.05) across the torrefaction temperature levels irrespective of biomass sample types. The results in Table 2 indicate that as the torrefaction temperature levels increased, the volatiles got reduced.

The biomass type - torrefaction temperature interaction effects in volatile matter is shown by Figure 1(b) and it is not as pronounced as in equilibrium moisture content, as no profiles intersect each other. The volatile matter profiles show that at torrefaction temperatures below 250 °C, the volatile matter content was generally reducing at slower rate. However between 250 °C and 275 °C, the volatiles reduced at faster rate in all biomass samples and slowed down after 275 °C. Similar observations were reported by several authors [51, 52] who investigated torrefaction of biomass. This seems to indicate that the most effective torrefaction temperature to reduce the volatiles in all the biomass samples under investigation is within 250 °C–275 °C temperature range. This is the temperature range at which most of the hemicellulose is decomposed and therefore the raw biomass emit large quantity of volatile matter.

The fixed carbon content (FC) increased across all the torrefied biomass sample types under investigation as illustrated in Table 2. The fixed carbon content of the torrefied seed cake (29.3%) was significantly higher (P < 0.05) than the torrefied stem (22.8%) and the torrefied fruit husk (24.8%). This shows an increase in fixed carbon content of 17.8%, 16.1% and 42.2% for the seed cake, the stem and the fruit husk respectively when compared to their raw form results presented in Table 1. The biomass samples became relatively rich in fixed carbon and as the other biomass elements such as moisture and volatiles got reduced. The relatively high increase in fixed carbon content in the torrefied fruit husk is likely to be due to a strong increase in carbon in fruit husk after torrefaction as mentioned in Section 3.1.2. There was also a change in trend, as after torrefaction the fixed carbon in the fruit husk was now higher than that of the stem whereas before torrefaction the fixed carbon in the stem (19.65%) was higher than in the fruit husk (17.41%). The increase in the fixed carbon was relatively low in the torrefied stem and this could be attributed to the fact that the *Jatropha* stem sample composed more hemicellulose than the other two biomass samples. The hemicellulose is easily degraded through volatilization reactions. The other reason maybe that the relatively high bulk density in the seed cake and fruit husk increased resistance to heat transfer and therefore gave the materials more time to form fixed carbon. The proportional increase in fixed carbon across the biomass sample types could also be attributed to the proportional reduction in EMC and volatile matter. A similar sentiments were echoed by Peng et al. [33], who attributed carbon increase to the removal of moisture and oxygen containing volatiles during torrefaction. The increase in fixed carbon is also attributed to the carbonization compounds which are formed during torrefaction processes [47, 53]. This seemed to be strong in the torrefied fruit husk as it experienced strong increase in fixed carbon.

The results in Table 2 also showed that the fixed carbon content increased with an increase in torrefaction temperature which, is an opposite of the EMC and the volatile matter trend. The fixed carbon increased from 19.2% to 35.7% as the torrefaction temperature was raised from 200 °C to 300 °C. This increase could also be attributed to increase in carbon as the torrefaction temperature levels were increased.

The biomass sample type - torrefaction temperature interaction effect on the fixed carbon content is demonstrated by Figure 1(c). The results show that at temperature levels below 250 °C, the fixed carbon content is increasing at relatively slow rate in all the biomass sample types. However at torrefaction temperature levels above 250 °C the rate of fixed carbon accumulation increased. This seems to indicate that the

torrefaction temperature levels below 250 °C were not sufficient enough to decompose the biomass materials under investigation as stated earlier in this section. This is consistent with the findings by Filfli et al. [51] who reported that the torrefaction temperatures below 250 °C are ineffective when working with torrefaction of wood briquettes. The results in Figure 1(c) also show that the torrefied seed cake and fruit husk profiles intersect at around 275 °C. This seems to imply that the fixed carbon content of the torrefied fruit husk was increasing at a faster rate than the fixed carbon of the torrefied seed cake. It also suggest that at around 300 °C, the torrefied fruit husk and stem profiles are closing to each other. The fixed carbon content profiles are aligned to the volatiles profile which show that as the volatiles reduced, the fixed carbon increased at a similar trend. The results in Figure 1(c) suggest that temperature range between 250 °C and 275 °C was the ideal torrefaction temperature range as all the biomass samples recorded the highest fixation rate of carbon.

The results in Table 2 also show that the ash content increased across all the biomass sample types when compared to the results of the raw biomass samples presented in Table 1. The ash content of the torrefied fruit husk (24.5%) was significantly higher than (P < 0.05) of both the torrefied seed cake (15.4%) and stem (25.3%). However there was no significant difference (P > 0.05) between the ash content of the torrefied seed cake and stem. The results show that there was a sharp increase in ash content of the torrefied seed cake by more than 200%, followed by the torrefied stem (89%) and fruit husk (37%) in comparison to the results of the raw biomass samples presented in Table 1. This could be attributed to the mass loss as the extractives and the moisture in the biomass were removed during torrefaction. The increase in ash content could also be attributed to its non-volatility at the torrefaction temperature range. The high increase in ash content of the torrefied biomass could render it not suitable for gasification process [48]. However its utilization as a replacement for firewood especially after pelletisation maybe an alternative utilization of such resource.

It is also indicated in Table 2 that, as the torrefaction temperature increased from 200 to 300 °C, the ash content rose from 14.9% to 21.7% irrespective of the biomass sample type. The results in Table 2 also shows that there was no significant difference (P > 0.05) in ash content between 200 and 220 °C and also between 275 and 300 °C. This indicates that torrefaction temperature levels below 225 °C did not initiate clear decomposition of the biomass samples under study. This likely indicates that it may not be necessary to decompose the biomass samples material under review beyond 275 °C.

The results in Figure 1(d) show the biomass type – torrefaction temperature interaction effect on the ash content of the biomass samples under investigation. The results show that the ash content of the biomass sample types gradually increased with an increase in torrefaction temperature level. The torrefied seed cake and stem profiles intersected at around 255 °C, suggesting that the ash content increment rate in the seed cake was relatively higher than the stem. The ash content in the seed cake increased at a faster rate between 250 °C and 275 °C suggesting that the temperature range was more effective in decomposing volatile matter in the seed cake. This is the reason why the ash content in the torrefied seed cake increased sharply. In terms of proximate analysis it seems that 250 °C–275 °C is the ideal torrefaction temperature range for the biomass sample material under investigation. This is the temperature at which the torrefied biomass had relatively high rate of FC accumulation, highest rate of equilibrium moisture content and volatile matter loss.

3.1.2. Ultimate analysis

The elemental analysis brings an understanding on the vital elements that influence energy value and potential emissions. The results on the elemental composition of the torrefied biochar of *Jatropha* biomass are also presented in Table 2. The results indicate that the amount of carbon in torrefied biochar of the *Jatropha* seed cake was relatively high when compared to the torrefied stem and fruit husk. The results show that the torrefied seed cake carbon content was relatively high (54.5%) followed by stem (51.0%) and the biochar of fruit husk (49.6%). This displays a

significant increase in carbon content of 18%, 16% and 37.5% for torrefied seed cake, stem and fruit husk respectively when compared to the carbon content values of raw biomass samples presented in Table 1. A relatively high increase in carbon content in torrefied biochar of fruit husk corresponds to the highest increase in fixed carbon as presented in Section 3.1.1. This suggest that carbonisation occurred more in torrefied fruit husk than in seed cake and stem. This could be due to high ash content which is reported by Loo and Koppejan [54] that relatively high ash content obstruct heat penetration and diffusion of oxygen in the fruit husk. This is likely to have delayed the decomposition of the homo-cellulose in the fruit husk and therefore allowed it more time to carbonise. The enrichment of carbon in the torrefied biochar of the biomass sample material is a positive outcome as such condition rise carbon content which results in an elevated energy value. The rise in energy value of the torrefied biochar is demonstrated in Section 3.1.3 which shows that the energy values of the torrefied biochar was increased across all the biomass sample materials.

Furthermore the results in Table 2 demonstrate that the carbon content increased with an increase in torrefaction temperature level. The carbon content increased from 45.4% to 54.4% as the torrefaction temperature was raised from 200 °C to 300 °C. The trend is similar to one of fixed carbon and energy value as illustrated in Sections 3.1.1 and 3.1.3.

Figure 2(a) illustrates the effect of biomass sample type - torrefaction temperature interaction on the carbon content of torrefied *Jatropha* sample biomass. The results show that there was interaction between the factors under investigation as the profiles are not parallel. The results also show that the carbon content in the torrefied seed cake was relatively high at all levels of torrefaction temperature. The increment in carbon content was gradual as the torrefaction temperature level was raised before dropping after 275 °C. The profiles of the torrefied stem and fruit husk seems to be parallel within the torrefaction temperature range between 200 and 250 °C. This suggests that the two biomass sample materials behaved similarly at that range. However, the results also indicate that above 250 °C, the carbon content of the torrefied stem increased sharply before dropping at 275 °C while the carbon content of the torrefied fruit husk increased steadily until 300 °C. The carbon content of the torrefied biochar of the stem was similar to that of fruit husk at 300 °C. This appears to indicate that the biomass sample materials were behaving differently at torrefaction temperatures above 250 °C. Generally Figure 2(a) shows that the carbon content increased with an increase in torrefaction temperature across all the three biomass sample types. This resulted in an increase in fixed carbon and energy content as demonstrated in Sections 3.1.1 and 3.1.3.

The results in Table 2 further show that when hydrogen content mean values were compared across the biomass sample types irrespective of torrefaction temperature, the torrefied seed cake hydrogen content (6.6%) was significantly higher (P < 0.05) than stem (6.6%) and fruit husk (5.9%). This indicates an elevated hydrogen content in both the torrefied seed cake (9.0%) and fruit husk (11.0%) whereas the hydrogen content in the torrefied stem reduced (5.3%) in comparison to the values of the raw biomass samples presented in Table 1. The difference could be due to the variation in bulk density as the stem sample having low bulk density experienced more decomposition which released hydrogen into air. The hydrogen content behaviour of the torrefied biomass sample is also demonstrated by Figure 2 (b). The results generally shows that the hydrogen content reduced with an increase in torrefaction temperature unlike the carbon content which increased. The results show that at temperature below 250 °C the profiles were almost parallel and the reduction in hydrogen content was steady. It appears that at this temperature level the biomass sample materials behaved similarly. The three torrefied *Jatropha* biomass sample materials experienced an increase in hydrogen loss after 250 °C and it was more intense in the fruit husk. This reiterate the reasoning that the effective torrefaction temperature for the biomass materials under investigation is temperatures above 250 °C.

The results on nitrogen content are also presented in Table 2. The results show that the nitrogen content of torrefied seed cake (4.9%) was

significantly higher (P < 0.05) than that of stem (1.7%) and fruit husk (1.1%). This shows an increase in nitrogen content of 8.9%, 25.6% and 6.5% for the seed cake, stem and fruit husk respectively when compared to results in Table 1. The high content of nitrogen in seed cake could be attributed to its protein which contain significant amount of nitrogen atoms.

The results in Table 2 further illustrates that the nitrogen content increased with an increase in torrefaction temperature levels. This is likely to be due to the proportional loss of volatile matter and oxygen as the torrefaction temperature level was increased from 200 °C to 300 °C. The effect of biomass sample type - torrefaction temperature interaction on the nitrogen content is demonstrated by Figure 2 (c). The Figure indicates that the nitrogen was highest in the torrefied seed cake across the torrefaction levels. The results also show that the nitrogen content of the torrefied seed cake and fruit husk increased steadily at torrefaction temperature levels below 275 °C and immediately dropped after 275 °C. This appears to indicate that the temperatures above 275 °C were high enough to volatilize nitrogen into nitrogen gas in the two biomass types. The nitrogen in the torrefied stem steadily increased with an increase in torrefaction temperature up to 250 °C and thereafter shot up. This could be attributed to some proportional loss in hydrogen and oxygen which resulted in proportional increase in nitrogen.

The results in Table 2 also show that the oxygen content of the torrefied fruit husk (50.4%) was significantly higher (P < 0.05) than of the stem (41.3%) and seed cake (34.1%). This shows a reduction in oxygen content of 20.2%, 14.7% and 11.9% in seed cake, stem and fruit husk respectively in comparison to the results in Table 1. The reduction in oxygen content across the biomass sample materials enhanced their fuel value as it resulted in proportional increase in carbon and calorific value. The reduction in oxygen content was relatively low in the torrefied fruit husk and this could be attributed to its high ash content as demonstrated in Section 3.1.1. High ash content hinders diffusion of oxygen in the biomass and therefore reduced combustion process in the fruit husk.

The same results in Table 2 also show that oxygen content reduced with an increase in torrefaction temperature level. The oxygen content reduced from 46.0% to 37.5% when the torrefaction temperature was raised from 200 °C to 300 °C. This corresponded to an increase in energy content as demonstrated in Section 3.1.3. The biomass sample type - torrefaction temperature interaction effects on the oxygen content is illustrated by Figure 2(d). The Figure shows that the oxygen content was highest in the torrefied fruit husk and lowest in the seed cake at all torrefaction temperature levels. The results also demonstrate that there was a steady reduction in oxygen content in the three biomass sample materials as torrefaction intensity increased.

3.1.3. Energy content (HHV), mass and energy yield of torrefied Jatropha biomass

The energy content, mass loss and energy yield are some of the most important parameters used to establish the suitability of biomass for solid fuel use. These parameters were therefore carried out and the results are also presented in Table 2 and Figures 3 and 4.

The results presented in Table 2 show that the energy content of the torrefied *Jatropha* seed cake (21.6 kJ/g) irrespective of the torrefaction temperature levels was significantly higher than (P < 0.05) of the torrefied *Jatropha* stem (18.9 kJ/g) and *Jatropha* fruit husk (17.2 kJ/g). This is an improvement of 12%, 3%, and 27% in HHV of the torrefied seed cake, stem and fruit husk respectively when compared to values reported in Table 1. The values show relatively high improvement in the HHV of the torrefied fruit husk and this could be attributed to increase in its fixed carbon as indicated in Sections 3.1.1. The increase in fixed carbon is reported to lead to longer burning of the biomass fuel [55]. The increase in fixed carbon in all biomass sample materials could be due to the small loss of the carbon elements in comparison to hydrogen and oxygen and this resulted in an increase in the heating value of the torrefied biomass [14]. The assessment of the HHV means due to torrefaction temperature effects irrespective of the biomass sample type shows that the HHV

increased from 16.9 kJ/g to 23.6 kJ/g as the torrefaction temperature level was increased from 200 °C to 300 °C. This is echoed by several authors [18, 21, 30] that the energy content increase with an increase in torrefaction temperature intensity. The HHV increase is accompanied by mass loss as the biomass sample emits the volatiles and moisture content as highlighted in Section 3.1.1.

The effects of biomass type - torrefaction temperature interaction on the HHV are also presented in Table 2 and demonstrated by Figure 3. The results indicate that the HHV generally increased with a rise in torrefaction intensity. This is reported to be the primary driver of torrefaction as a biomass pre–treatment technique [6]. The results also show that, the HHV of the torrefied seed cake increased from 19.9 kJ to 25 kJ; the torrefied stem increased from 17.4 kJ to 21.1kJ; and the torrefied fruit husk increased from 13.5 kJ to 24.8 kJ as the torrefaction temperature level was raised from 200 °C to 300 °C. The HHV of the torrefied seed cake is lower than the 23.0 kJ–28.7 kJ range reported by Gan et al. [56]. The difference in energy content could be due to the difference in the biomass condition and probably also the torrefaction conditions. The results in Figure 3 show that at torrefaction temperature levels below 250 °C, the impact of the interaction was not well manifested. This is indicated by the parallel profiles of HHV of the three *Jatropha* biomass materials under investigation. However after 250 °C, the shape of the profiles changed as the HHV of the torrefied fruit husk increased at a faster rate than the other two biomass types. This could be due to the relatively high increase in fixed carbon as demonstrated in Section 3.1.1. The impact of the biomass type - torrefaction temperature interaction is highlighted by the energy ratio presented in Table 2. It shows that at torrefaction temperature levels below 250 °C, energy ratio was highest in the torrefied seed cake (1.03–1.07) and the torrefied fruit husk and stem were almost the same. However at temperature range 275–300 °C the energy ratio of the torrefied fruit husk was the highest (1.48–1.83) followed by the torrefied seed cake (1.12–1.30) and the torrefied stem (1.03–1.15). This indicates that torrefaction temperature levels above 250 °C were more effective in improving the energy content of the fruit husk. The energy content of the torrefied stem and the seed cake increased gradually especially after 275 °C but not as exponential as of the torrefied fruit husk.

The biomass type effect was insignificant (P > 0.05) on the mass yield, however the torrefaction temperature effect showed some significance (P < 0.05) as presented in Table 2. The results show that the differences in mass yield across the biomass types at different torrefaction temperature levels was relatively small. This seems to suggest that the mass yield reduced in a similar pattern across the biomass types as the torrefaction temperature level was increased from 200 °C - 300 °C. This implies that the major differences in mass yield could mostly be due to the torrefaction temperature effect.

The impact of temperature effects on mass yield irrespective of biomass type was very high as highlighted in Table 2. The mass yield reduced with a rise in torrefaction temperature level across the biomass sample types. The average mass yield irrespective of biomass type was in the range 94.7%–64.4% as the torrefaction temperature increased from 200 to 300 °C. The mass loss is this temperature range is mostly attributed to decomposition of hemicellulose [47]. The results in Table 2 further shows that a huge mass loss was experienced after 250 °C across all the biomass types. This indicates that the torrefaction temperature levels below 250 °C were not effective in decomposing the biomass materials under investigation. This is similar to findings by Phanphanich and Mani [52] who performed investigation on forest biomass.

The results in Table 2 show that the energy yield between the torrefied *Jatropha* seed cake and *Jatropha* fruit husk were not significantly different (P > 0.05). However both the torrefied seed cake and fruit husk energy yields were significantly different (P < 0.05) from the torrefied stem. The results also show that the energy yield of both the torrefied *Jatropha* seed cake and *Jatropha* fruit husk were closer to each other and higher than of the torrefied *Jatropha* stem. The higher energy yield in both the torrefied seed cake and fruit husk could be due to a higher HHV

at higher torrefaction temperatures (275 °C–300 °C) as indicated in Table 2. This is further demonstrated by the biomass type - torrefaction temperature interaction effects as illustrated by Figure 4. The results show that at torrefaction temperature levels below 250 °C, the energy yield of the torrefied seed cake was relatively high but reduced immediately after 250 °C. This might indicate that it is not necessary to torrefy the seed cake beyond 250 °C as there would not be any improvement in energy yield. Figure 4 also illustrates that the energy yield of the torrefied stem, was highest at 225 °C and this might indicate that torrefaction of the torrefied stem beyond this temperature will result in more energy loss than gain. The results also show several interaction of the profiles as the torrefaction temperature levels increased. This is an indication of the biomass type - torrefaction temperature interaction showing that the three biomass types' energy yield behaviour was different at various temperature levels. One distinctive feature of results in Figure 4 is a sharp increase in energy yield of the fruit husk at 250 °C–300 °C temperature range. The increase could be influenced by an increase in its HHV, carbon content and fixed carbon at the same temperature range.

It is generally accepted that a mass and energy balance of biomass torrefaction is retention of 70% of the original dry mass as a solid product, containing 90% of the initial energy content [18]. This might suggest that basing on energy and mass yield and taking into consideration other parameters under investigation, the ideal torrefaction temperature for the seed cake is 250 °C as it improved its energy content by 9%. The results in Table 2 show that the ideal torrefaction temperature for the fruit husk is 275 °C. The mass and energy yields of seed cake torrefied at 250 °C were 89.3% and 97.1%. On the other hand the fruit husk torrefied at 275 °C had mass and energy yield of 72.5% and 107.4%. The torrefied stem did not satisfy these conditions which means that on its own it may not be suitable for torrefaction. These values are also supported by the findings by Madanayake et al. [6] who reported that torrefaction of seed cake in excess of 275 °C would not be beneficial as far as HHV is concerned. The energy yield of the seed cake torrefied at 250 °C is comparable to findings by Gan et al [56] who also reported a value of 97%. This indicate that the seed cake torrefied at 250 °C maybe a viable option for use as a source of solid fuel when compared to the fruit husk and the stem. However the investigation of torrefaction of the blended maybe explored in the future.

3.1.4. Bulk density

The bulk density of biomass is very important as it influences its energy density and transportation costs. Generally the bulk density of biomass is reduced during torrefaction as it becomes more porous due to mass loss in the form of solids, liquids and gases [14]. The results on the bulk density of the torrefied biomass are presented in Table 2 and Figure 5. The results show that the bulk density of the torrefied *Jatropha* seed cake (0.56 g/cm³) was significantly higher (P < 0.5) than of the fruit husk (0.29 g/cm³) and the stem (0.15 g/cm³). The values are generally
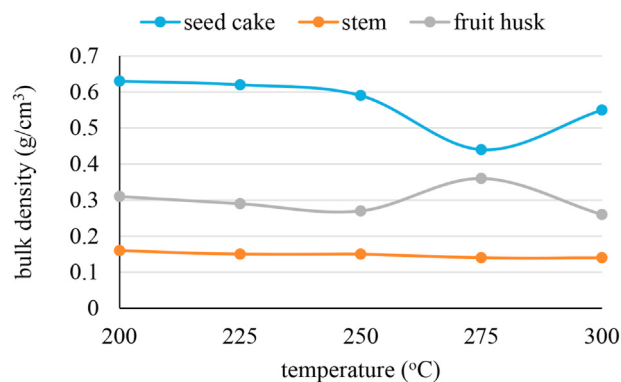
Figure 5. Biomass type - temperature interaction effects on the bulk density of torrefied *Jatropha* seed cake, fruit husk and stem.

lower than the bulk density of the parent raw biomass as illustrated in Table 1 which were 0.75 g/cm^3, 0.20 g/cm^3 and 0.37 g/cm^3 for the seed cake, the stem and the fruit husk respectively. This displays that the torrefied *Jatropha* seed cake recorded relatively high bulk density. This seems to suggesting that the torrefied *Jatropha* seed cake would be a better choice for use as a solid fuel when compared to the torrefied stem and the fruit husk as far as bulk density is concerned.

The results on the effect of torrefaction temperature irrespective of biomass type are also presented in Table 2. The results show that the bulk density decreased with an increase in torrefaction temperature levels. However there was no significant difference (P > 0.05) on the bulk density of biomass torrefied at 275 °C and 300 °C. This seems to indicate that in terms of bulk density there is no need to torrefy the *Jatropha* biomass material under investigation beyond 275 °C. This is agreeable to the findings of the proximate analysis in Section 3.1.1 which mostly showed that the temperature range 250 °C–275 °C is an ideal temperature for torrefaction of biomass under investigation.

The results in Figure 5 demonstrate the biomass type and torrefaction temperature interaction effects on the bulk density of the biomass under investigation. The interaction is mostly manifested on the torrefied seed cake and the torrefied fruit husk. The effects of the interaction is not that strong on the torrefied stem as its bulk density gradually reduced with an increase in torrefaction temperature. The results also show that the bulk density of the seed cake was gradually reduced at a slow rate from 200 °C to 250 °C and then steeply reduced between 250 °C and 275 °C. However there was an increase in bulk density of the torrefied seed cake as the torrefaction temperature increased from 275 °C to 300 °C. This was not an expected outcome as generally the bulk density reduces with an increase in torrefaction temperature. The increment may be attributed to carbonisation of the high density molecules. It could also be attributed to reduction in particle size during torrefaction [57] and this resulted in torrefied seed cake material becoming more compact. On the other hand, the bulk density of the torrefied fruit husk was reducing at a steady rate from 200 °C to 250 °C. However it increased as the torrefaction temperature was raised from 250 °C to 275 °C. This may also be attributed to carbonisation and reduction in particle size as a stated earlier in this section. The bulk density of the torrefied fruit husk then dropped as the temperature was raised from 275 °C to 300 °C. This could be due to the setting of active carbon which is more porous. This shows that there was no general behaviour on the bulk density of the torrefied biomass under investigation especially after 250 °C. This could be attributed to differences in lignocellulose composition of the three *Jatropha* biomass materials under investigation.

3.1.5. Hygroscopicity

Hygroscopicity of a biomass is an important characteristics as it influences storability, transportation and burning efficiency of biomass fuel [14, 58]. It was therefore carried out to see which torrefied *Jatropha* biomass material is low in hygroscopicity and therefore a better solid fuel source. The results on the hygroscopicity of the torrefied *Jatropha* biomass are presented in Table 2 and illustrated in Figure 6. The results in Table 2 show that the hygroscopicity of the torrefied *Jatropha* stem (49.62%) was significantly higher (P < 0.05) than of the torrefied fruit husk (37.78%) and the torrefied seed cake (21.69%). Furthermore the hygroscopicity of the torrefied fruit husk was significantly different (P < 0.05) from the torrefied seed cake. Generally torrefaction process reduced the hygroscopicity by 38%, 17% and 21% for the seed cake, the stem and the fruit husk respectively when compared to values of raw biomass in Table 1. The general reduction in the hygroscopicity of the torrefied *Jatropha* biomass material under investigation could be attributed to the loss of the hydroxyl group (OH) as the hemicellulose and cellulose are decomposed during torrefaction. The loss of the hydroxyl group makes the biomass more hydrophobic thereby reducing the microbial activities which makes it feasible to be stored in a humid environment [19, 46]. The overall results show that the ability of the torrefied *Jatropha* stem to retain moisture is higher than of the torrefied seed cake
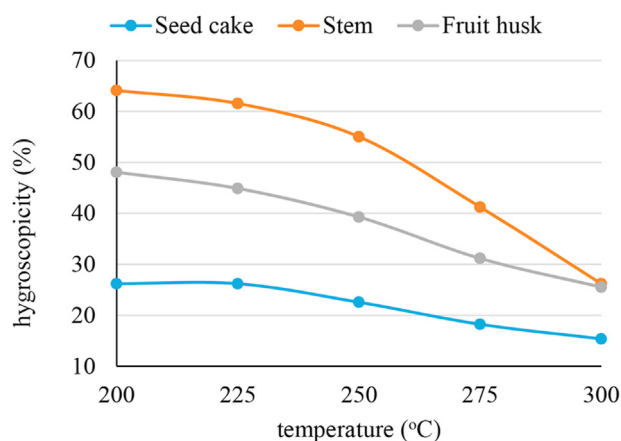

Figure 6. Biomass type - temperature interaction effects on the hygroscopicity of torrefied biomass.

and the torrefied fruit husk. This appears to suggest that the torrefied *Jatropha* stem had a relatively high degree for moisture retention, followed by the torrefied *Jatropha* fruit husk and the torrefied *Jatropha* seed cake. The torrefied seed cake recorded relatively low hygroscopicity across all temperature levels and therefore seem to be a good option for use as a source of solid fuel.

The results in Table 2 also show that the hygroscopicity was significantly different (P < 0.05) between the torrefaction temperature levels irrespective of the biomass type. The hygroscopicity decreased with an increase in torrefaction temperature though the difference was insignificant between 200 °C and 225 °C. This indicates that the torrefaction temperature effects on the two torrefaction levels was statistically the same. The reduction in hygroscopicity as torrefaction temperatures increase could be attributed to the destruction of the hemicellulose and cellulose in the torrefaction temperature range as stated earlier in this section. Similar sentiments were echoed by Stelte et al. [59] who stated that the increase in decomposition of hemicellulose and cellulose with torrefaction intensity resulted in reduced OH group that ultimately reduced moisture absorption by the torrefied material.

The results in Figure 6 demonstrate the biomass and torrefaction temperature interaction effects on the hygroscopicity of the biomass under investigation. The results show that the hygroscopicity of the torrefied seed cake was almost constant between 200 °C and 225 °C. It thereafter reduced gradually from 225 °C to 300 °C. The hygroscopicity profiles of the torrefied fruit husk and the torrefied stem were close to parallel between 200 °C and 250 °C. However after 250 °C the hygroscopicity of the torrefied stem was reducing at a faster rate than the torrefied fruit husk. This could be attributed to a higher loss of hydroxyl group (OH) due to decomposition of homocellulose in the stem. It must be noted that the stem contained more homocellulose in its raw form than the seed cake and the fruit husk. The results in Figure 6 also show that the hygroscopicity generally reduced with an increase in torrefaction temperature levels. This implies that the torrefied material became more hydrophobic with intensity of torrefaction. The general gain in reduction in the hygroscopicity of the torrefied biomass could be substantial on the transport cost and on the final valorisation process yield [60]. This is so because the material handling becomes less expensive and special storage facility is not necessary.

4. Conclusions

The effects of biomass type and torrefaction temperature on the torrefied *Jatropha* biomass material were determined in terms of elements composition, proximate analysis, bulk density, energy content and hygroscopicity.

The torrefaction process increased the carbon content across the biomass material and the seed cake had the highest carbon and hydrogen content; and lowest oxygen level at all torrefaction temperature levels.

The energy content of the three *Jatropha* biomass materials was increased from 19.9 kJ/g to 25.0 kJ/g in the seed cake; 17.4 kJ/g to 21.1 kJ/g in the stem and 13.5 kJ/g to 24.8 kJ/g in fruit husk as the torrefaction intensity was increased from 200 °C to 300 °C

The bulk density of the torrefied seed cake (0.63 g/cm^3–0.44 g/cm^3) was the highest at all levels of torrefaction when compared to the torrefied fruit husk (0.31 g/cm^3–0.24 g/cm^3) and the stem (0.16 g/cm^3–0.14 g/cm^3).

The seed cake had relatively low hygroscopicity (26.20%–15.36%) followed by fruit husk (48.06–25. 52%) and the stem (64.11%–26.20%) as the torrefaction temperature level was increased from 200 °C to 300 °C

The seed cake torrefied at 250 °C showed potential to be a source of solid fuel.

Declarations

Author contribution statement

Elias Kethobile: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Clever Ketlogetswe: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Jerekias Gandure: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

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The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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