Investigation of the effects of pelletizing pressure and binding wax on the fuel properties of torrefied Jatropha biomass.

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Abstract: Densification of the torrefied biomass is one of the approaches used to develop a carbon-neutral solid fuel with characteristics similar to of coal. The process highly enhances the biomass energy density and its hydrophobicity. However, difficulties are encountered when undertaking the densification process of the torrefied biomass as it has lost its natural binding capacities. Several binding agents have been used to try and supplement the lost natural binders. Binding agents are mostly used in the range 0.5 - 10% of the total mass . The literature shows that several attempts have been made to try and find suitable binding agents for different torrefied materials. However, the study on binders used during densification of torrefied Jatropha biomass material is limited. This study investigates the effects of different compression and wax binder levels on the solid fuel properties of Jatropha biomass. The study investigated three torrefied Jatropha biomass materials (stem torrefied at 225ºC, seed cake torrefied at 250ºC and fruit husk torrefied at 275ºC), pelletized at three compression levels and five binding wax levels. The findings from the study showed that the torrefied Jatropha seed cake pellets had superior solid fuel qualities in term of pelletised at the lowest pressure with 5% binding wax level showed higher solid fuel quality. The torrefied stem pellets generally exhibited poor pellet quality but its pellets made from lower pressure) and 10% binding wax were the most stable.

Key words: Jatropha plant, binding agent, biomass, densification, burning rate, pressure

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1. Introduction

A biomass solid fuel produced from torrefaction process presents a carbon-neutral option solid fuel which could replace coal. The solid fuel produced has both carbon content and hydrophobicity characteristics similar to coal as indicated in the previous study [1]. However, torrefaction process lowers its bulk density and this creates material handling, storage and transportation challenges [2, 3]. This is due to the fact that the product of torrefaction though it has high energy density, it is reported to be more porous and fragile. The product is further described as having decreased mechanical strength and increased dust formation [4, 5]. This makes densification of biomass after torrefaction a necessity in order to improve on these negative characteristics and make it more environmentally sustainable [6, 7]. The combination of torrefaction and densification results in an energy dense biomass solid fuel with many similar properties to coal [1, 8]. The densification of the torrefied biomass improves its energy density, the product is more uniform and is more convenient to transport, store and handle [9, 10]. This was observed by Uslu et al. [4] who reported the mass energy density of torrefied biomass pellet to improve form 18MJ/kg to 22 MJ/kg. The authors stated that the energy density is 20% higher than commercial wood pellets. This is similar to Peng et al [10] who reported the bulk densities of torrefied pellets to range from 750 kg m^{-3} to 850 kg m^{-3}, with the dry high heating value of 20.4 - 22.7 MJ/kg and the volumetric energy density from 14.9 to 18.4 GJ m^3. The authors further stated that this is far much superior when compared to conventional wood pellets.

The other important properties of torrefied biomass pellets is that they are hydrophobic and resistant to biological degradation [11]. These are very important properties because pellets with low water retention and high water resistance reduce the costs associated with pellets handling, storage and prolong their shelf-life. This was further emphasised by Peng et al. [10] who examined the moisture uptake of torrefied pellets in a humidity chamber at 30°C and 90% relative humidity after 48 hours. The authors reported that the saturated moisture uptake of torrefied pellets was much lower than regular control pellets (raw and untorrefied). This was also reiterated by Verhoeff et al. [12], who reported that, for torrefied pellets prepared at 225°C die temperature, the final moisture uptake was only 40% of the control (raw) pellets.

The densification of torrefied biomass seems to significantly improve the fuel properties of biomass, however it is reported to be more challenging than densification of raw natural biomass. The particles from the ground torrefied biomass are brittle and difficult to bind together through mechanical interlocking [13, 14]. This could be attributed to the loss of binding capability of hemicellulose and some lignin during torrefaction. It therefore requires high die temperature of 110°C to 230°C, high power consumption and the operation is unstable [15, 16, 10]. This was also echoed by Gilbert et al. [17] who worked on switchgrass and found pelletisation of its torrefied biomass not an attractive pre-process as the pellets from it were very brittle and possessed little mechanical strength and reduced bulk density. But after adding some tar, as a binding agent, to the torrefied switchgrass at higher temperature, the authors reported that the pellets were twice as strong as pellets made by cut fresh switchgrass.

Addition of binding agents in densification of torrefied biomass is therefore very critical to supplement those natural binders which were lost during torrefaction. Several binding agents have been used in biomass fuel pellet production especially for biomass which is difficult to bond such as torrefied biomass. Binding agents such as xanthan, guar gums, cellulosic binders, recycled pulp, recycled paper, nanolignocellose, wax, glycerol diatomite, carboxymethylcellolose, starch, cow dung are used in pelletisation of biomass [18, 19, 20, 21]. It seems the list is not exhaustive as it depends on the regions and their needs. Binding agents in the range 0.5-10% are added to help in bonding and increase the strength and durability of fuel pellets [22]. The success of the use of binding agents on torrefied biomass varies. Adhikari et al. [21], used proteinaceous binder to pelletize torrefied wood and observed that addition of binder at 2-3% increased the durability of the torrefied pellets from 93% to about 97%. The addition of the binders also significantly lowered the moisture content from 8% to 6%. However, the authors further observed that the addition of binders have no effects on the bulk density. Shang et al. [23] investigated the blending of rapeseed oil with torrefied biomass and revealed that pellets made from untreated wood chips had the highest strength compared to the pellets made from torrefied chips with addition of 2 % rapeseed oil. Other authors including Cao et al. [24] pelletized torrefied woody biomass with caster bean cake and found the optimal conditions for energy consumption and pellet strength to be torrefaction at 270 °C and a blending with 15% castor bean cake. Bai et al. [25] used peanut shell as a binding material and the results revealed that peanut shell is an effective and inexpensive binder while optimized process conditions were obtained with 15% peanut shell and 10% water content. Bazargan et al. [26] investigated the effect of starch application as a binding material during the compaction of palm kernel shells. The authors demonstrated that the produced biochar pellets presented good tensile crushing strength, impact resistance, and water resistance. The application of raw saw dust as a low-cost binder for the preparation of pellet form torrefied biomass was investigated by Peng et al. [27] on torrefied biomass and concluded that sawdust with mean particle size below 1mm can potentially be applied effectively to the densification process.

The literature shows that several attempts have been made to try and find suitable binding agents for different torrefied materials. However, from literature, there are limited studies of binders used during densification of torrefied Jatropha biomass material. Thus in this work different compression and wax binder percentage levels were used to investigate the solid fuel properties of Jatropha biomass. The study investigated three torrefied Jatropha biomass materials (stem torrefied at 225^{o}C, seed cake torrefied at 250^{o}C and fruit husk torrefied at 275^{o}C), pelletized at three compression levels as presented in Table 1 and five binding wax levels (0%, 5%, 10%, 15% and 20%) were used.

2. Materials and Methods

2.1 Preparation of sample

The sample material preparation and torrefaction processes were carried out following the previous work [1, 28]. The torrefied biomass material used in the experiment were Jatropha seed cake, Jatropha fruit husk and Jatropha stem torrefied at 250^{o}C, 275^{o}C and 225^{o}C respectively. A study by Kethobile et al. [1] showed that Jatropha seed cake torrefied at 250^{o}C had superior solid fuel properties when compared to other biomass materials under investigation. It was therefore the main sample material in present investigation. However, the other two sample materials formed part of the investigation for comparison sake and to further investigate if they are options for future research works. They also showed better fuel properties within their biomass types. The torrefied Jatropha seed cake material was then mixed with binding wax (Stearic Acid) at 0, 5, 10, 15 and 20%. The torrefied fruit husk was only mixed with binding wax at 0, 5 and 10% only and stem was only mixed at 0 and 10%. This was done because they were not the main sample material, however the information obtained maybe useful for future research work as stated earlier in this section. The 15% and 20% biomass-wax mixtures were only used at a lower pelletizing pressure (P1) on the torrefied Jatropha seed cake because when applied at higher pressures, the pellet collapsed. The 15% and 20% biomass-wax mixtures were also employed on the fruit husk and stem biomass at compression pressure P1 (Table 1), however the compressed pellets collapsed before the compression load was removed. They were therefore excluded from the experimental runs.

2.2 Pelletisation of the torrefied biomass

The pelletisation process was carried out using Pellet Press EQUILAB EQP-100. The specification of the pellet press shows that it could be adjusted between 10 and 40 tonnes. It can also take sample diameter of 0.04 m, and its peak working pressure is 50 bar/cm^{2}. The press could be set at different pressures/forces though for the test runs under review three pre - set pressure cycles were used. The set pressures/forces are presented in Table 1. These are the pressures which were pre -set during the commissioning of the machine.

Table 1: Pressure/Force cycle parameters used to pellet the sample material

No.	Cycle 1			Cycle 2		
	Time (s)	Force (ton)	P (MPa)	Time (s)	Force (ton)	P (MPa)
P1	16	22 (216kN)	171	07	22 (216kN)	171
P2	25	34 (334kN)	265	11	36 (353kN)	280
P3	05	39 (383kN)	304	05	40 (392kN)	311

The determination of pressure exerted on the sample material was calculated according to equations 1, 2 and 3. Newton's second law of motion, states that force equals mass times acceleration.

$$F = ma \qquad (1)$$

Where

F is force (Newton)
M is mass (kg)
a is acceleration due to gravity (m/s^2).

The cross sectional area was calculated using equation 2.

$$A = \pi r^2 \qquad (2)$$

For all the samples the diameter used was 0.04 m which corresponds to the diameter of the aluminium cups used to hold the sample material. The cross sectional area was then calculated as π*0.02m^2 which equals to 1.26 * 10^{-3} m^2 (12.6 cm^2). The height of the aluminium cup was 0.016m. This makes the volume of the cups to be 2.01 *10^{-5}m^3 (20.1 cm^3). Pressure was then computed according to equation 3.

$$Presure = \frac{Force\ (KJ)}{A(m^2)} \qquad (3)$$

Each biomass sample material was filled to top into the aluminium cup. It was then tapped to settle the sample material and this resulted in the mass of each biomass sample filled into the cup to be 10.0 grams, 5.0 grams and 3.0 grams for torrefied seed cake, fruit husk and stem respectively. The initial pellet density of the sample material before pelletizing was then calculated according to equation 4 and it was found to be 0.793g/cm^3, 0.397g/cm^3 and 0.238g/cm^3 for torrefied seed cake, fruit husk and stem respectively.

$$Pellet\ Density = \frac{mass}{volume} \qquad (4)$$

Once the sample materials were put inside the aluminium cups, they were then inserted in the compression chamber after selecting pressure parameters as shown in Table 1. The compression was then initiated which follows two cycles. The compression is a two cycle process because some sample materials were assumed to contain some gas which could form hollows during compression. During the decompression of the pellets, this gas will try to leave out, generating cracks and imperfections in the surface of the pellets. To avoid this problem, the pellet press uses a double cycle of pressing. These cycles have intermediate time that allow the occluded gas inside the pellet disc to be removed after first pressing thus securing a better compaction during the second cycle of pressing [29].

The sample materials described under Section 2.1 were then subjected to each compression levels presented in Table 1 and resulted in 11 experimental treatments for torrefied Jatropha seed cake pellets denoted as JSC P1, JSC P1 5, JSC P1 10, JSC P1 15, JSC P1 20, JSC P2, JSC P2 5, JC P2 10, JSC P3, JSC P3 5 and JSC P3 10. The fruit husk sample materials were 9 symbolized as FH P1, FH P1 5, FH P1 10, FH P2, FH P2 5, FH P210, FH P 3, FH P3 5 and FH P3 10 and the sample units for the stem were 6 and abbreviated as STEM P1, STEM P1 10, STEM P2, STEM P2 10, STEM P3 and STEM P3 10. This resulted in 26 experimental units replicated three times for each parameter under investigation.

2.3 Characteristics of the torrefied Jatropha biomass pellets

The factors which were used to characterize the torrefied biomass pellets were moisture content, hydrophobicity, pellet density and burning rate properties. The determination of moisture content followed the procedure described in Kethobile et al. [28]. For the determination of hydrophobicity, the torrefied pellets were immersed in distilled water for 4 hrs following previous studies [30, 31, 32]. The pellets were then allowed to dry at room temperature conditions. The moisture retained in the pellets were measured at 1, 2, 3,4,5,20,24 and 72th hour denoted as H1, H2, H3, H4, H5, H20, H24 and H72 respectively. The measured moisture retained were then used to estimate hydrophobicity of the torrefied pellets.

The pellet density was estimated by using equation 4. The mass of the pellet was determined using a laboratory balance with readability of 0.10 mg and a vernier calliper was used to measure the diameter and length of the pellet for determination of the volume.

The pellet burning rate was determined according to the procedure followed in the literature [30, 33]. A fire insulator, paraffin burner, tripod stand, and wire gauze were placed on the measuring balance and their weight recorded. One pellet was placed on wire gauze and the burner was used to ignite the pellet fuel. All the apparatus were positioned on top of a mass balance to record instantaneous measurements of the mass every 10 seconds throughout the combustion processes, until all the pellets were completely burnt and constant mass was obtained. The weight loss was computed using the expression in equation 5.

$$\text{Burning rate}\left(\frac{\text{g}}{\text{second}}\right) = \frac{\text{sample burnt (g)}}{\text{time taken(s)}} \qquad (5)$$

3. Results and Discussion

The section presents the results on moisture content, pellet density, hydrophobicity and burning rate characteristics of the torrefied Jatropha biomass fuel pellets under investigation. The ANOVA showed that there was significant difference ($P < 0.05$) between the treatment means on the parameters under investigation. The results are presented in Sections 3.1, 3.2, 3.3, 3.4 and Fig. 1 to 18.

3.1 Moisture content (equilibrium)

The moisture content of biomass fuel is one of the parameters which hugely influence its calorific value and its burning characteristics. It was therefore evaluated in this study and the results are illustrated by Fig. 1. The separation of means using least significant difference (lsd) showed that generally the torrefied stem (STEM) biomass pellets had the highest moisture content followed by the torrefied fruit husk (FH) and the torrefied Jatropha seed cake (JSC). The results in Fig. 1 show that STEM P2 10 (6.59%) was the highest followed by STEM P1 10 (6.10%) and JSC P3 10 (1.60%). The trend was also observed in the study by Kethobile et al. [1] where moisture content of torrefied stem was the highest followed by the fruit husk and the seed cake. This could be attributed to the fact that the Jatropha stem biomass used was torrefied at lower temperature (225^{o}C) and therefore most of the hydroxide molecules which are known to react with moisture were not destroyed during torrefaction processes.

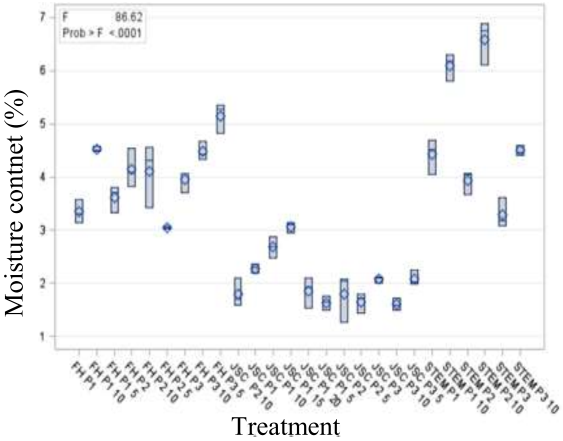

Fig. 1: Effects of pelletisation pressure and binding wax on the moisture content of torrefied Jatropha biomass

Detailed observation on the pellets of the torrefied stem shows that the moisture contents of STEM P2 10 (6.59%), STEM P1 10 (6.10%), and STEM P3 10 (4.49%) were significantly higher ($P < 0.05$) than of STEM

P2 (3.93%), STEM P3 (3.29%) and STEM P1(4.42%). The results are further illustrated by Fig. 1 which highlights that the stem pellets which contain wax had more moisture content than those produced without wax. This appears to indicate that wax increased the moisture content of the torrefied biomass by 26 - 40%. This is a big difference which is in contrary to what was reported by Adhikari et al. [21] who stated addition of wax to reduce the moisture content of biomass pellets. The relatively high percentage moisture increase could be attributed to the collapse of the pellets during compaction. The Jatropha stem sample materials used in the experimental runs were torrefied at lower torrefaction temperature as stated earlier and therefore most of its hemicellulose which help in bonding was likely still playing a major role. However, addition of wax seems to have created some voids for moisture to penetrate the structure and trapped within. It appears that those sample material without wax were able to bond relatively tight and left little voids for air moisture to enter. It must be noted that there is a limitation in the amount of binding material that can be added to aid bonding and this was also demonstrated in the present investigation. Most of the moisture in the non-wax samples could be attributed to OH-bonding in the hemicellulose compounds. The increase in pelletisation pressure had some influence on the moisture content of the torrefied stem fuel pellets as the moisture content of STEM P1 pellets was significantly ($P < 0.05$) higher than the moisture content of both STEM P2 and STEM P3. This suggest that the compaction pressures from 280 MPa and above on the torrefied stem reduced the voids between particles and within particles and therefore less moisture to enter. The STEM P3 pellets with moisture content value of 3.29% was the lowest and therefore seem to be the best option within the STEM treatments. However concrete conclusion could only be made once other parameters which influence the solid fuel value are investigated.

The comparison of the moisture content of the pellets made from torrefied fruit husk shows several overlaps in terms of significance. However, FH P3 5 (5.15%) was significantly ($P < 0.05$) the highest followed by FH P1 10 (4.52%) and FH P3 10 (4.48%). The FH P2 5 (3.05%), FH P1 (3.35%) and FH P1 5 (3.62%) were the lowest in moisture content within the FH treatments. The results are further illustrated by Fig. 1 which shows that though most of the observations were not statistically different, the moisture content of fruit husk pellets made from lower pressure (FH P1) seems to be lower than one from higher pelleting pressures (FH P2, FH P3). This could be attributed to pellet collapse at pressure above 280 MPa which created some internal cracks within the pellets. Further observation shows that the wax could have also increased moisture content of torrefied Jatropha fruit husk pellet as it was observed in torrefied stem pellets though not significant. Considering the FH pellets, it appears that FH P2 5 (3.05%), FH P1 (3.35%) and FH P1 5 (3.62%) demonstrated favourable moisture content characteristic and they could therefore be regarded as the best within the FH treatments.

The pellets from torrefied Jatropha seed cake (JSC) generally showed lower moisture content when compared to fruit husk and stem as mentioned earlier. The torrefied Jatropha seed cake pellets could therefore generally be regarded as the best options for use as solid fuels when compared to the stem and fruit husk. Observations within the JSC revealed that most of the moisture content were not significantly different ($P > 0.05$). For example, the moisture content of the pellets made from JSC P3 10, JSC P1 5, JSC P2 5, JSC P2, JSC P2 10, JSC P3 and JSC P1 20 were not significantly different ($P < 0.05$). However, JSC P1 15 (3.07%) and JSC P1 10 (2.28%) were statistically ($P < 0.05$) the highest followed by JSC P1 and JSC P3 5. The moisture content of JSC P3 10 (1.6%) and JSC P1 5 (1.63%) were the lowest though not significantly different ($P < 0.05$) from JSC P2 5, JSC P2, JSC P2 10, JSC P3 and JSC P 1 20. The results are further illustrated by Figure 1 which shows that the moisture content of the lower pressure (JSC P1) pellets were higher than of the higher pressures (JSC P2, JSC P3). The data suggest that compaction pressure above 280MPa on the torrefied seed cake pellets reduced the voids between particles and within particles. It may also indicate that the torrefied seed cake pellets were able to stand the higher pressures without collapsing and thus resulted in a higher dense solid material. The result on the moisture content seem to imply that most of the JSC pellets could not be separated and were the most desirable. This shows a broad choice which is inconclusive, however investigation of other parameters such as pellet density and hydrophobicity helped in selecting the most desirable pellet within the torrefied jatropha seed cake.

3.2 Pellet Density

Pellet density is an important characteristic because it influences handling, transportation and storage of solid fuel as mentioned earlier in Section 1.0. It was therefore investigated on that regard. The analysis of variance (ANOVA) depict a significant difference ($P < 0.05$) amongst all the treatment units. The separation of means using least significant difference (lsd) showed that JSC P3 and JSC P1 10 were the highest with pellet density of 0.94g/cm^3 and FH P3 10 was the lowest with pellet density value of 0.50g/cm^3. This shows an increase of about 19% in pellet density of the JSC P3 and JSC P1 10 pellets when compared to pellets density before compaction in Section 2.2. The pellets density of the FH P3 10 though was the lowest, had a 35% pellet density increment when compared to the initial pellet density values in the same section. However, JSC P3 and JSC P2 10 were not significant different ($P>0.05$) from JSC P1 5, JSC P3 5, JSC P1 20. This appears to suggest that the difference in pellet pressure and wax content combination did not bring any significant differences on pellet density of the torrefied Jatropha seed cake. It seems that any of these treatment combination for Jatropha seed cake could be an approprite fuel pellet of relatively higher density. The results are further demonstrated by Fig. 2 which shows that JSC P3 and JSC P1 10 had the highest density and the lowest was FH P3 10.

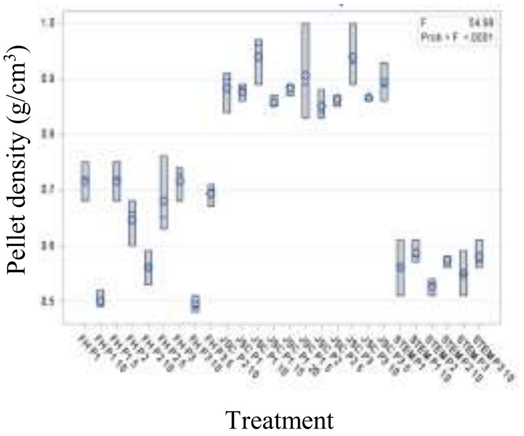

Fig.2: Effects of pelletisation pressure and wax on the pellet density of torrefied biomass.

Fig. 2 generally illustrates that the pelletized torrefied Jatropha seed cake biomass had a higher pellet density, followed by the torrefied fruit husk and stem. The pellet density values of torrefied Jatropha seed cake biomass are similar to the values reported by Gaitán-Alvarez ·et al [34] who reported results on torrefied wood of tropical species. The pellet density follow a similar trend which was demonstrated by the bulk density of the raw biomass and the torrefied biomass as obsereved in previous studies [28, 1]. From the results analysis of the torrefied Jatropha seed pellets it is appropriate to concluded that JSC P3, JSC P1 10, JSC P1 5, JSC P3 5 and JSC P1 20 are the best in terms of pellets density. However, JSC P1 20 showed poor burning characteristics and instability after water molecules absorption as indicated in Section 3.3 and 3.4. It could therefore be considered unsuitable for solid fuel use.

The separation of means also showed that for the fruit husk pellets (FH); FH P1, FH P3, FH P1 5, FH P3 5 and FH P2 5 were not significantly different ($P > 0.05$). However, they were significantly higher than FH P2 10 (0.56 g/cm^3), FH P1 10 (0.50 g/cm^3) and FH P3 10 (0.49 g/cm^3) as their pellet density was ranging from 0.65

g/cm^3 to 0.72 g/cm^3. It appears that an increase in wax percentage from 5 % to 10% lowered the pellet density of the torrefied fruit husk. However, the increase in pelletisation pressure had little effect on the pellet density as majority of the treatment had similar pellet density. This is also illustrated by Fig.2 which shows that FH P1 10, FH P2 10 and FH P3 10 were the lowest in pellet density amongst the fruit husk biomass. The observation suggest that an increase in the wax percentage lowered the interlocking capacity of the torrefied fruit husk particles. This was also observed during experimental run trials when wax percentage of 15% and 20% were carried out. The pellets made from the high wax percentage collapsed before the pressure load was removed. This likely explains why the FH pellets with wax absorbed more moisture as indicate in Section 3.1. It could then be concluded that for the torrefied Jatropha fruit husk, a wax content of 10% and above is not recommended as it is likely to reduce the pellet density of the torrefied fruit husk under the current experimental conditions. The overlapping of the pellet density amongst the FH material seems to further suggest that the best pellets could be selected from FH P1, FH P3, FH P1 5, FH P3 5 and FH P2 5.

The observation on the pelletisation of torrefied stem biomass showed that most of the treatments had no significant difference ($P > 0.05$), however the pellets with some wax percentage (STEM P1 10, STEM P2 10, STEM P3 10) showed superior pellet density when compared to pellets without wax (STEM P1, STEM P2, STEM P3). This is also illustrated by Fig. 2 which shows that STEM P1 10 had the highest pellet density (0.59g/cm^3) and STEM P2 was the lowest (0.52 g/cm^3). This shows an increse in pellet denisty of 148% and 118% for STEM P1 10 and STEM P2 respectively. However, it must be noted that, though STEM P1 10 was the highest, it was only significantly different ($P < 0.05$) from STEM P2. The observation seem to suggest that the addition of wax to torrefied stem biomass had some influence on the pellet density of the torrefied stem but to a lesser degree when compared to FH pellets. The high pellet density of the torrefied stem with wax seems to have also influenced their lower hydrophobicity as indicated in Section 3.3.

The general observation is that biomass of lower density result in solid fuel of low pellet density and vice versa. Previous studies by Kethobile et al. [28] showed that Jatropha seed cake biomass had the highest bulk dentistry followed by the fruit husk and stem. This is agreeable to findings by Gaitán-Alvarez et al. [34]

3.3 Hydrophobicity

A solid fuel which could stand harsh environmental conditions such as exposure to high humidity and rainy season is highly desirable. These conditions adversely affect the calorific value and burning properties of the solid fuel hence, investigation of the hydrophobicity of the torrefied fuel pellets. The statistical analysis was carried out for each time interval (H1 – H72) as presented in Fig. 3 to 10; and the drying pattern of each treatment combination and biomass material is also presented in Fig. 12 to 14.

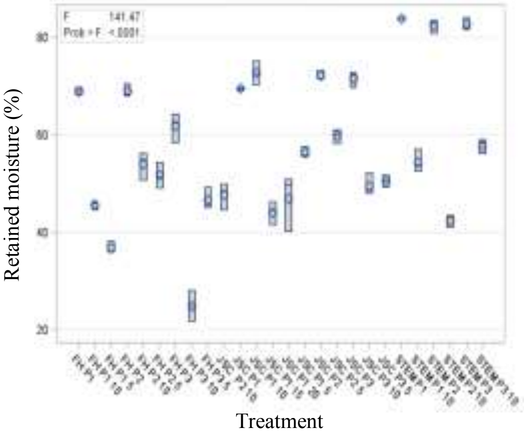

Fig.3: Hydrophobicity test of torrefied Jatropha biomass at H1 time

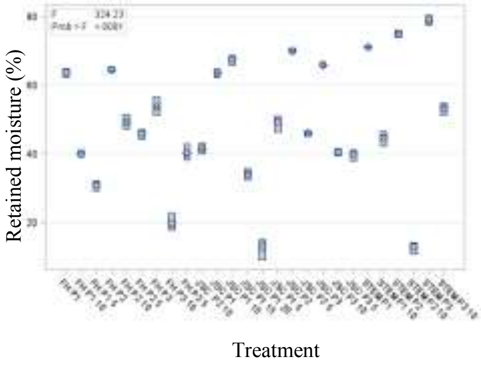

Fig. 4: Hydrophobicity test of torrefied Jatropha biomass at H2 time

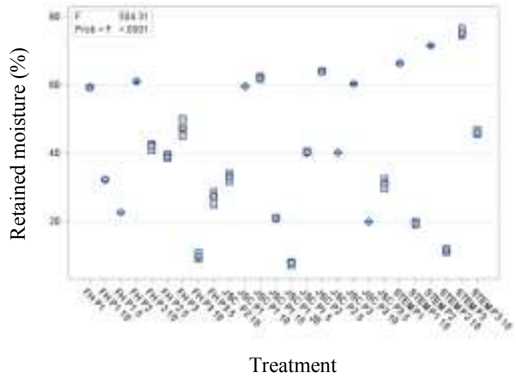

Fig. 5: Hydrophobicity test of torrefied Jatropha biomass at H3 time

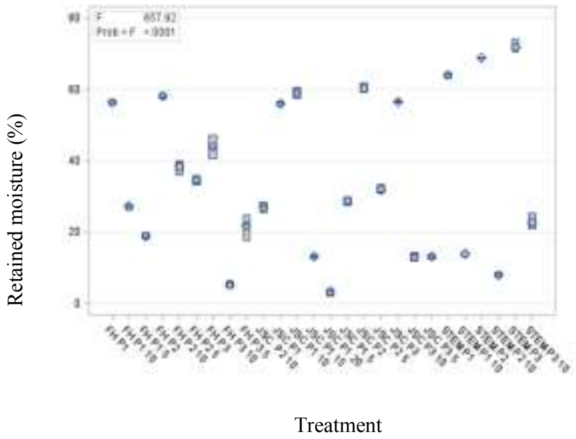

Fig.6: Hydrophobicity test of torrefied Jatropha biomass at H4 time

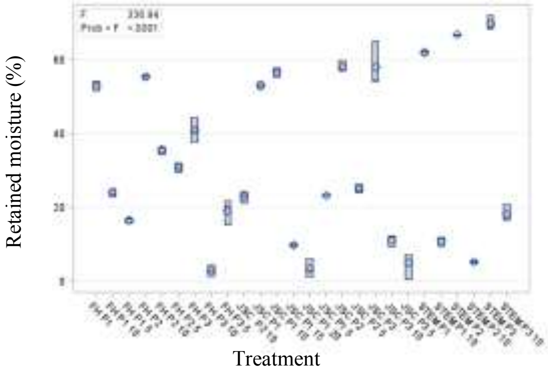

Fig. 7: Hydrophobicity test of torrefied Jatropha biomass at H5 time

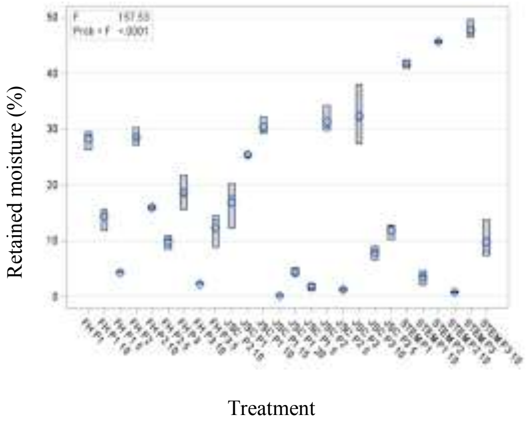

Fig. 8: Hydrophobicity test of torrefied Jatropha biomass at H20 time

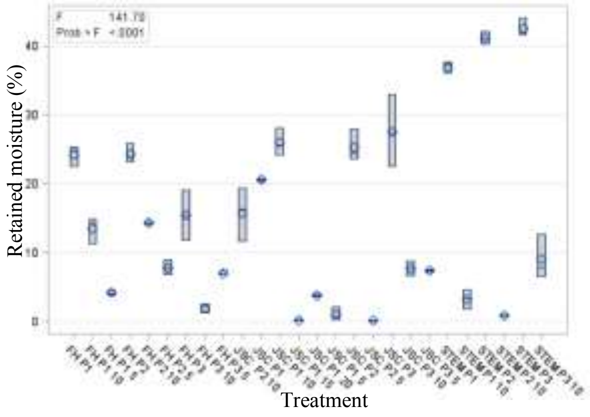

Fig. 9: Hydrophobicity test of torrefied Jatropha biomass at H24 time

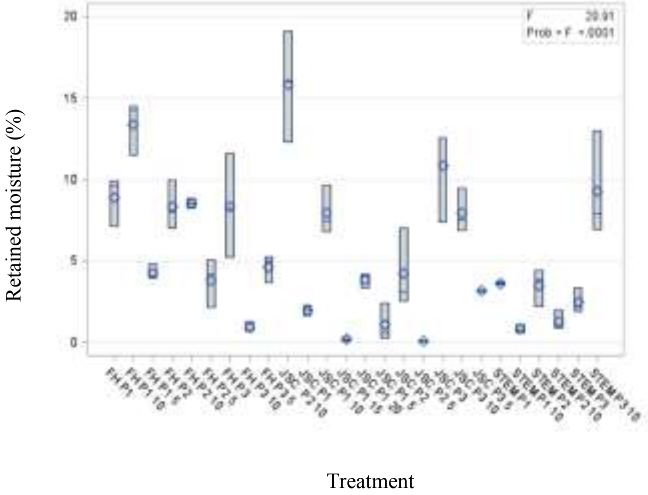

Fig. 10: Hydrophobicity test of torrefied Jatropha biomass at H72 time

The ANOVA portrayed that there was significant difference ($P < 0.05$) among all the treatments at all-time intervals. The results in Figures 3 to 10 show that the difference amongst the treatments was not clear at the beginning of drying (H1 – H4) but as the time elapsed (H5 – H72), the stem treatments without wax (STEM P1, STEM P2, STEM P3) appear to have retained more moisture contents than others. They swelled and even the pellet structure collapsed as illustrated by Fig. 11 (a) and (b). This shows that they were more hydrophilic than all the other pellets.

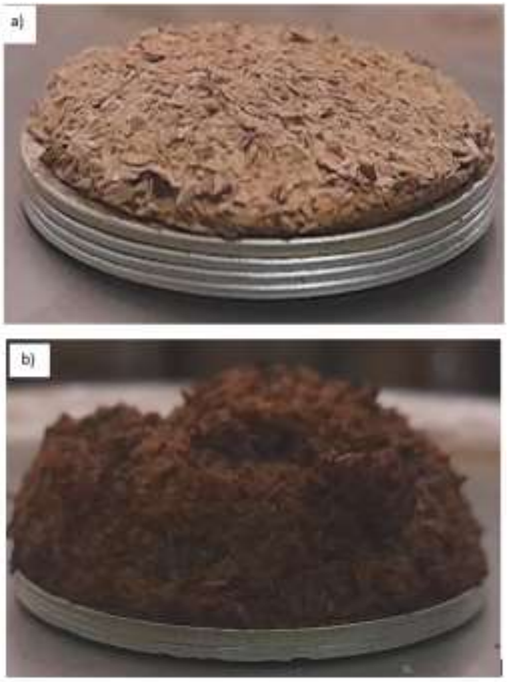

Fig. 11: Non-wax torrefied Jatropha stem pellets a) before and b) after immersed in distilled water

This is also shown by separation of means (lsd) and Fig. 12 which illustrates that they were consistently higher than the other treatments across the time intervals in terms of moisture retained. The higher moisture retention in the stem pellets with no wax could be attributed to the fact that they were torrefied at lower temperature and therefore still contained hemicellulose molecules which are known to attract moisture as mentioned in Section 3.1. However, after 72 hours (H72) of air drying, non-wax stem pellets (STEM P1, STEM P2 and STEM P3) showed significant reduction in moisture retained as indicated by Fig. 12. This could be attributed to the collapse of their pellets structure as shown by Fig. 11(b). The water molecules were now able to easily exit the biomass particles especially as there was no wax to impede their escape. The high moisture retention and swelling characteristics of the non-wax Jatropha stem pellets makes them unsuitable for solid fuel use unless they are stored in a dry place. This will therefore results in more cost for special storage needs. The stem pellets with 10% wax showed good hydrophobicity continuously as also illustrated by Fig. 3 to 10. If one considers torrefied stem pellets only, STEM P2 10 showed good hydrophobicity though it was closer to STEM P1 10. They could therefore be considered a better option for solid fuel use.

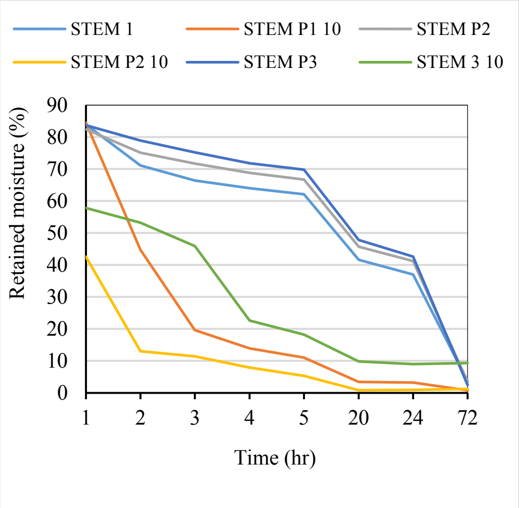

Fig. 12: Drying profile of the torrefied Jatropha stem pellets

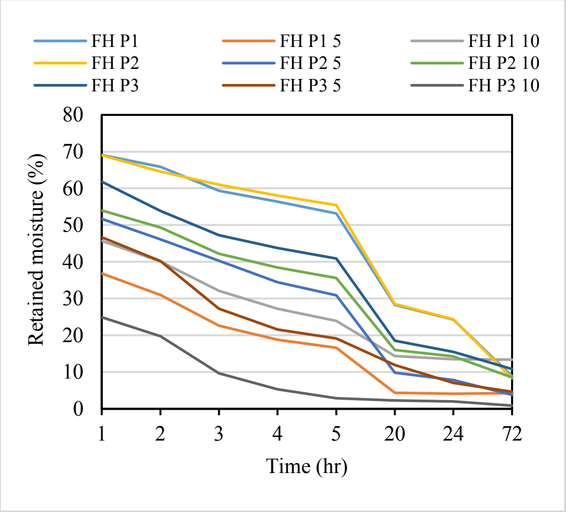

Fig. 13: Drying profile of the torrefied Jatropha fruit husk pellets

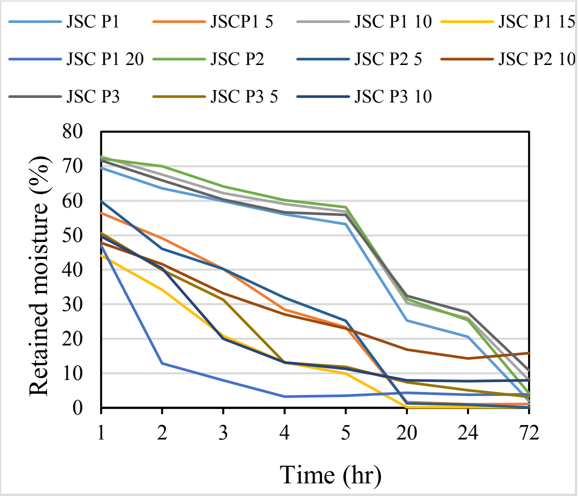

Fig. 14: Drying profile of the torrefied Jatropha seed cake pellets

However, the moisture content of stem pellets with wax were the highest amongst the stem materials before hydrophobicity test as was indicated by Fig. 1 in Section 3.1. Nonetheless the value was less than 20% which is acceptable for a solid fuel as indicated in litrerature [35, 36] .

The Jatropha fruit husk pellets (FH) showed that FH P3 10 and FH P1 5 were consistently the lowest in terms of moisture retention. The statistical analysis as illustrated by Figures 3 to 10 shows that FH P3 10 and FH P1 5 showed lower water retention capacity from H1 to H72. This is also illustrated by Fig. 13 which shows the drying pattern of the pellets. The good hydrophobicity of FH P1 5 could also be attributed to its high pellet density as indicated in Section 3.2. This therefore indicates that amongst the fruit husk pellets it could be selected as far as moisture retention and hydrophobicity is concerned. Torrefaction is reported to make biomass more hydrophobic by the removal of hydroxyl groups as the biomass decomposes with an increase in temperature [15]. This could be the reason why the hydrophobicity of FH pellets was generally higher than the stem and seed cake.

The Jatropha seed cake pellets analysis is a bit complicated as there are several overlaps and changes as time changed from H1 to H72. However, it should be noted that biomass suitable for solid fuel use, is the one which retains less moisture and dries faster. In these experimental runs, the torrefied seed cake pellets with higher wax percentage (JSC P1 15, JSC P1 20) absorbed less moisture and stayed consistent across the time intervals. However, it was observed that after immersing in distilled water, they showed instability as they crumbled after absorbing some water molecules. The burning rate test runs in Section 3.4 also showed that during heating, these pellets melted into liquid mortar during combustion. These are some of negative characteristics which are not suitable for solid fuel especially for their potential use in boilers. For time interval H1 – H5, with exclusion of JSC P1 15 and JSC P1 20, the JSC P3 5 and JSC P3 10 were statistically the lowest ($P < 0.05$) amongst the torrefied Jatropha seed cake pellets. However, at time interval H20 – H72; JSC P2 5, JSC P2 10 and JSC P1 5 started to show similar pattern as illustrated in Fig. 14. This means that though JSC P2 5, JSC P2 10 and JSC P1 5 were not amongst the lowest in terms of moisture retention at the beginning, they dried faster. They could therefore be considered together with JSC P3 5 and JSC P3 10 as the best option for JSC. They also demonstrated relatively better stability when compared to JSC P1 15 and JSC P1 20.

The general conclusion that can be made from the hydrophobicity analysis is that the torrefied Jatropha seed cake pellet and fruit husk showed superior characteristics when compared to torrefied stem pellets. The stem pellets without wax for them to be used as solid fuel they must be stored under waterproof environment otherwise they would disintegrate into individual particles.

3.4 Burning rate

The ANOVA showed that generally the burning rate of the torrefied Jatropha fruit husk (FH) was significantly ($P < 0.05$) slower than the burning rate of both the torrefied fruit husk and stem pellets. This is illustrated by Figures 15, 16, 17 and 18.

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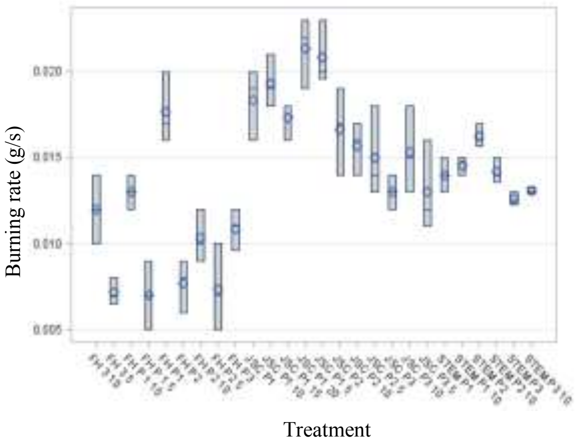

Fig. 15: Burning rate of the torrefied Jatropha biomass pellets

The results in Fig. 15 show that most of FH pellets had a significantly ($P < 0.05$) slower burning rate of less than 0.013 g/s when compared to the STEM and JSC. The slower burning rate of the torrefied fruit husk pellets could be attributed to the fact that they were a product of higher torrefaction temperature (275°C) whereas the stem and seed cake pellets were torrefied at 225°C and 250°C. A study by Kethobile et al. [1] showed that the Jatropha fruit husk torrefied at 275°C had more fixed carbon and less volatiles when compared to seed cake and stem torrefied at 250°C and 225°C respectively. The slower burning rate of the torrefied fruit husk pellets could therefore be attributed to the fact that a biomass fuel torrefied at a higher temperature is more stable and burns slowly. The results in Fig.15 also show that within the FH biomass, FH P1 (0.017g/s) had the fastest burning rate whereas FH P1 5 (0.007g/s) had the slowest burning rate. However, FH P1 5 was statistically similar ($P > 0.05$) to FH P3 5, FH P2 5, and FH P2. This is further illustrated by Figure 16 which shows these FH 1 5 pellets took longer time of more than 700 seconds to burn out when compared to FH P1 which took about 320 seconds. FH P1 was statistically ($P < 0.05$) the fastest in terms of burning rate and this shows relatively weak characteristics for biomass to be used as a solid fuel.

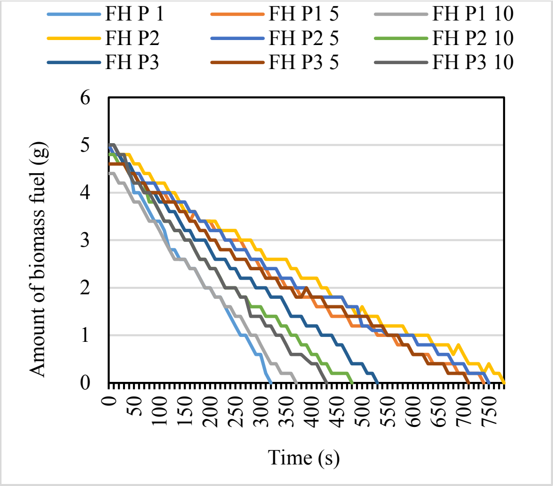

Fig. 16: Decaying of the torrefied Jatropha fruit husk (FH) pellets

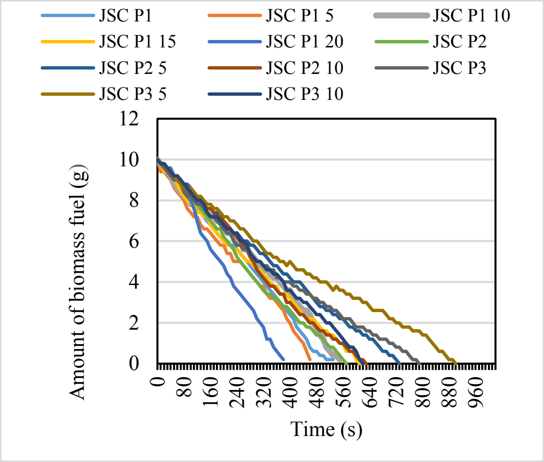

Fig. 17: Decaying of the torrefied Jatropha seed cake (JSC) pellets

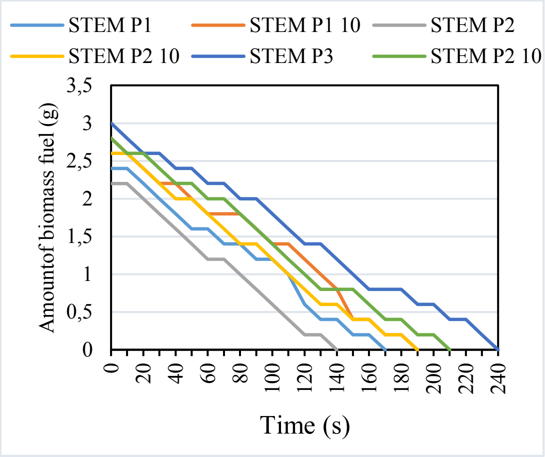

Fig. 18: Decaying of the torrefied Jatropha stem (STEM) pellets

The ANOVA showed that within the torrefied JSC pellets, the JSC P3 5 (0.013g/s) was statistically the slowest in terms of burning rate. Hoever it was not statistically separated ($P > 0.05$) from JSC P3, JSC P2 5, JSC P3 10 and JSC P2 10. This indicates that they had similar combustion rate.The JSC P1 20 (0.021 g/s) was statistically the fastest in terms of burning rate, however it was statistically similar to JSC P1 5, JSC P1 10 and JSC P1. These results are further demonstrated by Fig. 15 and 17 which shows that within the JSC pellets, the burning rate of the pellets made at pressure above 280MPa were slower than of pellets made at lower pelletising pressure (P1). The Figures generally reveals that the JSC pellets which were made from high compression pressure burned at slower rate of less than 0.017g/s and therefore likely to be suitable for solid fuel use. Usually a biomass with a slower burning rate is prefered as a source of heat as it would provide a steady source of heating. The results in Fig. 17 also show that it took the P1 pellets shorter time of less than 650 seconds to decay when compared to P2 and P3 pellets which took up to 900 seconds to burn out. During the experimental runs it was also observed that JSC P1 20 and JSC P1 15 melted into a liquid mortar before burning into gas. This is a negative characteristic for solid fuel because it can results in clogging of boilers and chimneys during combustion. This will also increase the maintenance costs of boilers as there will be a need for more frequent cleaning. The JSC P1 20 and JSC P1 15 also showed instability when immersed it water as indicated in Section 3.3.

The analysis of the stem results shows that STEM P3 (0.0126g/s) had the slowest burning rate though only statistically different ($P < 0.05$) from STEM P2 (0.0167g/s). However, the STEM P3 showed low characteristic of moisture repellent as indicated in Section 3.3. Infact all the stem pellets without wax (P1, P2, P3) showed poor hydrophobicity and therefore if they are to be used as fuel they should be stored in a moisture proof environment. This therefore means that STEM P3 10 (0.0131g/s), STEM P2 10(0.0142g/s) and STEM P1 10 (0.0146 g/s) could be considered as a source of solid fuel within the stem treatments.

4. Conclusions

The JSC P3 10, JSC P1 5, JSC P2 5, JSC P2, JSC P2 10 and JSC P3 had the lowest moisture content (1.6%) amongst all the treatments. The FH P1 (3.3%) and FH P1 5 (3.62%) had the lowest moisture contnet within the FH treatments whereas the STEM P3 (3.29%) was the most favourable in terms of moisture contnet within the stem treatments.

JSC P3, JSC P1 10, JSC P1 5 and JSC P3 5 had the highest pellet density of more than 0.8 g/cm^3 which makes them more favourable for solid fuel use. Within the FH pellets the FH P1, FH P1 5, FH P2, FH P3 and FH P3 5 had the highest pellet density ranging from 0.65 g/cm^3 to 0.72 g/cm^3. The pelletisation process increased the pellet density of the stem pellets by 118% to148% and STEM P1 10 had the highest pellet density (0.59g/cm^3) within the stem pellets.

FH P3 10 and FH P1 5 showed favourable hydrophobicity though they were similar to JSC P3 5, JSC P2 10, JSC P2 5, JSC P2 10 and JSC P1 5. Wihin the the torrefied stem pellets, the wax addition improved their hydrophobicity as STEM P1 10 and STEM P2 10 had superior hydrophobicity within the stem pellets.

The burning rate of the FH pellets was generally the slowest and within the FH pellets; FH P1 5, FH P3 5, FH P2 5 and FH 2 with a burning rate of approximately 0.007 g/s were the best. However within the JSC pellets, JSC P3 5, JSC P3, JSC P2 5, JSC P3 10 and JSC P2 10 had the slowest burning rate ranging from 0.013g/s to 0.015 g/s. This was similar to the burning rate of the STEM pellets with wax (P1 10, P2 10, P3 10).

The overall conclusion considering all the parameters under investigation is that JSC P3, JSC P3 5, JSC P1 5 and JSC P2 5 showed superior solid fuel qualities amongst all the treatments under investigation. They showed best results in 3 out of 4 parameters which were investigated.

Acknowledgements

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