Steam explosion of oil palm residues for the production of durable pellets

Pak Sui Lam^{a,}, Pak Yiu Lam^a, Shahab Sokhansanj^{a,b}, C. Jim Lim^a, Xiaotao T. Bi^a, James D.
Stephen^{c,e}, Amadeus Pribowo^{d,e}, Warren E. Mabee^{c,e}*

^aDepartment of Chemical and Biological Engineering, University of British Columbia,
2360 East Mall, Vancouver, BC, V6T 1Z3, Canada

^bEnvironmental Science Division, Oak Ridge National Laboratory, P.O. Box 2008,
Oak Ridge, TN, 37831-6422, USA

^cQueen's Institute for Energy and Environmental Policy, Queen's University, 138
Union Street, Robert Sutherland Hall, Kingston, ON K7L 3N6, Canada

^dDepartment of Wood Science, University of British Columbia, 2424 Main Mall,
Vancouver, BC V6T 1Z4, Canada

^eTorchLight Bioresources Inc., 1901-5000 Yonge Street, Toronto, ON M2N
7E9, Canada

ABSTRACT

The effect of steam explosion pretreatment on the physical and mechanical
properties of the pellets made from empty fruit bunch (EFB) and palm kernel shell (PKS)
was investigated and compared to that of softwood Douglas fir (DF). It was found that the
high heating value of the empty fruit bunch was increased by 21% after steam explosion

* Corresponding author. Email: wilsonlam82@yahoo.com; Tel: +604-355-8811; fax: +604-822-6003;

pretreatment. The pellet density of EFB and Douglas fir pellets did not change while the pellet density of PKS increased from 1.13 to 1.21 g/cm³ after steam explosion. That may be attributed to the rapid volatilization of high mass fraction extractives during high pressure steaming and lead to the shrinkage of micropores of the PKS fibers. The maximum breaking strength of steam exploded EFB and PKS were increased by 63 and 45%, respectively. The required compaction energy for the steam exploded EFB pellet is 44.50 J/g while that of the untreated EFB pellet is 30.15 J/g. Similar to Douglas fir, the required extrusion energy for the steam exploded EFB pellet was about 6 times than that of the untreated EFB pellet. The increased extrusion energy is mainly contributed by the increase in mono-saccharides by auto-hydrolysis during steam explosion pretreatment.

Keywords: Empty fruit bunch; Palm kernel shell; Pellet; Density; Compression energy; Steam explosion

1. Introduction

Palm oil is an important cooking ingredient and accounts for one third of the world's vegetable oil market in 2007 [1]. In southeast Asia, around 85% of palm oil is produced in Malaysia and Indonesia and palm oil is currently the only crop used as feedstock for biodiesel production [2]. Palm oil has to be processed and refined by mechanical pulping from the oil palm bunches. During the palm oil extraction process, the oil palm bunches were initially sterilized by low pressure steam at 140 °C and 0.28 MPa and followed by extracting the palm oil from the fruit bunches by threshing [3]. Threshing is a process of which a rotary drum or a fixed drum equipped with rotary beater bars to detach the fruit from bunches. The residue produced during the threshing is the empty fruit

bunch (EFB). The fruit bunch is further digested by steaming at 80 to 90 °C for breaking down the oil bearing cells [4]. The pure palm oil is then obtained by pulp pressing on the digested mixture and followed by clarification, drying and storage. Meanwhile, the palm kernel shell (PKS) are extracted as by-product. It was reported that there were 232 million bone dry tonnes of oil palm residues produced from these process [5, 6].

Disposal of substantial agricultural residues is an urgent and critical issue for the palm oil mills. Currently, they are decomposed in open fields when open incineration cannot be applied as disposal method. As a result, a significant of energy is wasted. It is of question how to utilize these abundant oil palm residues effectively by converting EFB and PKS into useful energy. EFB and PKS are agricultural materials with different chemical composition but with similar high heating value (HHV) around 18 - 19 MJ/kg [7]. It is expected that they can be burnt to recover similar energy as the woody biomass. They are good supplement when wood pellets are in short supply.

From the life cycle analysis (LCA) of different potential applications of using EFB for energy production in Malaysia, the most attractive and promising application is 100% firing EFB and PKS for combined heat and power (CHP) [8]. However, the raw EFB are bulky with high moisture content and makes it difficult to be burnt or gasified with high efficiency and low emissions. Similar to the pretreatment of woody biomass, pelletization of these oil palm residues help to eliminate these problem, for example, the feeding performance of these residue to the downdraft gasifier or combustion unit is much improved due to their lower moisture content and regular particle size [9]. EFB pellets exhibit three times higher bulk density, lower moisture content and with reduced particle sizes compared to their raw materials, which are preferred feedstock for combustion to

65 produce heat and power [10].

66 Gasification of wood pellets results in a richer producer gas while EFB pellets give
67 a poorer one with higher contents of non-combustible compounds [11]. Another barrier of
68 using EFB and PKS as biofuel for combustion is that they have a higher ash content
69 between 2 – 5% wt. [7] than woody biomass (around < 0.2 % wt.) [12]. This may impose a
70 significant ash handling, slagging and fouling problems during combustion. Applying
71 water leaching prior to pellet production for metal and ash removal would be
72 recommended to prepare a good quality feedstock to the power plant [7, 13].

73 Steam explosion pretreatment had been reported as an effective pretreatment for
74 improving the handling, storing and fuel properties of the softwood pellets [12, 14, 15]. It
75 was reported that the steam exploded Douglas fir pellets exhibited a stronger mechanical
76 strength than that of untreated Douglas fir pellets. From the hardness test, the required
77 force to break the steam exploded Douglas fir pellets range between 1.4 and 3.3 times than
78 that of untreated Douglas fir pellets depending on treatment severity [14]. The steam
79 exploded Douglas fir pellets exhibited a better moisture adsorption resistance compared to
80 the untreated Douglas fir pellets. This was attributed to the reduction of hydroxyl groups of
81 hemicellulose and the shrinkage of fibre pores after the steam explosion pretreatment [16].
82 The improvement in binding ability between the Douglas fir fibers was contributed by the
83 bonding between the mono-sugars and re-condensed lignin of the fiber; for which are
84 produced during the saturated steam auto-hydrolysis between 200 – 220 °C (1.6 – 2.4 MPa)
85 for 5 – 10 min and followed by a rapid decompression [17]. Meanwhile, these mono-sugars
86 and structural changes of the Douglas fir fibers led to a higher required compression and
87 extrusion energy for producing steam treated Douglas fir pellets compared to the untreated

Douglas fir pellets. Therefore, it is necessary to understand the mechanical properties of different types of biomass by characterizing their chemical composition as well as the effect of steam explosion pretreatment on their pellet quality and production energy usage.

At present, there is limited literature reporting the mechanical properties of pellets made from oil palm residue [18 - 20]. It was demonstrated that a PKS briquette blended with palm fiber and using waste paper as binding agent gave the best mechanical properties [20]. However, the briquettes produced solely of PKS without binders were easy to disintegrate in the hardness test. This suggests that there is a need of pretreatment or adding binder to enhance their pellet strength.

The objectives of this research are to characterize the effect of steam explosion on the mechanical strength of the pellets made from the oil palm residues (i.e. EFB and PKS) and to quantify the spent energy for pellet production using a single die tester. The physical and mechanical properties of the untreated and steam exploded EFB and PKS pellets were also characterized. By using the previous studies of untreated and steam exploded Douglas fir pellets as baseline, this research finding would be beneficial to the biomass researchers and the emerging oil palm pellet industry designing a safe process of oil palm residues to produce high quality solid biofuels.

2. Materials and methods

2.1 Materials

The Empty Fruit Branches (EFB) and Palm Kernel Shell (PKS) used in this research were obtained from the Palm Oil Industrial Cluster (POIC) Sabah Sdn Bhd in Lahad Datu, Malaysia, and received with 25 % (w.b.) moisture content (wet basis). The

moisture content was determined based on the ASABE S358.2 standard [21]. The as-received EFB and PKS were conditioned to moisture content of average 15 % with ± 1 % (w.b.) at a drying temperature of 50 °C in a convection oven. The conditioned materials were further processed into ground particles with a Retsch SM100 model knife mill (Retsch Inc., Newtown, PA) equipped with a 6 mm screen size. The moisture content of the recovered ground particles from the knife mill conditioned to 10% prior to pelletization. For the Douglas fir (DF), the sample preparation was described in our previous publication [14].

The particle size analysis was performed according to the ASABE S319.3 standard [22]. The experimental setup was a Ro-Tap sieve shaker (Tyler Industrial Products, Mentor, OH). Exact 20 g of the ground sample was placed on top of the stack of sieves from the smallest to the largest mesh number. The mesh numbers of sieves for the particle size distribution were 7, 10, 14, 18, 25, 35, 45, 60, 80 and 100. The nominal sieve openings corresponding to the mesh numbers were 4, 2, 1.41, 1, 0.707, 0.5, 0.354, 0.25, 0.177, and 0.149 mm, respectively. The sieving duration was 5 min.

2.2 Steam explosion pretreatment

The steam explosion (SE) pretreatment of EFB, PKS and DF was carried out using the steam explosion unit in UBC Clean Energy Research Center (Fig. 1.). It consists of a 1 L steam reactor and a 2 L boiler for steam generation. The 1 L steam reactor was equipped with a 12.7 mm diameter ball valve (B-1) and controlled by an electrical actuator for a sudden depressurization of the steam treated mixtures into the collection vessel at ambient pressure. A 3 – zone tubular furnace (Lindberg/Blue M, STF55666C, Thermo Fisher

Scientific Inc., Waltham, MA, USA) was used to supply heat for the 2 L boiler to produce saturated steam.

Prior to feeding, the ball valve (B-1) must be in closed position to ensure the generated steam reached the target temperature and pressure before transferring to the steam reactor for pretreatment. Then, 30.0 g (w.b.) ground material was fed using a funnel into the steam reactor via the opened B-3 ball valve. The valve was closed once the feeding was complete. After that, 300 ml of water were pumped into the boiler to produce saturated steam at 220 °C with closed B-2, B-4 and B-6 ball valves. When the steam temperature reached the desired experimental condition, the saturated steam was allowed to flow from the boiler to the steam reactor via B-2 ball valve and steamed the material for 5 min at 220 °C. The ball valve B-2 was then closed to make the reactor for steaming. The temperature and pressure profile during steaming was logged at 1 data per second by Labview 8.2 software (National Instruments, Austin, TX, USA). The automatic solenoid valve (B-1) was activated to be opened through Labview when the target steaming time of 5 min was reached. The treated material was ejected at once into a container from the steam reactor and stored inside zip-lock bags in a cold room under 4 °C. In order to investigate the effects of steam explosion on steam exploded EFB and PKS pellets, no further milling and additional moisture was added into the steam exploded EFB and PKS prior to pelletization.

2.3 Pelletization

A single die pelletizing unit equipped with an MTI 50K (Measurement Technology Inc.) system was used to produce pellets for physical and mechanical characterization. The detail explanation of the unit's operation was reported in the previous literatures [7, 12, 23]. During the compression, 0.85 g of ground material was filled into the die channel to

form an initial loose bulk packing. The MTI machine was pre-set at a maximum of 4000 N downward compressive force. The moving speed of the piston was 10 mm/min downward. When the maximum compression force reached 4000 N, the piston stopped the movement and halted at that position for 15 s to undergo stress relaxation. After 15 s, the small block underneath the die channel was removed and the piston extruded the pellet out of the die channel. Five replicates of pellets were made for each sample. The data logging system connecting to the MTI system recorded the force and displacement data during compression and extrusion. The summation of the area under the force v.s. displacement curve of compression and extrusion was the total energy consumption to make a pellet.

2.4 Physical characterization

The moisture content of the treated and untreated ground material was analyzed according to ASABE S358.2 standard [21]. Triplicate samples with roughly 0.85 g of ground material were oven dried at 103 °C for 24 h to determine the moisture content based on the weight loss. The moisture content of pellets was calculated after pelletization due to wet mass loss. The high heating values of the pellets were determined by the oxygen bomb calorimeter (Parr 6100) from two replicates.

The ash content was determined using the NREL biomass chemical composition analysis [24]. Approximately 0.5 g of the fully dried sample was placed in a porcelain crucible inside a muffle furnace (Blue M Electric Company, Blue Island, IL). The temperature of the furnace was increased from the ambient temperature to 250 °C for 30 min and then to 575 °C for 3 h. The samples were cooled to 105 °C for 8 h until the samples were collected. The cooled samples were covered, removed from the furnace, and then cooled to room temperature inside a glass desiccator. The mass retained in the crucible was

expressed as percent ash content. The ash content measurement was repeated three times for each sample.

The mass, length and diameter of each pellet were measured immediately after its removal from the cylinder to calculate the pellet density. A true density was determined by measuring the total pore volume in a pellet by compressing nitrogen at 103 kPa into void spaces of the pellets using a Quantachrome Multipycnometer (Quantachrome, Boyton Beach, FL, USA). The weight of the pellet was measured using the ALC-80.4 analytical balance (Acculab, Edgewood, NY) with 0.0001-g precision. Porosity, the void space existing within a pellet, was calculated by the difference of the true density and the pellet density dividing the true density.

$$\varepsilon_0 = 1 - \frac{\rho_p}{\rho_s} \quad (1)$$

where ε_0 is the bulk porosity of pellet (dimensionless), ρ_p is the pellet density (g/cm^3) and ρ_s is the true density (g/cm^3) of the pellet.

2.5 Stress relaxation and hardness test

Recent study investigated the effect of steam explosion pretreatment on stress relaxation of steam exploded Douglas fir pellet by measuring the applied stress against time during creeping [17]. The force relaxation curves of pellets were normalized and linearized and represented as a straight line.

$$\frac{\sigma_0 t}{\sigma_0 - \sigma(t)} = k_1 + k_2 t \quad (2)$$

where σ_0 is the initial stress (GPa), $\sigma(t)$ the stress after time t at relaxation (GPa), t is time (s) and k_1 as well as k_2 are constants. Eq. (1) can be fitted to the stress relaxation data to

estimate k_1 and k_2 . The estimated k_2 value is then used in Eq. (3) to calculate E_A .

The asymptotic modulus (E_A) can be an empirical index of solidity which is the ability of the compressed powder to sustain unrelaxed stresses; E_A is defined as

$$E_A = \frac{\sigma_0}{\varepsilon} \left(1 - \frac{1}{k_2} \right) \quad (3)$$

where E_A is the asymptotic modulus (GPa) and ε is the strain (dimensionless or m/m).

For hardness test, a single pellet was placed on a compression plate fixture of the MTI machine and the 6.35 mm diameter compression rod was set to indent downward at the middle of the pellet. The compression rod was initially moved down to barely in contact with the pellet without applying a pre-loading force. Subsequently, the downward loading was then applied for indentation and the mechanical strength of the pellet was estimated from the force displacement diagram. The maximum breaking strength (MPa) of a pellet was calculated by the maximum force dividing the cross sectional area of the compression rod. The Meyer hardness (H_M) is defined as the applied force divided by the projected indentation area [14, 17],

$$H_M = \frac{F}{\pi(Dh - h^2)} \quad (4)$$

where H_M is the Meyer hardness (N/mm²), h is the indentation depth (mm), D is the initial diameter of a pellet cross-section (mm²), and F is the maximum force when the pellet is crushed (N).

3. Results and Discussion

3.1 Steam explosion pretreatment

The pressure and temperature profile of Douglas fir, EFB and PKS during 5 min steam explosion were depicted in Fig. 2 and Fig. 3, respectively. In general, both Douglas fir and EFB showed a slight increase of pressure for the first 2 min and decreased slightly for the remaining 3 min prior to a rapid depressurization occurred (i.e. explosion effect). The initial increase of pressure was due to the energy transfer from the high energy steam to the biomass particles for the facilitation of the auto-hydrolysis and evaporated the furfural/5-hydroxymethylfurfural produced from the dehydration of mono-saccharides derived from hemicelluloses. This was also agreed well with the increase in temperature for EFB and Douglas fir during the initial steaming. The condensation of steam on the particle surface resulted in a pressure drop after 3 min.

However, the pressure and temperature profile of PKS during steam explosion for 5 min at 220 °C was different from that of EFB and Douglas fir. The steam pressure of PKS was leveled off for the first min and kept increasing from 230 to 290 PSI prior to the rapid depressurization. Similarly, the temperature profile of PKS followed the same trend as pressure. The steam temperature increased from 208 to 240 °C within 2.5 min and remained level off around 238 °C for the remaining 2.5 min prior to rapid depressurization. The sharp increase in pressure and temperature indicated that there were volatiles generated during steaming of PKS instead of undergoing hydrolysis. The increase in pressure is more pronounced for PKS than that of EFB as PKS has a higher mass fraction of extractives than EFB. The EFB has 43.8 wt.% cellulose, 35 wt.% hemicellulose, 16.04 wt.% lignin and 4.8 % extractives [25] while the PKS has 30.59 wt.% cellulose, 30.64 wt.% hemicellulose, 20.41% lignin and 18.36 % extractives [26]. From our experiment, it was observed that there were some small fire sparks during the rapid depressurization. In

addition, there was a very strong odor from the collected treated PKS. This implies that an additional attention of potential fire or explosion hazard has to be paid when the PKS with high extractives content used as a raw material for producing pellets. The pellets continued to emit flammable gases, such as CO, H₂ and CH₄, during transportation and storage [27]. In hindsight, there may be a need of extractives removal of PKS prior to steam explosion pretreatment for producing durable pellets.

3.2 Physical and mechanical characterization

Fig. 4 shows the test samples after grinding, steam treatment and pelletization. For untreated ground particles, EFB has a slightly less dark color compared to PKS and with a smaller particle size distribution with a geometric mean diameter 0.31 mm (Fig. 5). In contrast, the geometric mean particle diameter of untreated PKS ground particle is 0.72 mm. However, the EFB powder exhibited a darker color than that of PKS with steam explosion pretreatment at 220 °C for 5 min. The dark color of the steam exploded EFB may be attributed to the Maillard reaction of hemicellulose and the degradation of extractives that was previously explained for the steam treated wood pellets color change [28]. EFB has a higher hemicellulose and lower lignin content compared to softwood. Due to a lower recalcitrance to saccharification of EFB, EFB is an excellent potential raw material for fuel ethanol production [29].

The increase in darkness of the steam exploded EFB was highly correlated with an increase in its high heating value (HHV) from 18.54 to 22.42 MJ/kg (wet basis). This corresponds to an increase of 21% of HHV (wet basis) by removing the moisture and volatiles with low heating value during steam explosion pretreatment. Surprisingly, this value was much higher than the increase in HHV of Douglas fir with 2.6%. For PKS, steam

explosion did not have a significant effect on the changes of heating values with a P-value < 0.05. Although steam explosion increase the high heating value of EFB by 21%, there was a considerable tradeoff that the ash content also increased from 5.47 – 8.08%. This was a reasonable result as there was a loss of volatiles during steam treatment. In order to reduce the ash content of EFB, water leaching is deemed as a possible pre-treatment process in removing the soluble ash from the surface of the EFB particles prior to steam explosion [13].

The EFB and Douglas fir pellets did not show a significant change of pellet density after steam explosion and were 1.14 and 1.08 g/cm³, respectively (Table 1). This is different from the previous report on increasing pellet density of other agriculture species: barley, canola, oat and straw, by steam explosion pretreatment [30]. The difference in pellet density was accounted by different steam explosion treatment severity being used in different studies. Adapa et al. (2010) reported steam exploded agricultural pellets were treated at a milder condition at 180 °C for 5 min [30]. Meanwhile, our current study chose a more severe treatment condition at 220 °C for 5 min. At higher treatment severity, there would be more major materials loss as vapor during steam explosion pretreatment (e.g. degradation of furfural from hemicelluloses and become vapor). As a result, the produced pellets treated at high treatment severity become lighter and results in a more or less the same pellet density when compared to untreated pellets. However, steam explosion pretreatment improved the pellet density of PKS from 1.13 to 1.21 g/cm³ and with a reduction of porosity from 17.9 to 10.1 %. This may attribute to the rapid volatilization of extractives during high pressure steaming and led to the shrinkage of micropores of the PKS fibers. For the EFB and softwood Douglas fir, they exhibited a very small change of

porosity within 1% after steam explosion pretreatment.

For the mechanical strength of the steam exploded pellets, the maximum breaking strength of EFB and PKS were increased by 63 and 45%, respectively (Table 2). Similar percentage increase was also observed for the Meyer hardness. Although there is a noticeable increase in mechanical strength of the steam exploded EFB and PKS pellets, their degree of percentage increase is not as much as the softwood Douglas fir. Lam et al. [17] reported that pseudolignin activated by steam explosion pretreatment was accounted for improving the binding ability of the softwood fibers to form durable pellets. In this case, it is less pronounced for the pretreatment on improving the pellets made from oil palm residue. This is because the native lignin content of the untreated EFB and PKS is low with 16.04 and 20.41% [3], when compared to the native lignin content of Douglas fir with 28% [17].

3.3 Compression behavior and stress relaxation

The compression behavior of the EFB and PKS with and without steam explosion was presented in Fig. 6. The compression profile of Douglas fir from our previous published literature was used as a base case for comparison [14, 17]. For the untreated EFB, the particles underwent a particle packing rearrangement when the force increased from 0 to 500 N. Note that the area under the curve of untreated EFB in this range is larger than that of steam exploded EFB. This means that the required compression energy of the steam exploded EFB is smaller than that of untreated EFB. This attributes to a smaller particle size of the steam exploded EFB particles, of which they can be easily compacted into the most packed structure under compressive force. However, when the compressive force increased further from 500 to 4000 N, it was found that the steam exploded EFB shows a

less steep slope in the plasticization region and required more energy to form a pellet compared to the untreated EFB pellet. The required compaction energy for the steam exploded EFB pellet is 44.50 J/g while that of the untreated EFB pellet is 30.15 J/g (Table 2). Similar to Douglas fir, the required extrusion energy for the steam exploded EFB pellet was about 6 times than that of the untreated EFB pellet. The increased extrusion energy may be contributed by the increase in particle surface roughness and the presence of mono-saccharides. The mono-saccharides on the particle surface introduced friction between particles and the inner surface of the single die. This result also agrees well with the increase in required energy for compression and extrusion for the other steam exploded agricultural pellets [30]. For PKS, there are no significant changes in the compression behavior and the associated compression and extrusion energy.

From the stress relaxation test, the dimensional stability of the steam exploded EFB pellets is better than that of the untreated EFB pellet. Lam et al. [17] reported that the asymptotic modulus of the compacted biomass can be an index to show the rigidity of the resulted pellets. A lower asymptotic modulus indicates that the biomass material is compressed and reached a lower residual stress after relaxation. As a result, the pellets were more dimensionally stable and do not change a lot in length direction after some storage time. The asymptotic modulus of the steam exploded EFB pellet decreased from 0.72 to 0.51 GPa (Table 2). This was caused by the change of the viscoelastic properties of the fiber by hydrolysis during steam explosion pretreatment. The hydrolysis of hemicellulose cleaves their bonding to form mono-saccharides (e.g. xylose). Therefore, the resulted fiber is cellulose – lignin matrix which has a higher hardness value and less likely to expand after relaxation.

However, there is no significant difference of asymptotic modulus for PKS and steam exploded PKS with the p-value < 0.05 . This is also supported by the similarity of the force displacement curve of steam exploded PKS and untreated PKS. The compression of PKS and steam exploded PKS just only show a slight difference in slopes (Fig. 6). The high extractive content of PKS is the key to retard the effect of steam explosion on activating the lignin of PKS for improving the binding of fibers (i.e. mass transfer limited). During high pressure steaming, the rapid devolatilization of extractives of PKS led to the shrinkage of micropores. As a result, this increases mass transfer resistance for saturated steam to diffuse into the middle lamella of PKS for lignin activation. This is also supported by the reduction of bulk porosity of the PKS pellet from 17.9 to 10.1 % after steam explosion pretreatment (Table 1). In the future, the study of mass transfer of steam diffusion through the wall of PKS middle lamella and the lignin distribution within the middle lamella should be carried out.

4. Conclusions

The mechanical strength and dimensional stability of both steam exploded empty fruit bunch and palm kernel shell pellets were improved by steam explosion pretreatment at 220 °C for 5 min. Both the EFB and Douglas fir pellets required higher compression energy to produce durable pellets. The percentage increase in compression energy of the steam exploded EFB pellet was higher than that of the Douglas fir softwood pellet. However, the percentages increase in Meyer hardness and maximum breaking strength of steam exploded EFB pellets are less than that of steam exploded Douglas fir pellets. The high extractive content of palm kernel shell (PKS) is the key to retard the effect of steam

explosion on activating the lignin for improving the binding of fibers. This research finding suggests that the new start up or existing steam exploded wood pellet plant may consider empty fruit bunch as an alternative feedstock to produce pellets in a similar safe processing regime and with similar energy consumption.

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Tables

Table 1

Biomass	Powder						Pellet				
	Moisture content ¹ (%)		High heating value ¹ (MJ/kg)		Ash content ¹ (%)		Pellet density ² (g/cm ³)		True density ² (g/cm ³)		Porosity (%)
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Untreated											
EFB	13.5	0.7	18.54	0.80	5.47	0.08	1.14	0.02	1.40	0.00	19.0
PKS	13.5	0.3	21.51	1.14	1.35	0.22	1.13	0.03	1.37	0.03	17.9
DF	6.9	0.1	18.82	0.30	0.27	0.02	1.09	0.04	1.43	0.00	23.8
Steam exploded											
EFB	7.3	0.4	22.42	0.91	8.08	0.27	1.13	0.03	1.37	0.03	17.9
PKS	6.7	0.3	21.99	0.20	1.85	0.21	1.21	0.03	1.35	0.00	10.1
DF	6.0	0.2	19.50	0.05	0.52	0.09	1.08	0.04	1.42	0.00	24.0

¹: Number of measurements: n = 3
²: Number of measurements: n = 5

Table 2

Biomass	Meyer hardness ³ (N/mm ²)		Maximum breaking strength ³ (MPa)		Asymptotic modulus ³ (GPa)		Compression energy ³ (J/g)		Extrusion energy ³ (J/g)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Untreated										
EFB	1.82	0.68	57.71	21.62	0.72	0.06	30.15	1.51	0.99	0.10
PKS	1.35	0.23	42.70	7.23	0.62	0.02	32.61	1.04	3.95	1.51
DF	1.60	0.20	18.00	4.00	1.33	0.03	20.45	1.67	0.49	0.03
Steam exploded										
EFB	2.97	0.23	94.06	7.30	0.51	0.03	44.50	4.56	5.81	1.34
PKS	1.95	0.89	61.83	28.20	0.59	0.04	31.81	1.38	5.16	0.45
DF	6.60	2.10	59.30	11.10	1.19	0.01	36.25	4.78	1.17	0.14

³: Number of measurements: n = 5**FIGURES**

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Material	Untreated	Steam treated	Untreated	Steam treated
EFB
PKS

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6.

FIGURE CAPTIONS

Fig. 1.: Piping and instrumentation diagram (P&ID) of steam explosion unit at UBC Clean Energy Research Centre (B: Ball valve; P: Pressure transducer; T: Thermocouple; PS: Pressure relief valve) [11]

Fig. 2.: Pressure profile of steam explosion of different biomass particles

Fig. 3.: Temperature profile of steam explosion of different biomass particles

Fig. 4.: Physical appearance of untreated and steam exploded EFB and PKS in the form of ground particle and pellet

Fig. 5.: Particle size distribution of the ground particles of EFB and PKS

Fig. 6.: Force - displacement of different biomass particles during compression (DF: Douglas Fir, EFB: Empty Fruit bunch, PKS: Palm Kernel Shell, SE: steam exploded)

TABLE CAPTIONS

Table 1: Physical properties of untreated and steam exploded EFB, PKS and DF

Table 2: Mechanical properties and energy input for pelletization of untreated and steam exploded EFB, PKS and DF

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