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

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HIGHLIGHTS

- Steam exploded empty fruit bunch and palm kernel shell pellets were characterized.
- High extractives content of PKS results in high pressure during steam explosion.
- Steam explosion increases the pellet density of PKS only, but not on EFB and fir.
- Steam explosion improves mechanical strength of steam exploded EFB and PKS pellet.
- The energy input to make steam exploded EFB pellet is higher than untreated one.

GRAPHICAL ABSTRACT

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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 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/cm^3 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.

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

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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 brunches 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 80–90 °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 produce heat and power [10].

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

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