Production and Characterization of Low-ash Empty Fruit Bunches (EFB) Pellets as a Solid Biofuel

Abu Bakar Nasrin (✉ nasrin@mpob.gov.my)

Malaysian Palm Oil Board <https://orcid.org/0000-0002-1898-4330>

Soh Kheang Loh

Malaysian Palm Oil Board

Mohamad Azri Sukiran

Malaysian Palm Oil Board

Nurul Adela Bukhari

Malaysian Palm Oil Board

Astimar Abdul Aziz

Malaysian Palm Oil Board

Joseph Lim

Global Green Synergy Sdn. Bhd.

Stephen Lim

Global Green Synergy Sdn. Bhd.

Eddy Chin

Global Green Synergy Sdn. Bhd.

Research Article

Keywords: oil palm biomass, sustainable energy, pellet, physical pre-treatment, densification

Posted Date: March 30th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-309743/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License. [Read Full License](#)

Version of Record: A version of this preprint was published at BioEnergy Research on August 14th, 2021. See the published version at <https://doi.org/10.1007/s12155-021-10316-x>.

Abstract

Fuel quality is among the major issues encountered for commercial production and utilisation of oil palm-based biomass pellets from empty fruit bunches (EFB). In this study, a physical treatment, namely sieving and water washing, was applied to EFB prior to densification using an industrial-scale plant. The physiochemical properties of the produced EFB pellets were compared with those without physical treatment as the control. The results showed that the physical treatment process had significantly enhanced the fuel properties of EFB pellets, particularly in reducing ash content. Both the treatments; sieving alone and a combined sieving and water washing of the feedstock managed to reduce the ash content of EFB pellets to < 4 wt.% and < 2 wt.%, respectively compared to > 5 wt.% of typical commercial EFB pellets. The reduction in ash content improved the calorific value of pellets to > 17.5 MJ kg⁻¹ which signified achieving a milestone for oil palm biomass-based heat and power generation from technical, operational, economic and environmental points of view. The findings also indicated that the combined sieving and water washing treatment method could potentially reduce further the unwanted ash-inducing elements in EFB pellets, in particular chlorine and potassium. This study demonstrated that the employed physical treatment is an immediate and cost-effective practical commercial approach to improve the fuel properties of EFB pellets.

Introduction

Renewable energy (RE) plays a significant role in shaping the total global primary energy supply, providing about 14% share in 2015 and would increase to 63% in 2050 [1]. The increasing use of biomass for energy exploitation as an alternative to fossil fuels is driven by environment benefits as it is a natural carbon sequester [2]. Biomass contributes about 10% and 13% to the world primary energy supply and final energy consumption, respectively, making it the fourth largest source of energy in the world, after oil, coal and natural gas [3]. According to Popp et al. [3], biomass accounts for 70% i.e. the biggest share of the total global renewable energy sources.

Biomass has been identified as one of the major resources for RE development in Malaysia. The country is blessed with an abundant amount of biomass, mainly as by-products from agro-commodity sectors such as oil palm and rice (paddy), forestry residues from wood and timber industries and municipal solid waste. The amount of biomass was estimated at 168 million tons (t) with potential renewable electricity of 2400 MW [4]. The oil palm industry is the single largest contributor of biomass resources in Malaysia, amounting to 90% of the country's total lignocellulosic biomass [5,6]. The oil palm lignocellulosic biomass is mainly generated from 5.90 million hectares of oil palm planted areas and 452 palm oil mills nationwide [7]. Assuming that the mean weight ratio of mesocarp fibre, palm kernel shell and empty fruit bunches (EFB) to fresh fruit bunches (FFB) is 13%, 6% and 23% [8,9] respectively, the estimated total solid biomass production from the palm oil milling sector alone was 40.3 million t (wet basis) based on 98.28 million t FFB processed in 2019 [10].

Despite being used mainly as a fuel in palm oil mill biomass boiler, the remaining unutilized and disposed portion particularly EFB is huge. There are many issues and challenges in utilizing raw EFB or pressed EFB fibers directly as a fuel, such as high moisture and oxygen contents, inherently inferior fuel properties, bulkiness and size heterogeneity [11]. All these contribute to a generally low bulk density and energy content, reduced thermal efficiency and increased pollutant emissions and operation cost of the fuel including biomass handling, processing and boiler maintenance [12].

Pelletisation is one of the promising options to improve physical and fuel properties of EFB, expanding its usage and marketability as a solid biomass fuel. The process can be part of integrated biorefinery concept within existing palm oil mills. Defined as mechanical densification, the process involves raw material pre-treatment for size and moisture

reduction, and compression of loose biomass into higher density and more uniform fuel using flat die or ring die pelletizer [13]. Woody biomass pellet typically has a bulk density of 200 – 650 kg m⁻³, <3 cm in length (L) and 1 cm in diameter (D) [14]. Pellet size dimension, particularly diameter depends on individual country's solid fuel standard requirements, e.g. Austrian and German Standards, 4-10 mm; Swedish standard, <25 mm; Italian Standard, 6-10 mm (depending on pellet category) while the recently developed European (EN ISO 17225-2) and International (ISO 17225-6) Standards, 6-12 mm and 6-25 mm, respectively [15]. Densified biomass in pellet form provides numerous advantages, among others, improved solid fuel properties, better combustion efficiency, ease of handling, storage and logistic [16].

Many studies have reported positive impacts of biomass pellets on combustion process and emission. Several examples are: reduction of 80% (minimum) CO and SO₂ emissions using pellets of oil cake, rape straw and birch sawdust in a low-temperature biomass boiler [17], combustion efficiency of 92% using wood pellets [18], ~2% thermal efficiency increment relative to an increased combustion efficiency and heat exchanger areas [19], and a low-ash biomass pellets of 2.0 wt.% burnt without any ash agglomeration problem [20]. Besides, co-firing of coal with wood pellets could improve the combustion reaction, reduce gaseous emission of SO_x and NO_x, and slagging ratio of wood pellets [21]. Combustion of forest biomass pellets in a boiler with intelligently designed air-fuel ratio generates lower CO and dust emissions than woodchips and lignite i.e. less than 100 ppm and 0.05 g h⁻¹, respectively [22]. Similarly, combustion of high quality wood pellets emits lesser particulate matters and CO, compared to low-density pellet or solid fuel [23]. To date, biomass pellet is commercially used for heat and power generation, co-firing in coal power plant and as a potential feedstock for production of second generation biofuel, mainly via thermochemical process [9,24].

There have been numerous research and development (R&D) works on EFB pellets by many researchers with the majority focusing on production and characterisation of EFB pellets [25-28,9]. Although the potential of EFB pellets is manifold, these studies nevertheless showed that their quality is relatively lower compared to commercial wood pellets, mainly due to high ash content and presence of inorganic matters [9]. These disadvantages have rendered full commercialisation of EFB pellets impossible in existing market, creating operational implication and significant challenges during fuel combustion and ash management.

Ash and inorganic elements such as alkali metals e.g. potassium (K), sulphur (S) and chlorine (Cl) generated from biomass combustion contribute to corrosion, slagging and fouling of boiler furnaces and stoves [15,29]. As a result, heat transfer efficiency and boiler performance are greatly reduced while maintenance and boiler operation cost increased. Raw EFB and EFB pellets contain ashes in the range of 5.75 to 9.41 wt.%; S, 0.12 -1.6 wt.%; Cl, 0.46-1.37 wt.% and K, 0.5-1.2 wt.% [30,25,26,28,31]. As comparison, wood pellets contain much lower concentrations of these elements i.e. 0.3 wt.% ash, < 0.01 wt.% S and Cl, and < 0.2 wt.% K [32,25], hence are of better advantageous and much preferred commercially as a solid biofuel.

In order to exploit global demand opportunities for high quality biomass pellets and to stay competitive, much efforts are geared towards improving fuel properties of EFB pellets. These include pre-treatment of EFB using various methods such as steam explosion, hydrothermal, washing and leaching techniques [33-35]. These approaches have been found technically efficient in removing inorganic matters, ash and Cl from the feedstock, and improving mechanical durability, strength and combustion characteristics of the derived pellets [35,36,33]. Water leaching study on EFB is able to reduce ash content from 5.47 wt.% to 2.63 wt.%, and K content from 2.42 wt.% to 0.36 - 0.69 wt.% [29]. Hydrothermal treatment applied on EFB has resulted in 55% reduction of ash content and lowered K and Cl contents to 0.84 wt.% and 0.18 wt.%, respectively [34]. Lam et al. [33] reported that a steam explosion treatment of EFB could increase gross calorific value (CV), density and breaking strength of EFB pellets by 20%, 7% and 63%,

respectively. Most of these studies are laboratory-scale experiments which require more time and investigations before an efficient and cost-effective full-scale pre-treatment technologies for commercial EFB pellets plant can be established [36][Hamzah, 2017 #164;Liu, 2017 #165].

As the demand for biomass pellets continues to grow worldwide, and wood pellets are technically more superior to the EFB pellets, commercial EFB pellets production which is on par with wood pellets must be fully exploited and developed for a competitive edge. Besides quality issue, other factors requiring attention are high EFB pellets production cost including operation and maintenance of the plant, and the associated environmental impacts. Previously, our life cycle impact assessment showed that production of EFB pellets was mainly due to the heavy consumption of fossil fuels [9]. According to Ali, Koukoulas [37], current focus in the biomass pellet industry is to improve process and optimise pellet quality across the supply chain which ultimately poses cost reduction opportunities.

Building on current technical capacity, biomass resource availability and potential market opportunity for pellets from oil palm biomass as well as an emerging option for palm oil mill biorefinery concept, some joint efforts between the Malaysian Palm Oil Board (MPOB) and an industry player, Global Green Synergy Sdn. Bhd. (GGS) were aimed at improving the process and quality of commercial EFB pellets. The study evaluated the impact of fuel pre-treatment on resulted fuel quality. It investigated the effect of physical treatment of raw material on fuel properties of EFB pellets, in complying with international solid biofuel standards. The physical treatment, namely sieving and water washing, was applied to the pressed EFB fibre prior to pelletisation process using a newly developed commercial-scale plant. The resulted EFB pellets were characterised and their quality was compared with solid biofuel specifications based on the European Standard (EN ISO 17225-2) for wood pellets (class B) and the International Standard (ISO 17225-6) for non-wood pellets (class B) requirements.

Materials And Methods

Materials

Pressed EFB fibers were used as the feedstock for the study. It was obtained from a palm oil mill located in Rantau, Negeri Sembilan. The pressed EFB fibers (2 - 3 t) were produced by shredding and pressing the raw EFB using a dual cutter shredder and screw-type press machine installed at the mill. EFB juice was also generated from this process as a by-product which can be further recovered as a technical-grade crude oil. These approaches are adopted by the mill as part of the strategies to reuse EFB volume for various value-added products and applications. The pressed EFB fibers were then transported to the site for production trials.

Physical treatment of feedstock and pelletizing process

Physical treatment of the pressed EFB fibers and the subsequent pelletization were conducted at a demonstration plant (1 t hr⁻¹) located in Mambau, Negeri Sembilan. Two types of physical treatment, namely sieving and a combined sieving and water washing, were applied to the feedstock. The sieving process of pressed EFB fibers was carried out using a 25-mm mesh size rotary sieving drum (D = 1200 mm, L = 6000 mm). The dirt passing through the sieving mesh was collected and weighed. For the combined treatment, pressed EFB fibers were sieved and then washed directly with water using spraying techniques for less than 30 seconds.

Figure 1 depicts the process flow used in physical treatment and production trials of EFB pellets. The pressed EFB fibers (without physical treatment) were used as a control (Test 1), while the physical treatment employed yielded 2 types of feedstocks for production of EFB pellets, namely sieved EFB fibers (Test 2) and sieved cum water-washed EFB

fibers (Test 3). Tap water was used for washing purpose. The pelletisation involved three main processes; a pre-pelletizing step for size and moisture reduction, a pelletizing process and a post treatment process. Size and moisture reduction of the pressed EFB fibers were carried out through a sequence of steps using shredder, rotary drying unit and grinder. A 30-kW downdraft biomass gasifier was used to supply hot gases for drying purpose. Hot gases for drying was about 200°C to 250°C for 5 to 6 minutes. All these processes was carried out to ensure that the size and moisture content of the feeding materials were less than 10 mm and 15% (wt./wt.), respectively prior to pelletising process. The pelletizing process was carried out using a ring die technology and the produced pellets were cooled and dried in the pellet silo using an air blower before packaging. Each test was replicated twice. Table 1 summarises type of machineries used for pelletizing process. The machineries were manufactured by GGS.

Analysis

The pressed EFB fibers (feedstock), pulverised EFB fibers (after grinding) and EFB pellets from each test were randomly selected and analysed for their fuel properties. Proximate and ultimate analyses as described by [Loh \[6\]](#) were performed. The proximate analysis to determine moisture, ash, volatile matter and fixed carbon contents was carried out using a thermogravimetric analyser (LECO TGA 701) according to ASTM 5142. The temperature and time required to determine moisture, volatile and ash contents were 107 °C and 2 hours, 950 °C and 20 minutes and 750 °C within 2 hours, respectively. The fixed carbon was determined by subtracting the percentage of the sum of volatile matter, moisture and ash content from the sample. The CV of the samples was determined using a bomb calorimeter (LECO AC 600) in accordance to ASTM D-5865. About 0.1 – 0.2 g of sample was used and placed in the sample holder of the combustion vessel. The combustion was carried out in the combustion vessel bucket for 5 minutes. LECO CHN 628 and LECO S 628 were used to determine carbon (C), hydrogen (H), nitrogen (N) and sulphur (S) contents according to ASTM D5373. Temperature and time of the combustion for CHN 628 ranged from 850 to 950 °C within 3 minutes, meanwhile combustion analysis for S was set at 1350°C within 2 minutes. The concentration of oxygen (O) was calculated by difference between 100% and the sum of C, H, N and S. The pellets dimension, namely diameter and length were measured using a digital caliper (Mitutoyo CD-20APX) according to EN 14127.

The density of the pellets was determined using the density kit (Mettler Toledo ML-DNY43) according to ASTM D792-08. It was calculated by dividing the mass of the pellets by its volume [\[31\]](#). An one-liter (l) container was used to determine the bulk density of the pellets according to the method described by [Theerarattananoon et al. \[38\]](#). The weights of the container filled full with pellets and the empty container were determined, and the weight difference obtained was divided by the volume of the container to get the bulk density. The feedstock and EFB pellets produced from Test 2 (sieving) and Test 3 (sieving and water washing) were further analysed for trace elements and Cl contents. Trace elements were determined via inductively coupled plasma-optical emission spectrometry (ICP-OES) (Perkin Elmer, USA). This analysis was outsourced to Espek Research & Advisory Services, Espek Sdn. Bhd.. Cl content was determined according to both the titrimetric method and combustion ion chromatography using a trace elemental analyser (Mitsubishi NSX-2100H & ABC 210), respectively. About 0.025 – 0.045 g of sample was weighed in a ceramic sample boat and placed in the pyrolysis tube. The sample was heated at 900°C for 15 minutes prior to Cl detection by the ion chromatography unit. The titrimetric method was performed by SGS (Malaysia) Sdn. Bhd..

The wastewater generated from the water-washed EFB fibers (Test 3) was collected and analysed for biochemical oxygen demand (BOD), chemical oxygen demand (COD), total nitrogen (TN), ammoniacal nitrogen (AN), total solid (TS), total volatile solid (TVS), suspended solid (SS), volatile suspended solid (VSS), volatile fatty acid (VFA) and oil and grease (O&G); based on the revised methods by DOE, Malaysia (1995) and the Standard Methods for Examination of Water and Wastewater (APHA, 2005) as described in [Loh et al. \[39,40\]](#). Pellet durability was determined using a Holmen pellet durability tester (model NHP 100) with a 100 g sample for a 60 seconds, in accordance to ISO 17831-

1:2015 as described by Brunerová et al. [31]. All the analyses were carried out in triplicate. Table 2 summarises the analyses employed in this study.

Results And Discussion

Physical treatment of raw material

The pressed EFB fibers used for this study were physically treated to obtain the sieved EFB fibers (Test 2) and the sieved and water-washed fibers (Test 3), prior to size and moisture reduction via pre-pelletizing process. The unwanted materials, less than 25 mm in size, passing through the sieving mesh were dirt including soils and stones, short and pulverized fibers which contributed to approximately 1% (wt/wt) of total raw pressed EFB fibers fed to the sieving drum. The wastewater generated from the washing process of EFB fibers was collected and analysed. Table 3 shows the characteristics of the wastewater generated. It appeared that the wastewater had much lower characteristics, in particular BOD and COD values compared to the raw palm oil mill effluent (POME) and hydrocyclone wastewater typically generated during the palm oil milling process. This finding indicates that it is possible to treat the EFB-washed wastewater using currently practiced POME treatment system if the EFB pellets production plant is part of the integrated activity in palm oil extraction.

Production trials and physical characteristics of raw material and EFB pellets

The feedstocks (untreated and physically-treated EFB fibers) were shredded, dried and pulverized to meet the required size and moisture content as a feeding material for pelletizing process. Moisture content and particle size of the feedstocks are two important parameters affecting pellet durability and bulk density [13]. For efficient pelletisation, many studies have suggested the allowable maximum limit of moisture content and particle size to be < 15% wt.% and 5 mm [31,13].

Table 4 summarizes the characteristics of pressed EFB fibers (raw material) and pulverized EFB fibers employing different physical treatment. The raw material appears to have heterogeneous characteristics, particularly with high variation of moisture content i.e. from 46 wt.% to > 65 wt.%. The pre-pelletizing process employed in this study managed to reduce significantly the moisture and size of EFB fibers to < 14 wt.% and < 10 mm in their pulverised forms, respectively, which are comparable to those in the literature. The bulk density of EFB fibers was therefore increased significantly from 62 to 152 kg m⁻³, thus able to facilitate better material flow throughout the production process.

The production trials conducted showed that binderless EFB pellets were successfully produced from untreated and physically-treated feedstock. The presence of lignin in EFB fibers, about 18%, acts as a natural binder [43]. The high pressure and temperature applied during the pelletisation had softened the lignin to act as an intrinsic resin for improving the particles binding during pelletisation [44,45]. The size and moisture content of the feeding material were also reduced to a suitable level for effective pelletization to produce EFB pellets of desirable quality without affecting the overall production process. Based on the production trials, it was estimated that about 2.35 – 2.50 t of pressed EFB fibers and approximately 160 kWhr of electricity were required to produce 1 t of EFB pellets. The relatively lower energy consumption in this study compared to those in the literature i.e. > 200 kWhr t⁻¹ pellet [43,9] was due to the use of partially-treated pressed EFB fibers, efficient machineries and biomass gasifier for EFB drying process.

Three types of EFB pellets were produced from this study, namely a typical EFB pellet using untreated EFB fibers (Test 1), and a low-ash EFB pellet from Test 2 and Test 3 using 2 different physical treatments. The insignificantly different physical properties of the resulted EFB pellets from Test 1 to Test 3 in Table 5 indicated that the different treatments

applied did not affect the physical properties of the pellets. The EFB pellets were relatively uniform in terms of diameter and bulk density although the varying length could affect the weight of individual pellet. On average, the diameter, length and bulk density of the produced EFB pellets were 8.4 mm, 40.0 mm and 661.7 kg m^{-3} , which complied with the requirement as stipulated in the European (EN ISO 17225-2) and International (ISO 17225-6) standards.

Pellets with high bulk density are preferred to facilitate logistics arrangement, storage and cost reduction. Pelletizing process could increase the bulk density of EFB pellet to $> 650 \text{ kg m}^{-3}$, far better than those of the raw and pulverised feeding materials in the range of $62 - 152 \text{ kg m}^{-3}$ (Table 4). Therefore, higher bulk density relates to an increased energy density i.e. more energy per unit volume of the resulted EFB pellets as a solid biofuel [46]. Moisture reduction, downsizing and densification process at the employed pressure and temperature in this study had largely influenced and compacted the loose EFB fibers to a much denser pellet form [44]. The average specific density (1306 kg m^{-3}) was higher than that reported by Tenorio et al. [28] and within the range required by the German standard, DIN 51731.

Table 5 also shows the durability index of EFB pellets produced. There was no differences in durability index of the pellets produced from untreated (Test 1) and physically-treated (Tests 2 and 3) EFB fibers. The mean value of 94.62% exceeding 80% can be regarded as high and acceptable although the value is slightly lower than those by the European and International standards [13]. Pellet durability index is an important parameter to describe capability of the produced pellets to tolerate shock and vibration during handling and transportation. Moisture content is a major factor affecting pellet durability level. An increasing amount of moisture beyond 14 wt.% causes pellet durability to drop significantly [38]. Other factors affecting pellet durability are particles size and type of pre-treatment of the raw material.

Table 6 shows the proximate and ultimate analyses of the three types of EFB pellets produced from this study. There were significant differences on the moisture and ash contents and the CV of the EFB pellets compared to the raw material (Table 4). Huge improvement was made on moisture content and CV of the pellets, at $>79.2\%$ and 65.0% , compared to $46.33 \text{ wt.}\%$ and 10566 kJ kg^{-1} , respectively from the pressed EFB fibers. The pre-pelletising step to reduce EFB's size and moisture and the pelletising process to densify the loose and pulverised fibers had proven to improve the two important fuel properties of the EFB pellets as a solid fuel.

The fuel properties of EFB pellets deriving from different physical treatment (Test 1 to Test 3) were relatively comparable except for ash content. The employed Test 2 involving sieving process had managed to reduce the ash content of EFB pellets to $3.63 \text{ wt.}\%$, compared to $4.66 \text{ wt.}\%$ that of an untreated normal EFB pellet. A combined sieving and water washing of EFB fibers (Test 3) had significantly reduced the ash content of EFB pellets to $1.58 \text{ wt.}\%$. This means physical treatment of raw material is necessary and should be incorporated at any commercial EFB pellets production line, in order to produce EFB pellets low in ash content for niche markets. As an agro-based by-product, EFB is naturally high in ashes plus easily contaminated by soil and dirt due to poor material handling, storage and transportation either at the mill or the pellet production plant compared to wood-based counterpart [9]. The use of an integrated gasifier system for drying EFB fibers provides smokeless cleaner hot gases compared to existing biomass burner utilised in pellets production site.

Besides creating ash-related problem, a higher ash content also decreases the CV of the biomass pellets [47]. An increase of $1 \text{ wt.}\%$ of ash content has resulted in CV reduction of $0.11 - 0.2 \text{ MJ kg}^{-1}$ [48,49]. In such situation, more biomass fuel sources are required to generate the same amount of energy. Previous studies reported a 1.18 to 1.39% higher biomass fuel consumption for every $1 \text{ wt.}\%$ increase in ash content [48,50]. By doing so, a higher ash production and management cost is anticipated due to frequent cleaning and machinery maintenance. High-ash

content solid fuel will also influence NO_x emission, in particular agro-based pellets, causing negative environmental impact [51]. Verma et al. [52] reported that the NO_x emitted from burning of straw pellet with 9 – 10 wt.% ash content was 7 times higher than that of wood pellet containing just 0.65 wt.% ash. This phenomenon is due to catalytic effect of the ash present; higher amount of ashes tend to provide more active sites to catalyse N into NO_x during the combustion [53,52]. Therefore, minimizing ash content in biomass fuel provides significant advantages from technical, operation, economic and environmental points of view for biomass-based heat and power generation. A combined sieving and washing pre-treatment in this study was able to solve the above-mentioned shortcomings. All the EFB pellets produced exhibited < 10 wt.% moisture content (Table 6). As a result, the EFB pellets had energy value significantly higher than the raw EFB as large initial water content would affect the recoverable heat. Similarly, lower moisture content had contributed to a higher CV leading to better combustion temperature and efficiency.

The elemental contents of the EFB pellets produced (Table 6) and their initial physically-treated feeding materials (Table 4) were insignificantly different but differed significantly from those of the raw material mainly due to high moisture content. The Van Krevelen plot (Figure 2) shows that the H/C and O/C atomic ratios of EFB pellets produced from different physical treatment (Tests 1-3) were closer to those torrefied EFB, coal and lignite [11] and significantly better than their raw material (pressed EFB fibers). These findings postulate that the pelletizing process largely involved both the mechanical and thermal (drying) processes to improve the physicochemical properties of the raw EFB fibers, in particular the significantly reduced moisture content, leading to an increased C but reduced O contents of the EFB pellets. Like other biomass [54], the EFB pellets contained > 99 wt.% of O, C and H with the latter two totally ~50 wt.%. CV of a biomass fuel is much dependant on the amount of C and H present where higher contents of these two elements contribute to better energy content. As biomass combustion is an exothermic reaction, combustion of higher amount of C and H with O₂ would release more heat while generate carbon dioxide (CO₂) and water [55,56]. Comparing the C and H contents of the following: torrefied EFB, 58.89 wt.% and 5.12 wt.% [11]; coal, 64.34 wt.% and 4.06 wt.% [57]; lignite, 58.5 wt.% and 3.0 wt.% [58] and pelletized EFB, 42.86 – 43.98 wt.% and 6.38 - 6.63 wt.% (this study), it is thus apparent that though the EFB pellets has a much lower CV amongst the solid fuels, its CV has been greatly improved compared to the raw material used. The results indicated that simple physical removal of moisture coupled with different sieving and washing co-treatment methods were sufficient to improve the CV of EFB pellets which then could perform much better as a fuel compared to normal EFB pellets.

N and S embedded in biomass fuel create undesirable pollutants, namely NO_x and SO_x during thermal combustion. Their concentration limits are important, as evidenced by the EN ISO 17225-2 (for wood pellets) and the ISO 17225-6 (non-woody pellets) standards demanding for environmental-friendly biomass pellets [15]. The N and S contents in the EFB pellets ranged 0.24-0.54 wt.% and 0.03-0.07 wt.%, respectively are notably and relatively lower compared to the standard limits as stipulated in the EN ISO 17225-2 (≤ 1.0 wt.%) and the ISO 17225-6 (≤ 2.0 wt.%), except for S content in the EFB pellets derived from Tests 1 and 2 which was 0.01-0.02 wt.% higher than the limit (0.05 wt.%) specified in the EN ISO 17225-2, hence are of advantageous for cleaner energy generation. Tenorio et al. [28] reported that a combustion study of EFB pellets generated a very low emission of NO_x (142.33 ppm) and none for SO_x, with flame temperature varies between 500 - 700°C. During combustion, the N and S contained in biomass are oxidised and volatilised to generate NO_x and SO_x. The physical co-treatment used in this study i.e. a combined sieving and water washing had further reduced the S and N contents of EFB pellets, and lowering further the potential of air pollutant emissions.

Table 7 shows major and minor trace elements exhibited in the pressed EFB fibers (raw material) and EFB pellets produced from Test 2 (sieving) and Test 3 (combined sieving and water washing). The trace elements present are mainly alkali and heavy metals, and their concentrations are relatively low and comparable to woody biomass pellets, except for K, Cl, Fe, Zn and Na. This difference may be due to the nature of the plant and their ability to uptake specific

compounds and nutrients from the ecosystem i.e. soil, water as well as fertilizers and pesticides applied [59]. As agro-based residues pellets, high contents of Zn and Fe of EFB pellets in particular is attributed to other natural factors concerning oil palm cultivation practices such as irrigation with treated or semi-treated effluent (wastewater from palm oil mill), chemical-based fertiliser, and organic sludge that is typically used in the soil environment and agriculture plantations for improving soil fertility [60]. In addition, their presence serve as micro-nutrients beneficial as an alternative feed material and for soil amendment to enhance plant/animal growth [61].

These easily vaporized high amounts of alkali metals (K and Cl) together with the present S and silicates in the EFB pellets would result in severe ash-related problems to boilers such as slagging, fouling and corrosion [62,6]. These elements would also have adverse effects on boiler operation, ash quality, particulate matters and pollutants emission [63]. The findings indicated that the applied sieving and water washing co-treatment could potentially reduce K, Cl and some heavy metals from the raw EFB feedstock at a minimum of 40% removal efficiency. This result corresponded with some of the previous studies, in particular concerning removal of K and Cl from EFB via other methods such as leaching and hydrothermal-washing co-treatment [29,35,34].

Conclusion

Two types of physical treatment of the pressed EFB fibers i.e. sieving and a combined sieving and water washing were assessed to study their effects on the fuel properties of the derived EFB pellets. The findings showed potential of these treatments as immediate and cost-effective means to reduce ash content of EFB pellets at commercial production plant. The sieving and water washing co-treatment employed could also significantly reduce some of the alkali metals, heavy metals, ash, Cl, N and S contents from the EFB pellets. It further enhanced environmental benefits particularly in reducing pollutant emissions and ash generation during combustion of the resulted EFB pellets. The fuel properties such as moisture and ash contents, bulk density and CV of the resulted EFB pellets were comparable to the woody biomass pellets and complied to the minimum specifications of the EN 14961-2 (for wood pellets) and the ISO 17225-6 (for non-woody pellets). The integrated physical treatment cum pelletisation of the pressed EFB fibers is technically viable, as was evidenced from the production trials in producing EFB pellets with improved quality to fetch better commercial values as an environmental-friendly solid biofuel and for development of second generation biofuel.

Declarations

Acknowledgement

The authors would like to thank the Director-General of the Malaysian Palm Oil Board (MPOB) for permission to publish this paper. Technical assistance from the staff of the Energy and Environment Unit of the Engineering and Processing Research Division, MPOB and industry collaborator, Global Green Synergy Sdn. Bhd. (GGS) were also deeply appreciated.

Funding information

This work was supported by MPOB and GGS under the collaborative project entitled “Development of a process system for the formulation and production of palm-based biomass pellets”.

Availability of data and materials

The data analysed in this manuscript are available from the corresponding author upon request.

Authors' Contributions

The following research activities were performed by specific authors: Conceptualization and methodology: A.B.Nasrin, J Lim, S Lim, E Chin; Formal analysis and investigation: A.B.Nasrin, J Lim, S Lim, E Chin Writing – original draft preparation: A.B. Nasrin; Writing – review and editing: S.K. Loh, M.A. Sukiran, N.A. Bukhari, A.A. Aziz

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Competing interest

The authors declare no known competing interests

References

1. Gielen D, Boshell F, Saygin D, Bazilian MD, Wagner N, Gorini R (2019) The role of renewable energy in the global energy transformation. *Energy Strategy Reviews* 24:38-50. doi:<https://doi.org/10.1016/j.esr.2019.01.006>
2. Hamzah N, Zandi M, Tokimatsu k, Yoshikawa K (2018) Wood biomass pellet characterization for solid fuel production in power generation. *International Journal of Renewable Energy Sources* 3:32-40
3. Popp J, Kovács S, Oláh J, Divéki Z, Balázs E (2020) Bioeconomy: Biomass and biomass-based energy supply and demand. *New Biotechnology* 60:76-84. doi:<https://doi.org/10.1016/j.nbt.2020.10.004>
4. Ozturk M, Saba N, Altay V, Iqbal R, Hakeem KR, Jawaid M, Ibrahim FH (2017) Biomass and bioenergy: An overview of the development potential in Turkey and Malaysia. *Renewable and Sustainable Energy Reviews* 79:1285-1302. doi:<https://doi.org/10.1016/j.rser.2017.05.111>
5. Shamsuddin AH (2012) Development of renewable energy in Malaysia-strategic initiatives for carbon reduction in the power generation sector. *Procedia Engineering* 49:384-391. doi:<https://doi.org/10.1016/j.proeng.2012.10.150>
6. Loh SK (2017) The potential of the Malaysian oil palm biomass as a renewable energy source. *Energy Conversion and Management* 141:285-298. doi:<https://doi.org/10.1016/j.enconman.2016.08.081>
7. Ahmad Parveez GK, Hishamuddin E, Loh SK, Ong-Abdullah M, Mohamed Salleh K, Mohd Noor Izzuddin Z, Sundram S, Azizul Hasan ZA, Idris Z (2020) Oil palm economic performance in Malaysia and R&D progress in 2019 *Journal of Oil Palm Research* 32 (2):159-190. doi:<https://doi.org/10.21894/jopr.2020.0032>
8. Sukiran MA, Abnisa F, Daud WMAW, Bakar NA, Loh SK (2017) A review of torrefaction of oil palm solid wastes for biofuel production. *Energy Conversion and Management* 149:101-120. doi:10.1016/j.enconman.2017.07.011
9. Nasrin AB, Vijaya S, Loh SK, Astimar AA, Lim WS (2017) Quality compliance and environmental impact assessment of commercial empty fruit bunch (EFB) pellet fuel in Malaysia *Journal of Oil Palm Research* 29 (4):570-578. doi:<https://doi.org/10.21894/jopr.2017.0002>
10. MPOB (2020) Malaysian Oil Palm Statistics 2019, 39th Edition. vol 289, 39 edn. MPOB, Malaysia
11. Sukiran MA, Daud WMAW, Abnisa F, Nasrin AB, Astimar AA, Loh SK (2020) Individual torrefaction parameter enhances characteristics of torrefied empty fruit bunches. *Biomass Conversion and Biorefinery*:1-12. doi:<https://doi.org/10.1007/s13399-020-00804-z>
12. Nudri NA, Bachmann RT, Ghani WAWAK, Sum DNK, Azni AA (2020) Characterization of oil palm trunk biocoal and its suitability for solid fuel applications. *Biomass Conversion and Biorefinery* 10 (1):45-55.

doi:<https://doi.org/10.1007/s13399-019-00419-z>

13. Younis M, Alnouri SY, Tarboush BJA, Ahmad MN (2018) Renewable biofuel production from biomass: a review for biomass pelletization, characterization, and thermal conversion techniques. *International Journal of Green Energy* 15 (13):837-863. doi:<https://doi.org/10.1080/15435075.2018.1529581>
14. Di Giacomo G, Taglieri L (2009) Renewable energy benefits with conversion of woody residues to pellets. *Energy* 34 (5):724-731. doi:<https://doi.org/10.1016/j.energy.2008.08.010>
15. García-Maraver A, Popov V, Zamorano M (2011) A review of European standards for pellet quality. *Renewable Energy* 36 (12):3537-3540
16. Lisowski A, Matkowski P, Dąbrowska M, Piątek M, Świętochowski A, Klonowski J, Mieszkalski L, Reshetiuk V (2018) Particle size distribution and physicochemical properties of pellets made of straw, hay, and their blends. *Waste and Biomass Valorization*:1-13. doi:<https://doi.org/10.1007/s12649-018-0458-8>
17. Kraszkiewicz A, Przywara A, Kachel-Jakubowska M, Lorencowicz E (2015) Combustion of plant biomass pellets on the grate of a low power boiler. *Agriculture and Agricultural Science Procedia* 7:131-138. doi:<https://doi.org/10.1016/j.aaspro.2015.12.007>
18. Verma V, Bram S, Delattin F, Laha P, Vandendael I, Hubin A, De Ruyck J (2012) Agro-pellets for domestic heating boilers: Standard laboratory and real life performance. *Applied Energy* 90 (1):17-23. doi:<https://doi.org/10.1016/j.apenergy.2010.12.079>
19. Ahn J, Jang JH (2018) Combustion characteristics of a 16 step grate-firing wood pellet boiler. *Renewable Energy* 129:678-685. doi:<https://doi.org/10.1016/j.renene.2017.06.015>
20. Roy MM, Dutta A, Corscadden K (2013) An experimental study of combustion and emissions of biomass pellets in a prototype pellet furnace. *Applied Energy* 108:298-307. doi:<https://doi.org/10.1016/j.apenergy.2013.03.044>
21. Guo F, Zhong Z (2018) Co-combustion of anthracite coal and wood pellets: Thermodynamic analysis, combustion efficiency, pollutant emissions and ash slagging. *Environmental Pollution* 239:21-29. doi:<https://doi.org/10.1016/j.envpol.2018.04.004>
22. Tucki K, Orynycz O, Wasiak A, Świć A, Mieszkalski L, Wichłacz J (2020) Low Emissions Resulting from Combustion of Forest Biomass in a Small Scale Heating Device. *Energies* 13 (20):5495. doi:<https://doi.org/10.3390/en13205495>
23. Ghafghazi S, Sowlati T, Sokhansanj S, Bi X, Melin S (2011) Particulate matter emissions from combustion of wood in district heating applications. *Renewable and Sustainable Energy Reviews* 15 (6):3019-3028. doi:<https://doi.org/10.1016/j.rser.2011.04.001>
24. Unchaisri T, Fukuda S, Phongphipat A, Saetia S, Sajjakulnukit B (2019) Experimental study on combustion characteristics in a CFB during co-firing of coal with biomass pellets in Thailand. *International Energy Journal* 19 (2):101-114
25. Erlich C, Fransson TH (2011) Downdraft gasification of pellets made of wood, palm-oil residues respective bagasse: experimental study. *Applied Energy* 88 (3):899-908. doi:<https://doi.org/10.1016/j.apenergy.2010.08.028>
26. Munawar SS, Subiyanto B (2014) Characterization of biomass pellet made from solid waste oil palm industry. *Procedia Environmental Sciences* 20:336-341. doi:<https://doi.org/10.1016/j.proenv.2014.03.042>
27. Kusumaningrum WB, Munawar SS (2014) Prospect of bio-pellet as an alternative energy to substitute solid fuel based. *Energy Procedia* 47:303-309. doi:<https://doi.org/10.1016/j.egypro.2014.01.229>
28. Tenorio C, Moya R, Valaert J (2016) Characterisation of pellets made from oil palm residues in Costa Rica. *J Oil Palm Res* 28:198-210. doi:<https://doi.org/10.21894/jopr.2016.2802.08>

29. Lam PY, Lim CJ, Sokhansanj S, Lam PS, Stephen JD, Pribowo A, Mabee WE (2014) Leaching characteristics of inorganic constituents from oil palm residues by water. *Industrial & Engineering Chemistry Research* 53 (29):11822-11827. doi:<https://doi.org/10.1021/ie500769s>
30. Abdullah N, Sulaiman F, Gerhauser H (2011) Characterisation of oil palm empty fruit bunches for fuel application. *J Phys Sci* 22 (1):1-24
31. Brunerová A, Müller M, Šleger V, Ambarita H, Valášek P (2018) Bio-pellet fuel from oil palm empty fruit bunches (EFB): Using European Standards for quality testing. *Sustainability* 10 (12):1-12. doi:<https://doi.org/10.3390/su10124443>
32. Chin K, H'ng P, Go W, Wong W, Lim T, Maminski M, Paridah M, Luqman A (2013) Optimization of torrefaction conditions for high energy density solid biofuel from oil palm biomass and fast growing species available in Malaysia. *Industrial Crops and Products* 49:768-774. doi:<https://doi.org/10.1016/j.indcrop.2013.06.007>
33. Lam PS, Lam PY, Sokhansanj S, Lim CJ, Bi XT, Stephen JD, Pribowo A, Mabee WE (2015) Steam explosion of oil palm residues for the production of durable pellets. *Applied Energy* 141:160-166. doi:<https://doi.org/10.1016/j.apenergy.2014.12.029>
34. Nurdiawati A, Novianti S, Zaini IN, Nakhshinieva B, Sumida H, Takahashi F, Yoshikawa K (2015) Evaluation of hydrothermal treatment of Empty Fruit Bunch for solid fuel and liquid organic fertilizer co-production. *Energy Procedia* 79:226-232. doi:<https://doi.org/10.1016/j.egypro.2015.11.469>
35. Novianti S, Zaini IN, Nurdiawati A, Yoshikawa K (2016) Low potassium content pellet production by hydrothermal-washing co-treatment. *Int J Chem Chem Eng Syst* 1:28-38
36. Hamzah N, Tokimatsu K, Yoshikawa K (2017) Prospective for power generation of solid fuel from hydrothermal treatment of biomass and waste in Malaysia. *Energy Procedia* 142:369-373. doi:<https://doi.org/10.1016/j.egypro.2017.12.058>
37. Ali OF, Koukoulas AA (2015) Approaches to energy pellet cost and quality optimization. *BioResources* 10 (4):6318-6320. doi:<https://doi.org/10.15376/biores.10.4.6318-6320>
38. Theerarattananoon K, Xu F, Wilson J, Ballard R, Mckinney L, Staggenborg S, Vadlani P, Pei Z, Wang D (2011) Physical properties of pellets made from sorghum stalk, corn stover, wheat straw, and big bluestem. *Industrial Crops and Products* 33 (2):325-332. doi:<https://doi.org/10.1016/j.indcrop.2010.11.014>
39. Loh SK, Mohamad NF, Ngan MA (2009) Characterisation of palm oil mill effluent (POME) for process control and baseline establishment MPOB Information Series (MIS) no. 493:4
40. Loh SK, Lai ME, Ngatiman M, Lim WS, Choo YM, Zhang Z, Salimon J (2013) Zero discharge treatment technology of palm oil mill effluent. *Journal of Oil Palm Research* 25 (3):273-281
41. Loh SK, Nasrin AB, Azri SM, Adela BN, Muzzammil N, Jay TD, Eleanor RAS, Lim WS, Choo YM, Kaltschmitt M (2017) First report on Malaysia's experiences and development in biogas capture and utilization from palm oil mill effluent under the economic transformation programme: current and future perspectives. *Renewable and Sustainable Energy Reviews* 74:1257-1274. doi:<https://doi.org/10.1016/j.rser.2017.02.066>
42. Ahmed Y, Yaakob Z, Akhtar P, Sopian K (2015) Production of biogas and performance evaluation of existing treatment processes in palm oil mill effluent (POME). *Renewable and Sustainable Energy Reviews* 42:1260-1278. doi:<https://doi.org/10.1016/j.rser.2014.10.073>
43. Nasrin AB, Choo YM, Lim WS, Joseph L, Michael S, Rohaya MH, Astimar AA, Loh SK (2011) Briquetting of empty fruit bunch fibre and palm shell as a renewable energy fuel. *Journal of Engineering & Applied Sciences* 6 (6):446-451. doi:<https://doi.org/10.3923/jeasci.2011.446.451>

44. Tumuluru JS, Wright CT, Hess JR, Kenney KL (2011) A review of biomass densification systems to develop uniform feedstock commodities for bioenergy application. *Biofuels, Bioproducts and Biorefining* 5 (6):683-707. doi:<https://doi.org/10.1002/bbb.324>
45. Uslu A, Faaij AP, Bergman PC (2008) Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation. *Energy* 33 (8):1206-1223. doi:<https://doi.org/10.1016/j.energy.2008.03.007>
46. Miranda T, Montero I, Sepúlveda FJ, Arranz JI, Rojas CV, Nogales S (2015) A review of pellets from different sources. *Materials* 8 (4):1413-1427. doi:<https://doi.org/10.3390/ma8041413>
47. Chin K, H'ng P, Chai E, Tey BT, Chin MJ, Paridah M, Luqman A, Maminski M (2013) Fuel characteristics of solid biofuel derived from oil palm biomass and fast growing timber species in Malaysia. *Bioenergy Research* 6 (1):75-82. doi:<https://doi.org/10.1007/s12155-012-9232-0>
48. Lieskovský M, Jankovský M, Trenčiansky M, Merganič J (2017) Ash content vs. the economics of using wood chips for energy: Model based on data from Central Europe. *BioResources* 12 (1):1579-1592. doi:<https://doi.org/10.15376/BIORES.12.1.1579-1592>
49. Zając G, Szyszlak-Bargłowicz J, Gołębiowski W, Szczepanik M (2018) Chemical characteristics of biomass ashes. *Energies* 11 (11):2885. doi:<https://doi.org/10.3390/en11112885>
50. Sheng C, Azevedo J (2005) Estimating the higher heating value of biomass fuels from basic analysis data. *Biomass and Bioenergy* 28 (5):499-507. doi:<https://doi.org/10.1016/j.biombioe.2004.11.008>
51. Ozgen S, Cernuschi S, Caserini S (2020) An overview of nitrogen oxides emissions from biomass combustion for domestic heat production. *Renewable and Sustainable Energy Reviews* 135:110113
52. Verma V, Bram S, Gauthier G, De Ruyck J (2011) Evaluation of the performance of a multi-fuel domestic boiler with respect to the existing European standard and quality labels: Part-1. *Biomass and Bioenergy* 35 (1):80-89. doi:<https://doi.org/10.1016/j.biombioe.2010.08.028>
53. Verma V, Bram S, Gauthier G, De Ruyck J (2011) Performance of a domestic pellet boiler as a function of operational loads: Part-2. *Biomass and Bioenergy* 35 (1):272-279. doi:<https://doi.org/10.1016/j.biombioe.2010.08.043>
54. Acda MN (2015) Physico-chemical properties of wood pellets from coppice of short rotation tropical hardwoods. *Fuel* 160:531-533. doi:<https://doi.org/10.1016/j.fuel.2015.08.018>
55. Demirbas A (2007) Effects of moisture and hydrogen content on the heating value of fuels. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 29 (7):649-655. doi:<https://doi.org/10.1080/009083190957801>
56. Obernberger I, Thek G (2004) Physical characterisation and chemical composition of densified biomass fuels with regard to their combustion behaviour. *Biomass and Bioenergy* 27 (6):653-669. doi:<https://doi.org/10.1016/j.biombioe.2003.07.006>
57. Zhang Y (2019) Trace elements characteristics of ultra-low emission coal-fired power plants. In: *Advances in ultra-low emission control technologies for coal-fired power plants*. Elsevier, pp 199-239. doi:<https://doi.org/10.1016/B978-0-08-102418-8.00006-1>
58. Pintana P, Tippayawong N (2013) Nonisothermal thermogravimetric analysis of Thai lignite with high CaO content. *The Scientific World Journal* 2013. doi:<https://doi.org/10.1155/2013/216975>
59. Chandrasekaran SR, Hopke PK, Rector L, Allen G, Lin L (2012) Chemical composition of wood chips and wood pellets. *Energy & Fuels* 26 (8):4932-4937. doi:<https://doi.org/10.1021/ef300884k>

60. Rai PK, Lee SS, Zhang M, Tsang YF, Kim K-H (2019) Heavy metals in food crops: Health risks, fate, mechanisms, and management. *Environment International* 125:365-385. doi:<https://doi.org/10.1016/j.envint.2019.01.067>
61. Kong S-H, Loh SK, Bachmann RT, Zainal H, Cheong K (2019) Palm kernel shell biochar production, characteristics and carbon sequestration potential. *Journal of Oil Palm Research* 31 (3):508-520. doi:<https://doi.org/10.21894/jopr.2019.0041>
62. Zhu D, Yang H, Chen Y, Li Z, Wang X, Chen H (2017) Fouling and slagging characteristics during co-combustion of coal and biomass. *BioResources* 12 (3):6322-6341. doi:<https://doi.org/10.15376/biores.12.3.6322-6341>
63. Shao Y, Wang J, Preto F, Zhu J, Xu C (2012) Ash deposition in biomass combustion or co-firing for power/heat generation. *Energies* 5 (12):5171-5189. doi:<https://doi.org/10.3390/en5125171>

Tables

Table 1 List of major equipment used in pelletizing process

Machine / equipment*	Designed capacity, t hr ⁻¹ (except for gasifier, kW)	Rated power consumption, kW (max)
Shredder	2.0 – 4.0	37.0
Biomass gasifier	30.0 kW	1.5
Rotary dryer and blower	2.0	13.0
Grinder	1.0	55.0
Pelletiser	1.0	75.0

* Manufactured in-house by Global Green Synergy Sdn. Bhd. (GGS).

Table 2 Summary of test methods and equipment employed in this study

Analysis	Standard / method	Equipment
Calorific value	ASTM D5865	LECO AC 600
Proximate analysis	ASTM 5142	LECO TGA 701
Ultimate analysis	ASTM D5373	LECO CHNS 628
Trace elemental analysis	ICP-OES	Perkin Elmer Aanalyst 400
Chlorine	Titrimetric	
	Combustion ion chromatography	Mitsubishi NSX-2100 & ABC 200
Specific density	ASTM D792-08	Mettler Toledo ML-DNY 43
Bulk density	EN 1097-3	1-l cylinder container
Durability	ISO 17831-1:2015	NHP Holmen 100
Pellet dimension	EN 14127	Mitutoyo CD-20APX

Table 3 Characteristics of wastewater from water-washed empty fruit bunches (EFB) fibers and palm oil mill effluent (POME)

Parameter, ¹ except for pH)	(mg L ⁻¹)	This study	Raw POME (mean)*	Hydrocyclone POME (mean)**	Regulatory discharge limit**
pH		5.47 ± 0.06	4.5	-	5 – 9
Biological oxygen demand		1131.67 ± 88.36	25000	5000	100 (50-20)
Chemical oxygen demand		6780.33 ± 247.89	50000	15000	-
Total nitrogen		131.67 ± 9.86	750	100	-
Ammonical nitrogen		10.33 ± 2.08	35	-	-
Total solid		5755.66 ± 150.32	40,000	-	-
Total volatile solid		4612.00 ± 158.18	34,000	-	-
Suspended solid		3233.33 ± 115.47	18000	7000	400
Volatile suspended solid		3066.67 ± 152.75	-	-	-
Volatile fatty acid		22 ± 1	-	-	-
Oil and grease		1950±100	4000	300	50

Source: *[42], **[45]

Table 4 Characteristics of raw empty fruit bunches (EFB) fibers and physically-treated feeding materials in this study

Parameter, wt.% except for calorific value and bulk density	Pressed EFB fibers (feedstock)	Type of physically-treated EFB fibers			Average (Test 1- Test 3)
		Test 1 (untreated)	Test 2 (sieving)	Test 3 (sieving and water washing)	
Moisture	46.33±23.85	7.95±0.05	13.54±0.12	9.39±2.06	10.29±2.9
Volatile matter	44.15±18.42	72.61±0.16	69.09±0.29	74.26±2.50	71.99±2.64
Ash	1.73±1.13	4.07±0.41	2.78±0.08	1.60±0.17	2.82±1.24
Fixed carbon	8.78±4.33	15.37±1.07	14.54±0.16	14.76±0.25	14.89±0.43
Calorific value (gross), MJ kg ⁻¹	10.57±2.66	17.38±0.07	16.78±0.11	17.68±0.46	17.28±0.46
Carbon	28.32±8.54	42.63±0.43	42.26±0.08	44.25±1.00	43.05±1.06
Hydrogen	8.15±0.92	6.36±0.05	6.71±0.03	6.59±0.09	6.55±0.18
Nitrogen	0.41±0.36	0.45±0.09	0.15±0.10	0.36±0.26	0.32±0.15
Sulphur	0.04±0.03	0.06±0.00	0.03±0.01	0.03±0.01	0.04±0.02
Oxygen	64.41±6.12	50.50	50.85	48.77	50.04
Bulk density,kg m ⁻³	62.00±2.82	152±5.66			

Table 5 Physical properties and durability index of empty fruit bunches (EFB) pellets

Parameter	Pellet (type of physical treatment)			Average	EN ISO 17225-2 (wood) and ISO 17225-6 (non-wood) (B class)
	Test 1 (untreated)	Test 2 (sieving)	Test 3 (sieving and water washing)		
Weight, g	3.24±0.011	2.93±0.19	2.03±0.19	2.73±0.63	-
Diameter (D), mm	8.27±0.67	8.45±0.06	8.43±0.13	8.38±0.10	6 - 8±1 (EN ISO) 6-10±1 (ISO)
Length (L), mm	46.12±3.07	40.33±4.16	33.53±3.56	39.99±6.30	3.15 ≤ L ≤ 40
Bulk density, kg m ⁻³	667.0±9.0	664.0±8.00	654.0±9.0	661.67±6.81	≥ 600
Density, kg m ⁻³	1309.6±0.1	1302.30±8.96	1306.75±2.63	1306.21±3.68	-
Durability, %	94.88±0.47	94.98±0.07	94.01±0.69	94.62±0.53	≥ 96.5 (EN ISO) ≥ 96.0 (ISO)

Table 6 Proximate and ultimate analyses of empty fruit bunches (EFB) pellets produced via different physical treatment

Parameter, wt.% except for calorific value	Pellet (type of physical treatment)			EN ISO 17225-2 (wood) – (B class)	ISO 17225-6 (non-wood) – (B class)
	Test 1 (untreated)	Test 2 (sieving)	Test 3 (sieving and water washing)		
Moisture	6.95±0.40	8.24±0.19	9.63±1.42	≤ 10.0	≤ 15.0
Volatile matter	71.31±0.37	71.57±0.45	72.87±1.91	-	-
Ash	4.66±0.14	3.63±0.09	1.58±0.06	≤ 2.0	≤ 10.0
Fixed carbon	17.07±0.45	16.56±0.36	15.93±0.44	-	-
Calorific value (gross), MJ kg ⁻¹	17.42±0.11	17.59±0.05	17.60±0.36	≥ 16.5*	Min. value to be stated*
Carbon	42.86±0.19	43.29±0.07	43.98±0.13	-	-
Hydrogen	6.38±0.08	6.53±0.04	6.63±0.06	-	-
Nitrogen	0.54±0.03	0.24±0.07	0.26±0.06	≤ 1.00	≤ 2.00
Sulphur	0.07±0.01	0.06±0.05	0.03±0.01	≤ 0.05	≤ 0.50
Oxygen (by difference)	50.14	49.88	49.10	-	-

*net calorific value

Table 7 Major and minor trace elements of pressed empty fruit bunches (EFB) fibers and EFB pellets

Parameter	Pressed EFB fibers (feedstock)	Pellet (type of physical treatment)		Wood pellet**	EN ISO 17225- 2 (wood)- (B class)	ISO 17225- 6 (non- wood) – (B Class)
		Test 2 (sieving)	Test 3 (sieving and water washing)			
P, wt. %	0.06	0.06	0.04	-	-	
K, wt. %	1.46	1.31	0.79	0.08	-	
Mg, wt. %	0.07	0.09	0.07	0.02	-	
Ca, wt. %	0.13	0.23	0.17	0.11	-	
B, ppm	6.3	20.9	21.0	-	-	
Cu, ppm	52.6	8.4	5.8	2.72	≤10	≤20
Zn, ppm	41.8	16.3	13.7	9.28	≤100	
Mn, ppm	17.7	21.1	12.1	91.10	-	
Fe, ppm	338.6	2394.0	641.3	91.70	-	
Na, ppm	301.0	377.5	278.6	60.00	-	
Pb, ppm	1.1	3.1	0.7	0.81	≤10	
Ni, ppm	5.3	1.5	0.7	0.52	≤10	
Hg, ppm	-	<10	<10	0.01	≤0.1	
Cd, ppm	0.00	<10	<10	0.005	≤0.5	
As, ppm	-	<10	<10	0.31	≤1	
Si, wt. %	3.38	0.98	0.86	-	-	
Cl, wt. % (method used)	0.67*	0.46(Titrimetric) 0.37 (NSX2100)	0.21(Titrimetric) 0.28 (NSX2100)	0.004	≤0.03	≤0.5

Source: *[34], **[62]

Figures

Figure 1

Process flow diagram for the production of low-ash empty fruit bunches (EFB) pellets

Figure 2

Van Krevelen plot of pressed empty fruit bunches (EFB) fibers (raw material) and EFB -pellets produced from untreated (Test 1), sieving (Test 2), sieving and water washing (Test 3) and physical treatment compared to torrefied EFB, lignite and coal [11]