

REVIEW ON DENSIFICATION OF PALM RESIDUES AS A TECHNIQUE FOR BIOMASS ENERGY UTILIZATION

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Abstract

Due to the tremendous amount of palm biomass residues produced during the palm oil extraction from fresh fruit bunch (FFB), it is inevitable to harness these biomass energy sources to cope with the depletion of fossil fuels and increase in global energy demand scenarios. Densification is one of the favourable techniques to improve the storage and transportation of biomass fuels in order to prevent dumped areas adjacent to palm mills and to prevent from becoming another waste product. This article reviews comprehensively on how type of palm biomass, compaction pressure and temperature, binder, pre- and post-treatments affect the physical and combustion properties of the palm biomass briquettes produced. Based on the previous researches, generally it can be said that the type of palm biomass, the compaction pressure and temperature, and type of binder affect both the physical and combustion performance of densified palm biomass. However, the effect of particle size could be observed only on the physical characteristics of densified products, whereas the effect on the combustion properties remains unclear. In addition, treatments such as pyrolysis, dry and wet torrefaction (hydrothermal treatment), and steam explosion have potential to be applied during briquette production in order to improve the combustion properties. In this review article, it is also suggested that the combination of densification and followed by wet torrefaction will enhance the combustion properties of palm biomass briquettes.

Keywords: Palm biomass, densification, briquette, pelletization, power plant, vehicle system

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1.0 INTRODUCTION

The depletion of fossil fuel and increase in energy demand have driven towards a transformation from over dependence on non-renewable fossil fuel to diversification of energy source including inexhaustible renewable types such as solar, wind, hydro and biomass [1]. In Malaysia, biomass is the most viable renewable energy sources and the large portion of it is mainly contributed by palm oil plantation [1]. Malaysia is the second largest palm oil producer in the world after Indonesia, and during the oil extraction from fresh fruit bunch, various palm biomass residues are generated. Fifteen years ago, the rate of generation for shell, fibre and empty fruit bunch (EFB) were 2.3 million tonnes/year, 5.4 million tonnes/year and 8.8 million tonnes/year, respectively [2]. However, about three years ago, these amounts increased more than twice [3]. Based on this fact, it is inevitable to harness

the tremendous amount of palm biomass produced every year to prevent the dumped areas adjacent to palm mills and to prevent from becoming another waste product of palm oil industry [4].

Densification is one of the favorable techniques to improve the storage and transportation of biomass fuels [5] for power plant application. In addition, the products of gasification of briquettes also have potential to be used for vehicle system [6]. Densification is known as a process of compressing raw materials into solid biofuel with higher density [5]. One of the advantages of this process is the increase in amount of energy per unit volume, thus could cause the storage and transportation procedures become more worthwhile. Besides, the densification process also can reduce the formation of dust and improve the combustion properties of biomass materials such as calorific value, moisture content and burning rate [4, 7]. Indeed, the briquettes produced must be

physically strong and durable, in which the performance is significantly affected by several important criteria such as material type, compaction or forming pressure, forming temperature, size of material and added binder [8, 9].

The main technologies for densification of raw materials are piston press and screw press, in which the advantages and disadvantages of each technology are shown by Table 1 and 2.

Table 1 Advantages and disadvantages of piston press technology (10, 11)

No.	Advantage	Disadvantage
1.	Wear of the ram could be reduced.	When production rate is increased, the quality decreases.
2.	Most cost-effective technology.	Briquettes are somewhat brittle.
3.	Various types of biomass could be processed.	
4.	Uniformity of the briquettes produced is possible.	

Table 2 Advantages and disadvantages of screw press technology (10, 11)

No.	Advantage	Disadvantage
1.	Output is continuous	Power consumption is higher if compared to that of piston press.
2.	Production of the briquettes are uniform	
3.	Carbonization is possible	
4.	Machine can run smoothly due to the absence of shock load.	

Basically, the densification products can be categorized into three categories based on the diameter; i) pellet, ii) briquette and iii) bale. However, the densification of palm oil biomass is only closely related to pellet and briquette, due to the necessary chopping and milling process before densification process [12]. Due to low supply of sawdust and wood residues for briquette production in the past few years, the palm biomass has become the potential substitution for sawdust [13]. Densification technique has been applied for palm biomass around fifteen years ago [2, 14], specifically briquetting process of palm shell and fibre. Since that, the physical and combustion characteristics of densified palm biomass produced under different approach have actively been investigated for various compositions, binders

and operating conditions. Types of palm biomass that have been utilized for making briquette are shell, mesocarp fibre, EFB fibre, frond, palm oil mill effluent (POME), and even bleaching earth.

This paper presents a review on the researches related to the effect of certain important parameters on the performance of densified palm biomass. Differ with the previous review paper by other researchers that focuses on the densification system to produce durability densified products [15], this paper reviews the physical (relaxed density, compressive strength, tensile strength, durability and etc.) and combustion (calorific value, moisture content, fixed carbon content, ash content, burning rate and etc.) properties of densified products that made of palm biomass. Several criteria that affect both properties such as raw materials, operating temperature, compaction pressure, type of binder as well as pre- and post-treatment applied, are discussed.

2.0 PHYSICAL CHARACTERISTICS OF DENSIFIED PALM BIOMASS

The effectiveness of densification process in producing briquette can be measured by determining the physical characteristics of the briquette in terms of strength and durability [9]. Several parameters that show the strength of a briquette are compressive strength, shear strength and water resistance. Meanwhile, the general parameter that represents the durability of a briquette is impact resistance. As mentioned previously, these parameters were significantly affected by raw material, operating pressure and temperature, size of materials, binders [8, 9] as well as treatment applied.

2.1 Effect of Raw Material

One of the earliest attempt to produce briquette made of palm biomass was performed by Husain *et al.* (2002) [2]. They used mesocarp fibre and shell in the weight ratio of 60:40 for making briquettes, with the addition of a synthetic binder (starch + water). In this case, the density and compressive strength obtained were around 1100-1200 kg/m³ and 2.56 MPa, respectively. This value of compressive strength was found sufficient to resist mechanical disintegration. The ratio of 60:40 was chosen because it was a common practice in mills to fire the boilers, that is supposedly decided based on amount produced per year for each type of biomass, in addition to the reliable physical and combustion performance. In this case, the annual production of mesocarp fibre was more than twice if compared to that of palm shell. However, if calorific value is taken as priority instead of the amount produced, the optimum mixing ratio is supposed to be 40:60 (mesocarp fibre:shell) [16, 17].

Based on the previous study [18], it was found that the use of palm shell could increase the hardness of the briquettes produced, but the quality in terms of brittleness is degraded. Akintunde [18] had proven this

fact by performing the tensile and compression test on the sawdust briquettes with the addition of palm kernel shell. The test revealed that when the amount of palm shell is increased, the load that the briquette can sustain in tension becomes less, thus indicates lower quality in terms of brittleness. However, during compression test, the briquettes with more palm kernel shell can sustain more load while the strain becomes less, thus indicates the improvement in hardness of the sawdust briquettes [18]. The similar advantage of using palm kernel shell for densification process was also observed by Lai *et al.* (2013) [41].

Sing and Aris (2012) [16] had carried out the test of compressive strength based on commonly practised method [2, 4, 7, 16], for 100% palm kernel shell and 100% mesocarp fibre briquettes produced from 40mm-diameter steel die. The test was performed by placing sample of briquette between two flat and parallel plates. The force that each briquette can withstand was measured by applying the vertical force until the briquettes fail. Based on their test, they found that the compressive strength of 100% mesocarp fibre briquette is about 2.5 times higher than that of 100% palm kernel shell briquette, that is supposed due to the fibrous structure of palm fibre. The fibrous structure causes the fibre tends to hold the whole briquette more firmly [16]. In addition to the compressive strength, the water resistance of both types of briquette was also tested by immersing the briquettes in a container filled with cold tap water, and followed by recording the time for dispersion in water, as practiced by Demirbas (1999) [19]. The results demonstrated that the water resistance belongs to briquette contains palm mesocarp fibre is better than that belongs to briquette contains palm shell, with an extra resistance time of 61 seconds before failure. Their study also revealed the other advantage of using mesocarp fibre in making briquette, that is the improvement in durability of the briquettes produced. Based on the durability test [20] for 100% mesocarp fibre briquettes, it can be said that the palm fibre could help to improve the durability, in which the initial mass of the 100% mesocarp fibre briquettes could be maintained even after four times of dropping from a height of 1.85 m on a flat steel plate [16]. The pellet consists of shell and mesocarp fibre shows the similarity with briquettes produced by Husain *et al.* (2002) in terms of physical characteristics, in which the ratio of 60:40 (mesocarp fibre:shell) was used to obtain high durability and strength [21].

With increasing amount of empty fruit bunch (EFB) produced per year and the availability of technologies to convert the bulky EFB into the fibrous form, number of researchers started to put their effort to investigate the potential of EFB to be utilized as raw material for densification process. The potential of the EFB as a solid fuel can be observed through the successful development of a model by a local company for briquetting dry EFB fibre and exportation of EFB solid fuel to Japan [22]. Until present, many researchers are still trying to improve the performance of EFB solid fuel in order to cope with the ever increasing energy

demand situation and depletion of non-renewable energy sources.

Based on the stability test of briquette that contains EFB fibre and shredded paper, it can be said that the increase in EFB fibre can improve the stability, in which the dimensional changes of the briquette produced is very small through the duration of four weeks [23]. This is mainly due to the role of EFB fibre in binding the particles in the briquette strongly [23]. This characteristic is supposed belongs to briquettes contain mesocarp fibre too, in which the mesocarp exists as fibrous form in nature.

With the aim to utilize EFB as much as possible while fulfilling standard DIN51731 requirement simultaneously, the mixing ratio of 60:40 (EFB fibre:mesocarp fibre) was selected as the optimum ratio for briquettes that contain EFB fibre and mesocarp fibre [7]. A comparison study has been performed to investigate the effect of EFB as well as mesocarp fibre and shell on the density of pellet [24]. Based on their study, it was found that at the same operating condition, the pellet contains palm shell has density that relatively high if compared to pellets contain the other types of palm biomass. This is mainly due to the smoother particle surface belongs to palm shell if compared to the other surfaces [24]. However, it has been proven by number of researchers that EFB can be converted to briquette or pellet provided that the EFB is pretreated (drying and resizing) in prior to densification process [13, 24].

Besides the briquettes that contain major type of palm biomass (mesocarp fibre, shell and EFB), several efforts have been put on the utilization of other types such as palm oil mill effluent (POME) sludge [25], oil palm frond [24-25] and even bleaching earth [26]. Based on the dimensional stability and crack (durability) analysis performed for briquettes contain mixture of palm oil mill effluent sludge and oil palm frond, the palm oil mill effluent sludge helps to increase the stability and durability of the briquettes. This is mainly due to the ability of the oily POME sludge to bind the particles of the briquettes tightly [25].

2.2 Effect of Compaction Temperature and Pressure

The densification of palm biomass can be performed at low temperature (ambient temperature) but a synthetic binding agent (starch, molasses etc.) is necessary when low compaction pressure (5-13.5 MPa) [2] is applied. The study performed by Husain *et al.* (2002) is one of the examples for this case. In their study, the briquettes produced have reliable compressive strength (2.56 MPa) and is considered sufficient to resist mechanical disintegration. The similar operating condition (low temperature and low compaction pressure) also was applied by Faizal *et al.* (2009 and 2010) to investigate the performance of briquettes that contain empty fruit bunch (EFB) fibre and mesocarp fibre [7, 27].

The synthetic binder is unnecessary when the densification is performed at very high pressure, as demonstrated by several previous experimental studies

[17, 28, 29]. Here, the pressure of more than 150 MPa is considered as very high pressure [17, 28]. At very high pressure, a natural binder, that is lignin is fluidized and it helps to bind the particles of a briquettes and pellets [30], therefore synthetic binders such as starch and molasses are unnecessary.

Number of researchers have investigated fundamentally the physical performance of palm biomass briquettes that contain mixture of mesocarp fibre and shell [2], and mixture of EFB and mesocarp fibre [7], under various compaction pressures. It was found that when the compaction pressure is increased, the relaxed density [2, 7] and compressive strength [7] also increase. Husain *et al.* (2002) also have proposed the relation between the relaxed density and compaction pressure as follows [2]:

$$P = ae^{bD} \quad (1)$$

where P is compaction pressure [MPa], and D is the relax density [kg/m^3], a and b are empirical constants.

As mentioned previously, the lignin that exists in the biomass begins to act as a binder when very high compaction pressure (above 150 MPa) is applied. However, at low compaction pressure, the lignin only shows its function as an effective binder when the biomass is densified at moderate temperature of 150°C-250°C [13]. Several researchers had performed the fundamental investigation on the effect of densification temperature on relaxed density [4, 24]. They found that not all types of palm biomass show the obvious trend of changes with respect to the temperature. Based on a study by Munawar and Subianto (2014), among several types of palm biomass (EFB, frond, shell and mesocarp), it was found that only pellet made of palm mesocarp shows an increase in density when the temperature is increased. This is supposed due to more lignin that acts as a binder is produced when the temperature is increased, and the deformation after densification is not the controlling factor for mesocarp pellet. However, for the other types of palm biomass, the trend is fluctuation, thus elucidates that the production of lignin is not the controlling factor within this temperature range. The similar trend (fluctuation) was also observed by Faizal *et al.* (2015) for the EFB briquettes produced under temperature of 150°C to 210°C [4]. In terms of compressive strength, a study has revealed that the compressive strength of EFB briquettes increases with an increase in compaction temperature [4]. This is supposed due to the stronger bond between particles via the lignin, when the temperature is increased.

2.3 Effect of Binder

Binder is very useful to hold the shape of densified palm biomass by binding the particles inside the densified products. The binding mechanism basically can be classified in four categories [10]: i) hardening binders, ii) molecular forces, iii) form-closed (interlocking) bonds, and iv) electrostatic forces. The binder used for densification of palm biomass can be

classified into two; i) natural and ii) synthetic. Then, the synthetic binder can be further categorized into two categories, namely as organic binder and inorganic binder. The natural binder is known as lignin, that presents during densification at very high pressure (>150 MPa) [17], or at modest temperature (150°C to 250°C) [13, 4, 24]. The organic synthetic binders that were commonly used in the most studies are starch (maize, tapioca, potato, and cassava), paper and molasses. Meanwhile, the inorganic synthetic binders used were asphalt [31], waste glycerol from biodiesel production sector [32], caustic soda and calcium carbonate [33].

Several scientific studies have been performed to investigate the performance of densified palm biomass with different binders [16, 17, 31, 33]. Razuan *et al.* (2011) [33] have performed an investigation on the effect of organic binders and inorganic binders on the tensile strength of pellet made of palm kernel cake. They found that the addition of small amounts of inorganic binders such as caustic soda and calcium carbonate can contribute to the significant improvement to the tensile strength of the palm kernel cake pellet, thus elucidates the ability of these inorganic binders to bind the loose particles. For instance, the addition of 2.0 wt.% caustic soda can improve the tensile strength of palm kernel cake pellet about three times while the addition of 5.0 wt.% calcium carbonate causes an improvement of 50%. Meanwhile, in the case of organic binders, only maize starch showed an improvement of tensile strength (about 40%) when small amount (10 wt.%) was added. But, the other organic binders (tapioca starch and potato starch) did not show any improvement for the same added amount.

In the other study performed by Sing and Aris (2013) [17], it was found that the addition of binder (10% of the total briquette weight) such as starch and paper can improve the physical characteristics of the briquettes contain mixture of palm kernel shell and palm fibre [17]. Based on the crack analysis that was conducted in their study by dropping the briquettes from a height of 1-2 meters, it was found that the crack appeared on the briquette with paper as binding agent demonstrated the least severe, thus demonstrates that paper is more suitable binding agent instead of starch. Based on the study performed by Ugwu and Agbo (2013), it can be said that briquettes with asphalt as a binder has better physical appearance if compared to briquette with starch. However, the briquettes with asphalt have lower quality in terms of combustion properties [31].

2.4 Effect of Particle Size

Prior to densification of palm biomass, it is desirable that the raw material is dried and ground first into pulverized (powder) form. The use of pulverized form is very important in order to achieve homogeneity and reliable physical characteristics. The fundamental studies on the effect of particle size on the

performance of palm biomass briquettes were performed by several researchers [13, 4].

Based on the experimental works performed by Nasrin *et al.* (2008) on the binderless EFB briquettes, it can be concluded that the physical appearance of a binderless palm biomass briquette is the best when smallest size of particles is used. This is mainly due to the increase in contact surface area when smaller size is used, thus stimulates the production of lignin which in turn improve the effectiveness of lignin as a natural binder [13]. The investigation performed by Faizal *et al.* (2015) on the EFB briquettes with various particle sizes also demonstrated the similar results. They showed that when smaller particles are used, the density of palm biomass briquettes becomes larger. This is because smaller particles fill the volume better and thus improve the density of the briquettes produced. In addition, they also demonstrated that when smaller size of particles is used, the compressive strength of the briquettes produced increases. This is supposed due to the reduction of inter-particles space when smaller size is used, thus improves the effectiveness of lignin in binding the particles [4].

2.5 Effect of Pre- and Post-Treatment

Pre-treatments of palm biomass and post-treatments of densified palm biomass have been explored by number of researchers nowadays [34-38] with the aim to improve the physical and combustion performance of final densified product.

In the study performed by Salema and Ani [2012] [34], EFB pellets has been subjected to pyrolysis process with a microwave system, that caused the change in physical appearance of the pellets. Here, the conversion to biochar with sufficiently high calorific value of 25 MJ/kg can be obtained, thus has potential to be utilized as solid fuel. It was found that the biochar yield strongly depends on the weight percentage of microwave absorber (activated carbon).

Nyakuma *et al.* (2015) has performed a post-treatment on the EFB pellets by dry torrefaction, that is known as mild pyrolysis [38]. The EFB pellets enclosed in aluminium foil were heated in different temperatures of 250°C, 275°C and 300°C. Here, aluminium foil was used to prevent the contact between the pellets and oxygen or air. It was found that the dry torrefaction causes a decrease in mass yield, from around 80% when torrefied at temperature of 250°C to around 43% at torrefaction temperature of 300°C. The decrease in mass yield is mainly due to the removal of moisture content, partial devolatilization and the breakdown of hemicellulose [39]. However, the decrease in mass yield of the torrefied EFB pellets is less than that of raw EFB [39].

Meanwhile, steam explosion process has been applied on empty fruit bunch (EFB) and palm kernel shell (PKS) in the study performed by Lam *et al.* (2015) [37]. They have demonstrated the reduction in the porosity of the pellets contained steam exploded PKS, thus causes an increase in density of the PKS pellets. This is mainly due to the shrinkage of micropores of the

PKS particles when the PKS was pretreated with high pressure steam explosion [37]. Meanwhile, the density of fibrous EFB does not really affected by this pretreatment [37]. In addition, it was found that the breaking strength of both palm biomass pellets was improved when the raw materials (EFB and PKS) were pre-treated with steam explosion process [37].

Besides the aforementioned treatments, hydrothermal treatment or wet torrefaction is also found as a potential process to improve the performance of palm biomass briquettes [36]. Differ with dry torrefaction [40], the palm biomass can be heated by using hot compressed water in prior to densification within the temperature range of 180°C to 260°C [36, 40] to produce hydrochar for various applications. However, based on our literature, the investigation on the performance of densified products treated with hydrothermal process has not been reported yet.

Generally, it can be said that the torrefaction process has been considered by number of researchers for their densification study in order to produce energy dense products.

3.0 COMBUSTION CHARACTERISTICS OF DENSIFIED PALM BIOMASS

In this section, the effect of raw materials, binders, operating temperature and pressure, as well as treatments on the combustion properties of densified palm biomass such as calorific value, moisture content and ash content are reviewed. The review in terms of burning rate is also enclosed in certain sections where related. As a benchmark, standard DIN51731 as shown by Table 3 is commonly used. In addition to DIN51731, the other benchmarks available are Onorm M 7135, DIN plus, Pellet Fuel Institute and ITEBE.

Table 3 Specifications stated by DIN51731 [13]

	Calorific Value [kJ/kg]	Moisture Content [%]	Ash Content [%]
DIN51731	17500	<10%	0.7

3.1 Effect of Raw Materials

Calorific value is one of the important criteria that demonstrates the performance of densified palm biomass. Shell has the highest calorific value if compared to mesocarp fibre and empty fruit bunch (EFB) fibre, as shown by Table 4. As mentioned by previous researchers, the high calorific value can be correlated with the high percentage of carbon and hydrogen composition [25, 42], and this was supported by results of ultimate analysis in Table 5. In addition, the results of proximate analysis as shown in Table 6 also demonstrate that the shell has relatively high content of fixed carbon.

Therefore, several studies had promoted the combination of shell and mesocarp fibre in order to

produce densified palm biomass with reliable combustion performance as well as physical performance [2, 17, 27, 32]. About 15 years ago, Husain *et al.* (2002) had developed palm biomass briquettes that contain mesocarp fibre and shell in the weight ratio of 60:40 [2]. The calorific value, moisture content and ash content of the briquettes produced were around 16.4 MJ/kg, 12% and 6%, respectively. Then, Sing and Aris (2013) used the weight ratio of 40:60 (mesocarp fibre:shell) [17]. In view of energy content and ash content as shown by Table 4 and 6, it is desirable to have a briquette with 100% palm shell. However, the mixing with palm mesocarp fibre is necessary when making briquette to prevent incomplete burning and production of black smoke [17]. Based on a previous study, the mixing is necessary when considering both the aspect of energy content and mechanical properties [16].

Table 4 Calorific value of main types of palm biomass [27]

Materials	Average Calorific Value (kJ/kg)
Shell	19584
Fibre from mesocarp	18098
EFB fibre	17465

Table 5 Ultimate analysis of palm biomass [2]

Component (wt.%)	Mesocarp Fibre	Shell	EFB
Hydrogen	6	6.3	6.3
Carbon	47.2	52.4	48.8
Sulphur	0.3	0.2	0.2
Nitrogen	1.4	0.6	0.7

Table 6 Proximate analysis of several types of palm biomass materials

	Moisture content %	Volatile matter %	Fixed carbon, %	Ash content, %
(i)**Palm kernel shell [17]	-	74.60	22.58	2.82
(ii)**Mesocarp fibre [17]	-	74.59	19.38	6.03
(iii)Empty fruit bunch fibre [13]	16.0	-not available	-not available	4.70
(iv)Pulverized empty fruit bunch [4]	7.0	75.5	14.0	3.50
(v)Palm kernel cake [13]	3.0	-not available	-not available	3.94
(vi)Oil palm frond [43]	7.39	72.53	5.81	14.27
(vii)Palm Oil Mill Effluent (POME) [25]	22	-	-	-

(-The sign " ** " indicates proximate analysis in dry weight percentage (dry wt. %))

Besides the mixture of palm kernel shell and mesocarp fibre, a mixture of EFB fibre and mesocarp fibre also could give the reliable combustion performance. Even though the calorific value of briquettes contain mixture of EFB fibre and mesocarp fibre (weight ratio 60:40) is lower than that of commonly used briquettes contain mesocarp fibre and shell (60:40), the value is still very close with DIN51731 requirement (>17500 kJ/kg) [7]. In addition, the combustion rate of the briquettes with mixture of EFB fibre and mesocarp fibre is higher due to better air circulation through the particles of the briquettes.

Besides calorific value, the moisture content is another important criteria since it affects the combustion performance as well as the physical performance of a densified product [21]. An increase in moisture content causes a drop in calorific value [25] and slow down the ignition speed of palm biomass pellet or briquette [24], and also reduces the durability index [21]. Most of the densified products made of palm biomass have moisture content that fulfill or very close to the commercial standard DIN 51731 (<10%) [2,4,13]. This is supposed due to the moisture content of the feedstock (palm biomass) before being densified, that fulfills or very close to standard DIN51731. However, several researchers performed the intensive drying process after briquetting process for briquette made of bleaching earth and husk to significantly improve the moisture content, from the range of 27-29% to the range of 8-15% (acceptable based on DIN51731) [26].

In terms of ash content, it is desirable to produce briquette with low ash content because ash could cause the occurrence of slagging process on the surface of water tube in a boiler, thus leads to the decrease in efficiency of the boiler [17]. Ash is incombustible residue left after combustion of biomass. The high ash content of densified palm biomass is undesirable because the quality in aspect of calorific value deteriorates. This is mainly caused by the residual ash that does not generate energy [44]. Based on the literature study conducted, it was found that the ash content of densified products contain various types of palm biomass still could not fulfill the requirement stated by DIN51731 (<0.7%), even though some of the values were close to the standard value. Table 7 below shows the ash content of several densified products contain different types of palm biomass. Based on the table, it can be said that the bleaching earth is the fuel with poorest quality, as asserted by Srisang *et al.* (2015) [26].

Table 7 Ash content of several types of densified palm biomass

	Mixture of mesocarp fibre and shell (ratio 60:40) [2]	100% Pulverized EFB [13]	100% Pulverized EFB [4]	Mixture of oil palm frond, water and glycerol [43]	Mixture of shell and mesocarp fibre (ratio 60:40) [17]	Mixture of bleaching earth, husk, tapioca starch and torch [26]
Ash Content [%]	6%	2.85	1 - 4	11.34 - 16.04	6.20	27 - 48%

3.2 Effect of Compaction Temperature and Pressure

Densification temperature is an important factor that could affect the combustion properties especially calorific value. When the operating temperature is relatively high, the calorific value of the densified products increases if compared to the value of the raw materials [24, 13, 4]. Nasrin *et al.* (2008) demonstrated that the calorific value of pulverized empty fruit bunch (EFB) increases from 17000 kJ/kg to around 17800 kJ/kg due to densification at temperature of 150 to 250°C. This can be elucidated by an increase in carbonized surface area when the temperature is increased [13]. The other study performed by Faizal *et al.* (2015) also showed the similar results, in which the densification at temperature of 150 to 210°C causes an increase in calorific value of pulverized EFB, from around 16130 kJ/kg (raw material) to around 17500 kJ/kg (after densification)[4]. The increase in calorific value due to the densification at such temperature level also could be observed for the pellet made of pulverized EFB, frond, shell and mesocarp [24]. Within the temperature range of 150°C to 210°C, the trend of changes in calorific value of EFB briquette with respect to the operating temperature is not clear, even though it can be observed that the average calorific value increases if compared to the value of raw material EFB [4]. However, when the temperature range is extended to include 250°C, the trend could be clearly observed, in which the value of calorific value increase with an increase in densification or compaction temperature [24]. Based on several previous investigations [4, 24], the effect of densification temperature on moisture content and ash content could not be clearly observed.

The effect of compaction pressure on combustion performance of briquettes contain mesocarp fibre and shell (weight ratio 60:40) has been investigated by Husain *et al.* (2002) and Faizal *et al.* (2010) [2, 7]. The latter group of researchers has also performed the investigation on briquettes contain EFB fibre and mesocarp fibre (weight ratio 60:40). They found that the changes in compaction pressure do not really affect the calorific value, moisture content and ash content of the briquettes produced. However, when the compaction pressure is increased from 3 to 11 MPa, the combustion rates of both types decrease by 45% of their initial combustion rates. Here, the initial combustion rate of the briquettes contain mixture of mesocarp fibre and shell was around 0.055 g/min while that of the briquettes contain mixture of

EFB fibre and mesocarp fibre was around 0.075 g/min. This is supposed due to the reduction of air gap between particles when the compaction pressure is increased [7].

3.3 Effect of Binder

Several studies have been performed to investigate the effect of binder on the combustion performance of palm biomass briquettes [31, 32, 43, 16]. Sing and Aris (2012) investigated the calorific value of briquettes contained mixture of palm kernel shell and mesocarp fibre with different binders, that were starch and paper. Based on their study, it was found that the use of paper as binder causes a higher calorific value if compared to the use of starch. Meanwhile, the other researchers had made comparison among 100% EFB briquettes with different binder, starch and asphalt in terms of several combustion characteristics such as calorific value, burning rate, heat output, ignition speed. They found that the briquettes with starch as binder gave the higher calorific value, higher burning rate and thus heat output, shorter time for ignition and less smoke produced during combustion [31]. Based on these two investigations, it can be said that the paper gives the highest calorific value, followed by starch and asphalt.

Meanwhile, the other researchers performed investigation on the effect of glycerol (as a binder) on the performance of densified products contained oil palm frond [43], and mixture of palm fibre and palm shell [32]. It was found that the addition of glycerol could improve the calorific value and reduce the ash content, but moisture content increases [43].

3.4 Effect of Particle Size

The combustion properties of densified EFB with various particle sizes have been investigated by Faizal *et al.* (2015) [4]. Even though the particle size does affect significantly the physical characteristics such as relaxed density and compressive strength of the briquettes produced, the effect on combustion properties such as calorific value, moisture content and ash content could not be clearly observed.

3.5 Effect of Pre- and Post-treatment

The effect of pyrolysis on the calorific value of empty fruit bunch (EFB) pellets was investigated by Salema

and Ani (2012). They found that the pyrolysis by microwave system could increase the value from 17000 kJ/kg to around 23000 kJ/kg [34]. In the other study, the EFB pellets were subjected to torrefaction process at temperature of 250, 275 and 300°C [38]. Based on their study, the calorific value was improved by almost 50% after torrefaction at 300°C for 1 hour. However, the torrefaction process causes the mass yield and thus energy yield decrease [38]. Therefore, the decrease in mass and energy yield is trade-off to the gained improvement in the calorific value. But, the decrease in mass and energy yield of the torrefied EFB pellets is less than that of the torrefied raw EFB [38, 45]. This is supposed due to the slower devolatilization process belongs to EFB pellets [38]. Finally, a group of researchers asserted that empty fruit bunch (EFB) treated with hydrothermal treatment (HT) has potential to be converted into briquette. This is mainly due to the improvement in calorific value of the EFB after treated with HT [36].

4.0 FUTURE TREND OF PALM BIOMASS UTILIZATION

Due to increase in global energy demand and motivation for transformation to the strong dependence on non-fossil fuels [46], alternative measures need to be actively implemented in order to harness the biomass energy resources in more effective ways. For the case of palm oil industry, the utilization of palm biomass residues such as shell, mesocarp fibre, empty fruit bunch (EFB), oil palm frond, palm oil mill effluent and even bleaching earth should be promoted widely. One of the potential techniques is torrefaction (dry or wet) that could improve the energy content of the raw biomass material, by increasing the content of fixed carbon. Here, it is desirable that the heat for the torrefaction process is supplied by the process of heat recovery, as example, power plants heat recovery.

Wet torrefaction, that is also known as hydrothermal carbonization, has advantage if compared to the dry torrefaction. Based on previous review study [47], the wet torrefaction is able to produce relatively high yields of carbonized solid fuel without the need for energy intensive drying process before and during the treatment [47].

Therefore, the combination of wet torrefaction and followed by densification of palm biomass as suggested by Novianti *et al.* (2014)[36] has potential to be practiced in the future for coping with the increasing global energy demand and awareness of utilization of biomass energy resources from palm oil industry. In addition, the technique with reverse direction, that is densification and followed by wet torrefaction also should be introduced in order to produce energy-dense solid biofuel. Based on a previous study related to combination of pelletization and dry torrefaction [38], the compact nature of the torrefied EFB pellets has higher mass yield and thus, energy yield if compared to mass yield and energy

yield belong to torrefied raw EFB without densification.

However, the implementation of wet torrefaction needs extra precaution steps since the process deals with relatively high pressures, range from around 1.0 MPa to 2.4 MPa. In this case, the initial cost for preparing safety related equipments should be taken into account.

5.0 CONCLUSION

The densification technique for palm biomass application was reviewed.

Generally, all types of palm biomass have potential to be harnessed in order to cope with the increasing global energy demand and the importance of dependence on non-fossil fuel. However, the mixing process of several types of palm biomass in prior to densification is necessary where appropriated in order to obtain the reliable physical characteristics and optimum combustion properties based on benchmark.

Overall, in addition to the type of palm biomass, the compaction pressure, compaction temperature, type of binder do affect the performance of densified products. The effect of particle size could be observed only on the physical characteristics of densified products, whereas the effect on the combustion properties is not clear.

The treatments such as pyrolysis, dry torrefaction, wet torrefaction (hydrothermal treatment) and steam explosion were applied with the aim to improve the energy content, even though the physical characteristics such as mass yield deteriorated for certain treatments. In this case, it is desirable that the reduction in mass yield is offset by the improvement in energy yield.

Finally, it is suggested that the combination of densification and followed by wet torrefaction will enhance the combustion performance of the densified palm biomass. However, precaution steps are necessary when dealing with the wet torrefaction process.

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