Making Blends of Agarwood Waste with Empty Palm Bunches or Rubber Wood Sawdust for Pelletized Biofuels

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This study created biomass-pellet fuel with reduced ash content from agarwood waste mixed with empty palm bunches (ACW+EPB), and from agarwood waste with rubber wood sawdust (ACW+RWS), utilizing the low ash value of the agarwood waste. The tested blends had a 1:1 ratio of agarwood waste and empty palm bunches, and a 1:3 ratio of agarwood waste and rubber wood sawdust. Comparisons were also conducted relative to Korean (Grade 4) (2014) and ENplus B (2014) commercial pellet standards. Before pressure molding, the mixture components were dried and ground in a pelletizing device with a motor power of 7.5 kW (380 V, 50 Hz), yielding 100 to 150 kg/h without added adhesive. The test results showed that ACW ash content decreased in the RWS hybrid, yet increased in the EPB mixture. The attributes of ash content, moisture content, and heating value of ACW+RWS satisfied ENplus B (2014) and Korean (Grade 4) (2014) standards at 1.70%, 4.50%, and 4,536 kcal/kg. The ACW+EPB also satisfied the Korean (Grade 4) standard at 4.20%, 6.50%, and 4,220 kcal/kg. Thus, the biomass pellets from the mixture of agarwood waste and rubber wood sawdust and that of agarwood waste and empty palm bunches were of suitable quality for commercial purposes.

Keywords: Ash; Agarwood waste; Rubber wood sawdust; Empty palm bunch; Biomass pellet

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INTRODUCTION

Agarwood (fragrant wood) is a wood species native to Thailand, where there are currently approximately 200,000 agarwood farmers nationwide. Thais have planted this tree on approximately 8 million Rai of land (1,280,000 hectares), corresponding to approximately 25 million agarwood trees across the country. The target is 100 million trees with an economic value of approximately five hundred billion Thai Baht (Sommuang 2019), or 16 billion USD. Agarwood cultivation is mostly in the eastern part of the country, including Chanthaburi, Rayong, Cholburi, and Trad provinces. The wood is distilled or put into a refining process, yielding a fragrant oil applicable in pharmaceutical and cosmetic products. This oil is among the most expensive aromatic volatile liquids. The ACW oil from Trat and Chanthaburi provinces of Thailand is extracted by a conventional aqueous distillation method. The agarwood is first cut to chips. Subsequently, the chips are dried, milled, and fermented in water for approximately 5 d to 10 d, followed by distillation for 5 d to 10 d (Jamroenprucksa 2007; Jindawech *et al*. 2015; Moungsrimuangdee *et al*. 2016) to extract the oil. Subcritical water extraction (Yoswathana *et al*. 2012), and supercritical fluid carbon dioxide extraction (Wetwitayaklung *et al.* 2009) are also used to extract ACW oil. The leftover from such refining, agarwood waste, is black charcoal retaining some fragrance. The waste is left to dry and later used to produce frankincense, incense sticks, *etc*. It has been frequently suggested to use agarwood waste for renewable energy, offering an alternative waste management approach that simultaneously creates value.

The rate at which industrial wastes are generated in Thailand is high and continuously increasing. The byproducts and wastes from the industrial sector and communities include empty palm bunches from the raw palm oil industry, rubber wood sawdust from furniture manufacturers or shops, and agarwood waste from its refining process, among others. Without proper management, such leftovers can impact human and animal health, and the environment overall. Pelletizing industrial waste can reduce its volume/quantity, and pelletized dried waste may be reused in industrial processes.

There are some obstacles to using biomass pellets as fuel, partly from energy efficiency concerns. Core security and environmental impacts must be considered, especially regarding ash that is inorganic waste from furnace combustion. The ash is composed of silica, calcium oxide, magnesium oxide, and other components that cannot be burned. It tends to have a low density and a small particle size (approximately 200 1 microns), and large ash accumulation can lead to problems in the furnace regarding ash removal (Department of Industrial Works 2012). The accumulation of large amounts of bottom ash and slag in the combustion chamber of a boiler can damage the boiler (Greinert *et al.* 2020). Ash is a difficult material to transport due to the large amount of secondary dust. Therefore, the quality of solid biofuels based on the ash content is referred to the Standard ISO 17225-1: 2014 (Čubars and Poiša 2017). The ash content is also one of the most important fuel characteristics in Korean (Grade 4) (2014) and ENplus B (2014) commercial pellet standards. That is, the ash should be less than 2%, 6%, or 10%, as these are the limits in the standards for ENplus B (2014), Korean Pelletized Biomass (Grade 4) (2014, and Thailand Pelletized Biomass (high quality) (TIS 2772-2560 (2017), respectively. If these standards are satisfied, then the cost of ash elimination is comparatively low. High ash content is a negative feature in fuels, because it makes the automation of combustion more difficult (Čubars and Poiša 2017). Inefficient combustion can result in higher levels of ash residue. On the other hand, a low rate of ash production can also indicate completed combustion. More complete combustion is beneficial in releasing less carbon monoxide (CO) (Sadaka and Johnson 2017). While CO does not directly cause climate change, it contributes to the formation of tropospheric ozone and greenhouse gases such as methane and carbon dioxide.

The above details suggest developing agarwood waste into biomass pellets because it is of interest as a candidate source of alternative renewable energy. Apart from being clean, low cost, and ready-to-use for energy, biomass has various sources, such as wood, energy plants, agricultural waste, industrial waste, community waste, *etc.* (Strezov 2014), while its transformation into energy is also varied (Akbi *et al.* 2017). Moreover, biomass is the only secured resource that can be converted to all types of energy (Kambo and Dutta 2014. Converting biomass to a dry solid is a basic aspect of pelletizing it (Obernberger and Thek 2004). There have been many studies on biomass in recent years, such as those studying biomass from wood and wood waste (Toscano *et al*. 2013; Ahn *et al*. 2014; Križan *et al*. 2015), biomass pellets from agricultural waste (Lu *et al*. 2014; Crawford *et al*. 2015; Tenorio *et al*. 2015; Liu *et al*. 2016), biomass pellets from industrial waste (Razuan *et al.* 2011; Chavalparit *et al*. 2013), and biomass pellets from community rubbish and sediment waste, *etc*. (Li *et al*. 2015; Kijo-Kleczhowska *et al*. 2016). In Thailand, particularly in its southern part, rubber trees and oil palms, the two main plants of economic value, are well suited to produce biomass pellets from their wastes. Wood pellets from rubber tree trunks, branches, and saw dust are commercially produced (Saosee *et al*. 2020). Empty oil palm fruit bunches (EFB) are also suitable for producing pelletize biofuel (Brunerová *et al*. 2018). However, fuel pellets from agarwood waste, alone or mixed with either rubber wood saw dust or EFB, have not been investigated before.

Therefore, this study assessed the feasibility of fuel wood pellet production from agarwood waste when blending it with either rubber wood saw dust or EFB. The quality of these biomass pellets was assessed based on ash content in relation to the Korean (Grade 4) (2014) and ENplus B (2014) standards.

EXPERIMENTAL

Materials

Agarwood (Aquilaria Crassna) waste

Agarwood (ACW)waste was received from Agro-Production Community Enterprise, a community in Trat province (Trat, Thailand). The ACW waste was a by-product of ACW oil extraction by aqueous distillation.

Empty palm bunches

Empty palm bunches (EPB) are left over after palm oil pressing during the manufacture of raw palm oil. It was obtained from Smothong Group Co., Ltd., Surat Thani, Thailand.

Rubber wood sawdust

Rubber wood sawdust(RWS) is industrial waste from rubber wood processing during furniture manufacture. It was donated by Mitr-Dee Suratthani Limited Partnership, Surat Thani, Thailand.

Prior to their use in producing biomass pellets, the ACW, EPB, and RWS were placed in sunlight to reduce moisture. Subsequently, these components were ground and sieved to sizes smaller than 1 mm. Next, they were oven dried between 100 and 120 °C for 20 to 25 h to remove moisture. The final moisture level was controlled to between 10% and 15% by mass, and the dry powders were stored in sealed plastic bags.

Chemical Attributes and Elemental Analysis

The chemical elements in the ACW, EPB, and RWS raw material wastes were determined by using X-ray fluorescence spectrometry (XRF, PW2400, Philips; Elisabeth, Netherlands) in Sequential Type Spectrometry mode, using an analyzer crystal to disperse the X-rays by wavelength.

Pelletizing the Biomass Mixes

The pelletizing was conducted to increase density (Reed and Bryant 1978) and to transform the biomass to regularly shaped solids, using a KN-D-200 biomass pelletizing machine (Zhengzhou Known Imp. & Exp. Co., Ltd., Zhengzhou, China), with a 7.5 kW (380 V, 50 Hz)-motor and production capacity of 100 to 150 kg/h. The pelletizing was not a continuous process (Bhattacharya and Shrestha 1990) and was done without added adhesive in the biomass mixes. The energy input of the pellet press can be reduced by almost 40% when using preheating of biomass, compared to using biomass without preheating, and this would allow increasing the production rate (Aqa and Bhattacharya 1992). Three replicates were used in tests of pellet density, moisture content, ash content and heating value.

Pellet Density

The produced pellet was weighed and measured for its dimensions, and its volume was estimated from the formula for a cylinder as $\pi r^2 h$. The apparent pellet density was then calculated by the formula,

$$D = (M / V) \tag{1}$$

where D is pellet density (g/cm^3), M is weight of the specimen (g), and V is volume of the specimen (cm).

Moisture Content Test

The analysis based on the standard ASTM D3173 (2011) was performed by placing the biomass pellets in a forced-air drying oven (Memmert #UF750plus; Memmert GmbH + Co. KG, Buechenbach, Germany) at 105 °C for 24 h. The calculation was as follows,

$$\text{Moisture content} = (A - B) / (A) \times 100 \tag{2}$$

where A is the weight of specimen before placing in the oven (g) and B is the weight after removal from the oven (g).

Ash Content Test

The analysis was based on the standard ASTM D3174 (2012) and was performed by burning the biomass pellet specimen in a muffle furnace (model MF-Series 1200C; Hanyang Scientific Equipment Co., Ltd., Seoul, South Korea) at 500 °C for 30 min. The temperature was later set higher to between 700 and 750 °C for a duration of 6 h until the weight of the fireproof container with the ash became stable. The calculation was as follows,

$$\text{Ash content} = (C - D) / (E) \times 100 \tag{3}$$

where C is the weight of container and ash (g), D is the weight of container (g), and E is the weight of specimen (g).

Heating Value Test

The analysis was based on the standard ASTM D240 (2017) and was performed by completely burning the biomass pellet specimen in a bomb calorimeter (IKA Calorimeter System C5000 Control; IKA-Werke GmbH & Co. KG, Staufen, Germany). The 0.5-g biomass pellet was weighed, and the benzoic acid standard was employed to obtain the approximate energy of 6.318 cal/g. The core idea of direct calorimetry was used in measuring the heat released from burning the specimen. The specimen was placed in a chamber charged with high pressure oxygen before allowing an electric current to move through a fuse and ignite the combustion.

Volatile Matter and Fixed Carbon

The volatile matter (%) in pellets was determined based on the standard ASTM D3175 (2007). The crucible was heated in a muffle furnace (model MF-Series 1200C; Hanyang Scientific Equipment Co., Ltd., Seoul, South Korea) at 950 °C for 6 min and then cooled in a desiccator for 20 mins. A 1 g sample of the pellet was placed in a weighed crucible that was closed with a cover. The crucible with 1g (±0.5 g) pellet sample was heated in the furnace at 950 °C for 7 min and then cooled in a desiccator. It was weighed again as soon as it had cooled down. The weight loss (%) was calculated as follows,

$$\text{Weight loss (\%)} = [(W_i - W_f)/W_i] \times 100 \tag{4}$$

where W_i is the weight of sample before heating (g) and W_f is the weight after heating (g).

$$\text{Volatile matter (\%)} = \text{Weight loss (\%)} - \text{Moisture (\%)} \tag{5}$$

Fixed carbon was calculated by using equation (6):

$$\text{Fixed carbon (\%)} = 100 - [\text{moisture (\%)} - \text{ash content (\%)} - \text{volatile matter (\%)}] \tag{6}$$

Quasi-Static Mechanical Strength of Pellets

The biomass pellet diameters were 6.05 ± 0.05 mm for ARW pellets, 6.11 ± 0.05 mm for RWS pellets, 6.10 ± 0.06 mm for EPB pellets, 6.13 ± 0.02 mm for ACW+RWS pellets, and 6.03 ± 0.06 mm for ACW+EPB pellets. The biomass pellet lengths were 21.09 ± 0.49 mm for ARW pellets, 24.85 ± 1.21 mm for RWS pellets, 22.85 ± 1.09 mm for EPB pellets, 29.67 ± 0.39 mm for ACW+RWS pellets, and 23.67 ± 0.09 mm for ACW+EPB pellets. In testing the strain rate was 1 mm/min with a 10 kN load cell for all tests. This test method and parameters were based on the axial quasi-static compressive test of pellets in Williams *et al*. (2018). The ends of each pellet were ground using sand paper. Three pellets of each type were tested.

The compressive strength of the pellet is defined as the stress at the point of failure, and ductility as the strain of the material at failure. Young's moduli of the pellets were obtained from the gradient of the initial linear portion in the stress–strain curve. Elastic strain is defined as the elastic limit (strain at the end of the linear portion of the stress–strain curve).

RESULTS AND DISCUSSION

XRF Analysis of Primary Attributes of Biomass Pellets from ACW, EPB, and RWS Raw Materials

Chemical elements of raw materials

Table 1 shows that the dominant metal elements in agarwood waste were 2.267% calcium (Ca), 0.704% iron (Fe), 0.600% potassium (K), 0.285% silicon (Si), and 0.259% chlorine (Cl). EPB and RWS contained calcium at 4.087% and 1.593%, respectively. Calcium contributed the highest percentage because it is a nutrient typically found in plants, and it provides no impact on functional properties of biomass pellets. In addition to its general importance to plants, calcium also affects cell walls, thus strengthening tree trunks. The content of sulfates and chlorine compounds accelerate high-temperature corrosion of a boiler (Andrzej *et al.* 2020). The 0.259% chlorine content in ACW was higher than that of EPB. Obernberger *et al*. (2006) suggested that 0.1% Cl is the threshold content above which furnace damage occurs, and furnace damage occurs also when the content of sulfur in the fuel is >0.2%. The 0.259% chlorine of ACW was the highest content and exceeded the threshold, while chlorine content in EPB was low at 0.092% and RWS was free from chlorine. However, the 0589% sulfur content of EPB was over the limit content of 0.2%. On the other hand, there is a relationship between the content of ash and heavy metals Fe, Mn, Cu, and Zn (Mierzwa-Hersztek *et al.* 2019)

Table 1. ACW Chemical Elements Determined by Using an XRF Spectrometer

Elements		Mass Fraction (%)		
Name	Symbol	ACW	EPB	RWS
Calcium	Ca	2.267	4.087	1.593
Iron	Fe	0.704	0.290	0.098
Potassium	K	0.600	0.483	0.801
Silicon	Si	0.285	1.055	0.045
Chlorine	Cl	0.259	0.092	-
Sulfur	S	0.155	0.589	0.053
Manganese	Mn	0.134	0.052	0.096
Aluminum	Al	0.133	0.053	0.013
Copper	Cu	0.093	0.066	0.081
Magnesium	Mg	0.088	0.195	0.082
Zinc	Zn	0.061	0.026	0.024
Phosphorus	P	0.050	0.135	0.038
Sodium	Na	0.025	0.007	0.081
Strontium	Sr	0.013	0.009	0.010

ACW Biomass Pellet Fuel Attributes

The ACW moisture content and heating values, shown in Table 2, satisfied ENplus B (2014) and Korean (Grade 4) (2014) standards. It was also found that ACW ash content was as high as 3.30%, though not high enough to meet the ENplus B (2014) standard, because it contained magnesium oxide, silica, and phosphorus (Table 1) at the high concentrations of .0088%, 0.285%, and 0.050%, respectively. These substances are non-combustible and cause a large quantity of ash to form.

Table 2. ACW Biomass Pellet Fuel Attributes

Attributes	ENplus	Korean	Pellet
	ENplus B	4th grade	ACW
Ash content (%)	≤ 2.0	≤ 6.0	3.30
Moisture content (%)	≤ 10	≤ 15	6.00
Heating Value (kcal/kg)	≥ 3,955	≥ 4,040	4,572
Volatile matter (%)	-	-	78.15
Fixed carbon (%)	-	-	12.55

If a large amount of ash is produced, burning becomes problematic and ash removal becomes difficult (Department of Industrial Works 2012). Raw materials producing less ash are most suitable for pelletized fuel; such materials can help reduce ash and related problems that would increase costs from fuel use. Moreover, the volatile matter and the fixed carbon contribute to heating value. Fixed carbon is quite high here, and one volatile component was also high. Clearly, these contribute to easy ignition and long duration of burning (Gil *et al.* 2010; Warajanont and Soponpongpipat 2013). ENplus B (2014) and Korean standard (Grade 4) (2014) do not specify volatile matter or fixed carbon values of biomass pellets. The volatile matter and fixed carbon values of empty palm bunches are 80.89% and 12.60%, respectively (Alias *et al*. 2014), while for rubber wood these are 86.30% and 13.10% (Shariff *et al*. 2016).

Accordingly, the mixture proportions were adjusted to increase biomass value by producing biomass pellet fuel with low ash generation. Because agarwood waste has a low ash content, it was used as the main raw material in combination with empty palm bunches or rubber wood sawdust. The ash contents of the mixture proportions shown in Table 3 satisfy the standards: ≤ 2.0 for ENplus B (2014), and ≤ 6.0 for the Korean standard (Grade 4) (2014).

Table 3. Proportions of Mixing Agarwood Waste with Empty Palm Bunches or with Rubber Wood Sawdust to Satisfy Ash Content Standards

Biomass Pellet Fuel	Proportion	Standards	Ash Content
ACW: EPB	1 :1	Korean Grade 4 (2014)	≤ 6.0
ACW: RWS	1 :3	Enplus B(2014)	≤ 2.0

Attributes of Biomass Pellet Fuel from ACW, ACW+EPB, and ACW+RWS Forming

Additionally, the honeycomb sheet used as a mold during hot pressing was heated to between 70 and 80 °C (Kosher *et al.* 1982), which softened the lignin in the biomass to bind the pellets together (Samson *et al.* 2000; Gilbert *et al.* 2009). The softening of lignin depends strongly on moisture content. Thus, the lignin served as an adhesive in the pellets, providing cohesion forces (Bhattacharya and Shrestha 1990). In addition, the hot pressing might have caused bonding between hemi-celluloses (Mobarak *et al.* 1982).

Table 4 shows the biomass pellets of cylindrical shape. The length and density of ACW, EPB, and RWS pellets were higher than those of ACW+EPB and ACW+RWS because the lignin better held particles together, leading to a higher density (Kang *et al.* 2017). A stronger pressing helped slow down deterioration in water, due to structural effects that also helped the biomass pellet burn efficiently. In addition, changing the blend ratio (an easy alteration) would give similarly sized pellets with stable weights.

Ash Content

Figure 1 shows the ash contents of ACW, RWS, EPB, ACW+ RWS, and ACW+EPB. The ACW+RWS sample with a 1:1 blend ratio met both the ENplus B (2014) and Korean biomass pellet (Grade 4) (2014) standards, as the ash content was 1.70% higher than in RWS, yet lower than in ACW. The ACW+EPB sample satisfied the Korean (Grade 4) (2014) standard at 1:3 blend proportions and an ash content of 4.20% higher than in ACW, but lower than in EPB. These results showed that the blend proportions and choice of raw materials allowed for the control of ash content in the biomass pellets. Other factors affecting the ash content were magnesium oxide, silica, and phosphorus. If a raw material produces ash in large quantity, the combustion will be poor and there will be subsequent difficulties in ash removal (Department of Industrial Works 2012).

Table 4. Forming Features of Mixed Biomass Pellets

Biomass Pellet Fuel	Quality of Biomass Pellet Fuel		
	Forming Ability	Density (g/cm^3)	Appearance of Biomass Pellet Fuel
ACW	The mixture and particles harmoniously bond at a very good level	1.40	
EPB		1.40	
RWS		1.41	
ACW+ EPB	The mixture and particles harmoniously bond at a good level	1.31	
ACW + RWS		1.30	

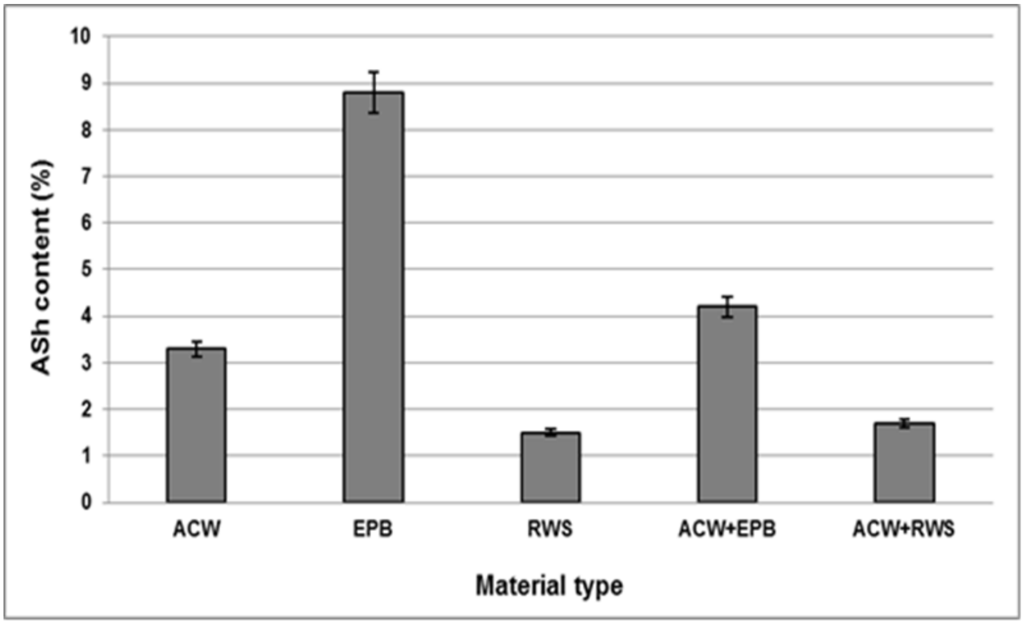

Fig. 1. Ash contents in the tested biomass pellets

Moisture Content

Figure 2 shows the moisture contents of ACW, RWS, EPB, ACW+RWS, and ACW+EPB matching both ENplus B (2014) and Korean biomass pellet (Grade 4) (2014) standards. This was because the raw materials were from the same source, plant biomass, thus necessitating a standard requirement because the moisture content affects combustion.

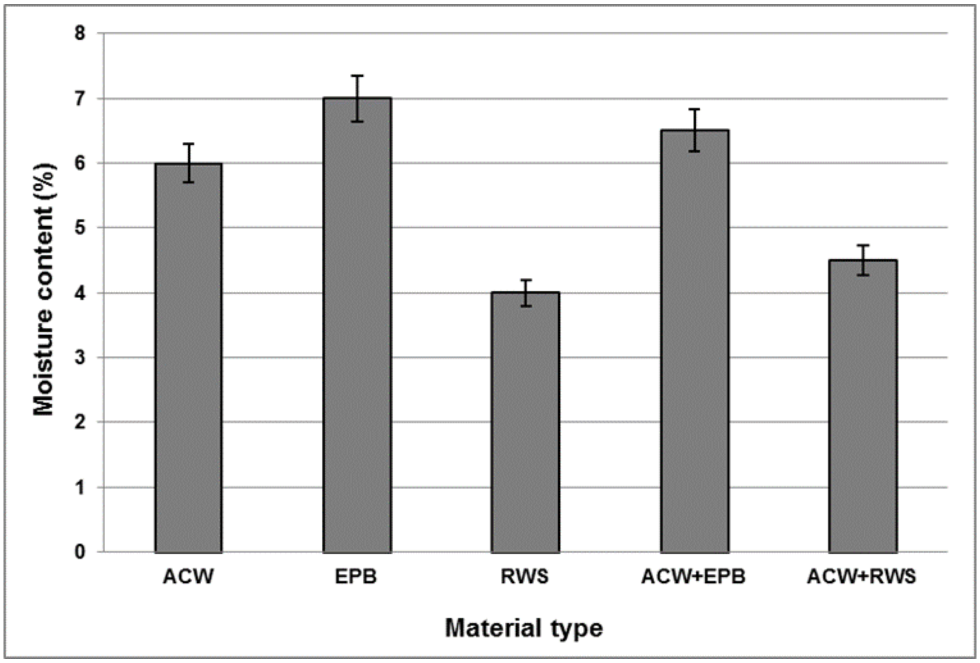

Fig. 2. Moisture contents of the biomass pellets tested

In the presence of high moisture, the heat from combustion is partly lost in evaporation (Williams *et al*. 2012). Moreover, moisture also affects the density and degrades the mechanical strength of the pellets (Theerarattananoon *et al*. 2011; Zamorano *et al.* 2011). Additionally, ACW+EPB at a 1:1 proportion had a 6.5% moisture content, higher than in ACW but lower than in EPB. Conversely, ACW+RWS, at a 1:3 ratio had a 4.5% moisture content, higher than in RWS and lower than in ACW. The blend proportions and choices of materials determined pellet moisture content, which is an important attribute affecting the conversion of biomass to energy, as a high moisture content causes energy losses.

Heating Value

As shown in Fig. 3, ACW, RWS, EPB, and ACW+RWS show combustion heat contents satisfying ENplus B (2014) and Korean (Grade 4) (2014) standards. The biomass heating values state heat energy obtained from one weight unit of biomass with complete burning (Boudrahem *et al*. 2011). The ACW had the highest heating value because agarwood contains some aromatic oil that was not fully released in the oil-refining process. This oil served as a superior fuel in combustion. The ACW+EPB in a 1:1 mix had a 4,220 kcal/kg heating value, higher than EPB, yet lower than ACW by, respectively, 1.10% and 8.34%. Similarly, ACW+RWS in a 1:3 proportion had a 4,536 kcal/kg heating value, higher than RWS but lower than ACW by 3.87% and 0.79%. The heating values of biomass pellets in this study can be considered "good" (Gil *et al.* 2010; Warajanont and Soponpongpipat 2013; Kang *et al.* 2017), as the blend components had high heating values. The blend proportions and choice of component materials enabled control of the heating value of the pelletized biomass. Moreover, the moisture content in the pellets affected their heating value (Department of Industrial Works 2012). However, various physical differences in wood, bark, wood fiber, *etc.*, such as the hardness of wood, might directly impact the heating value of pelletized biomass.

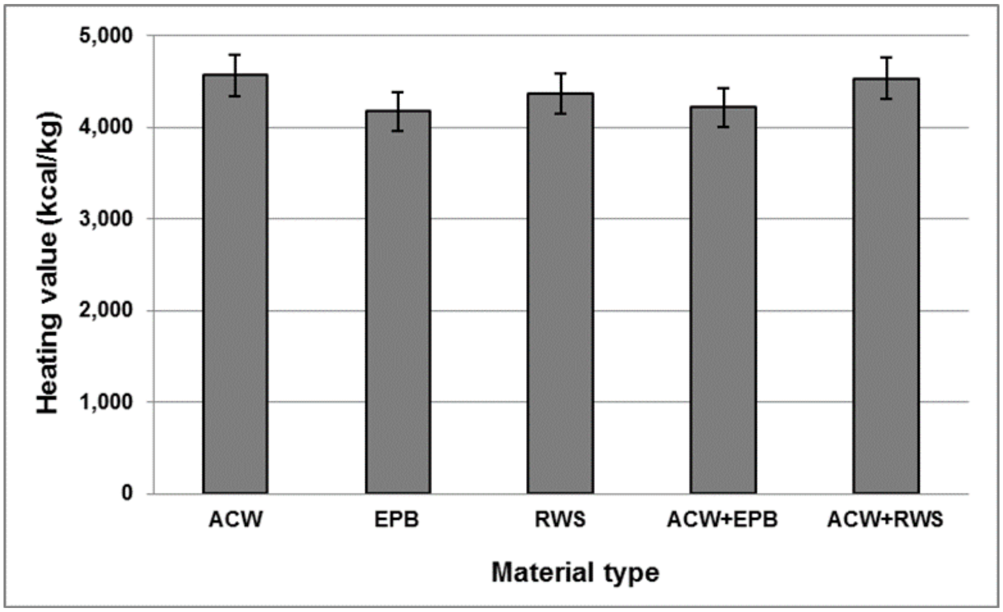

Fig. 3. Heating values of the tested biomass pellets

Quasi-Static Mechanical Strength of Pellets

Table 5 summarized the quasi-static mechanical properties of ACW, EPB, RWS, ACW+EPB, and ACW+RWS biomass pellets. Compressive strength and ductility describe the properties of the pellets at the point of failure and at elastic maximum strain, and the Young's modulus describes the initial response up to elastic limit (straight line) in the stress–strain curve. Compressive strength and Young's modulus of RWS pellets were higher than those of ACW and EPB pellets. This indicates that bonding between RWS particles was stronger than with ACW or EPB. The compressive strengths and Young's moduli of mixed biomasses of ACW+EPB and ACW+RWS types were similar to those of RWS pellets. The compressive strength and Young's modulus of these pellets were comparable to the steam exploded pellets reported by Williams *et al*. (2018). It is possible that bonding of ACW mixed either EPB or RWS was stronger, but the standard deviations in compressive strengths of ACW+EPB and ACW+RWS pellets were large. Heterogeneous particle size distributions contribute to the large standard deviations. Pellet bonding is influenced by the pellet processing methods, the chemical composition, and the moisture content. Thermal softening of lignin polymer chains during the pelletizing results in strong bonds in pellets made from untreated wood biomass (Williams *et al*. 2018). A high concentration of wax combined with a relatively low lignin concentration gives poor adhesion and low compression strength of the pellets (Stelte *et al*. 2011). In addition, the correlation between pellet durability and optimal moisture (10%) is positive, while pellets with 5% moisture had low strength and moisture higher than 15% damaged the pellets during storage (Ungureanu *et al*. 2018). The pellet durability could be estimated based on compression strength, as the durability increases with compression strength exponentially (Shang *et al*. 2012). The strength of biomass pellets is essential for the pellets to endure storage and transport.

The elastic strain and ductility of EPB, RWS, ACW+EPB, and ACW+RWS biomass pellets were similar and slightly lower than those of ACW biomass pellets.

Table 5. Average and Standard Deviation (SD) of Compressive Strength, Young's Modulus, Elastic Strain, and Ductility of Biomass Pellets Tested in Axial Direction

Biomass Pellet Type	Compressive Strength (MPa)		Young's Modulus (MPa)		Elastic strain (%)		Ductility (%)	
	Average	SD	Average	SD	Average	SD	Average	SD
ACW	16.03	4.87	392.72	56.00	4.94	1.59	7.35	0.51
EPB	11.94	2.42	435.67	154.36	3.55	0.69	4.15	0.80
RWS	24.84	3.10	787.94	174.76	3.24	0.72	5.43	1.34
ACW+EPB	23.18	13.75	834.30	360.38	2.62	0.68	4.39	0.02
ACW+RWS	22.92	8.82	993.82	225.55	2.04	0.31	3.91	1.33

CONCLUSIONS

1. Agarwood waste, which has a low ash content, was employed in this study. The agarwood waste contained only 3.30% ash, which was mainly composed of magnesium oxide, silica, and phosphorus.
2. While the ash did not meet the ENplus B (2014) standard, it met the Korean (Grade 4) (2014) standard. Thus, to improve the quality as regards ash content, agarwood waste

was mixed with empty palm bunches at a 1:1 ratio, which satisfied the requirements of Korean (Grade 4) (2014) standard in ash content, moisture content, and heating value, respectively 4.20%, 6.50%, and 4,220 Kcal/kg.

3. Agarwood waste mixed with rubber wood sawdust at a 1:3 proportion satisfied both ENplus B (2014) and Korean (Grade 4) (2014) standards, with the ash content, moisture content, and heating value at 1.70%, 4.50%, and 4,536 Kcal/kg, respectively.
4. Moreover, these ACW+EPB and ACW+RWS blends could be molded into homogeneous pellets. These biomass pellets made from raw material mixtures generated comparatively little ash on combustion, which would give these fuel pellets a cost advantage in power generation use.

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