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PHYSICOCHEMICAL, MECHANICAL AND THERMAL PROPERTIES EVALUATION OF BIOFUEL PELLETS FROM SAGO BARK AND *ACACIA MANGIUM* WASTES

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The demand for raw materials for biofuel pellet is growing, causing an increase in the costs of purchase and production. Fuel pellet is one of the solid fuels that can overcome the shortcomings of energy crisis. Therefore, studies on the potential of various biomass sources as a raw material is essential to fulfil the demand. The objective of this study is to determine the energy properties of pellet produced from sago and *Acacia mangium* wastes and their mixtures. The influence of pelletisation on physical, mechanical and thermal characteristics of pellet were properly investigated. The pellets produced were found characteristically to have a higher calorific value (17.5–18.3 MJ kg^{-1}) which is comparable to the European (EN) (>16.5–19 MJ kg^{-1}) and Korean standards (>4300 kCal kg^{-1}) requirements. The optimal properties of biofuel pellets with a sago bark content of 50% and less, such as durability (97.5–99.3%), ash (1.42–1.43%), sulphur (0.04%) and chlorine (0.08–0.17%) contents, were found to be better compared to biofuel pellets of higher sago bark content. These findings satisfied the international EN and Korean standards for export market. The current study demonstrated the potential of producing sustainable energy sources from the biomass mixture of sago and *A. mangium*, which may prove to be a competitive substitute for fossil fuels.

Keywords: Sago, A*cacia mangium*, pellet, energy properties, calorific value

INTRODUCTION

Malaysia's fast-growing population and rapid urbanisation has caused an increase on energy demand. Among the conventional energy resources produced, fossil fuel serves as the country's primary source of energy, covering about 78.1% (46.0% of natural gas and 32.1% of petroleum). However, due to the vast usage of fossil fuels, Malaysia is facing key issues such as diminishing supply of fossil fuel raw materials and environmental pollutions. Besides, it also contributes to one-third of greenhouse gases (GHGs) global emissions. Therefore, the need for exploring new alternatives and greener sources of energy is critical to address the issues effectively. In addition to ensuring a sustainable energy demand, the usage of renewable energy can help reduce environmental problems, particularly GHG emissions. Among the potential renewable energy sources, biomass-based energy emerges as the favorable option in Malaysia, considering the concerns regarding sustainability of raw materials supply. According to Rasat et al. (2016), biomass has the greatest potential for usage among the current renewable energy sources.

Over 230 billion tonnes of biomass are produced in Malaysia yearly, especially from the forestry and agricultural sectors. Currently, some of these wastes are being used as fuels in boilers to generate steam. Some are being used as animal feedstocks and fertilisers, while the rest are disposed or burned. These wastes can be bulky to store and can seriously pollute the air and water, lowering the quality of the surrounding environment if dispose illegally (Rahman et al. 2013). Converting biomass into dense solid pellet addresses these issues towards their use as renewable solid fuels. It does not only generate income but also minimises wastes, GHG emissions, and carbon emissions (Chen et al. 2017, Prajapati et al. 2019). Furthermore, the cost-effectiveness of generating solid fuel pellets from biomass is enhanced by the low cost of raw materials and the ability of automatic mills to replace labour-intensive mills. In Malaysia, the cost of solid fuel pellets is still lower than that of fossil fuels because biomass is readily available and sustainable.

Among the most popular methods for expanding the value of biological and agricultural commodities by converting biomass into biofuels is pelletisation. According to Widiputri et al. (2022), pellets have become a very popular renewable fuel source. Densification allows this method to make solid biofuels in the form of pellets and minimises the volume of biomass, improving the quality of the energy produced (Artemio et al. 2018). Compared to other biofuels, pellets significantly improve biomass conditions and offer greater economic viability. Renjani and Wulandani (2019) also suggested that increasing the additional value of waste and addressing environmental issues are two ways to use biomass as solid fuel. Utilising biomass pellets has several advantages over traditional solid fuels, including higher calorific value (CV), stability as a substitute energy source, and cost-effectiveness. Besides increasing energy density due to their low moisture and ash content, these pellets minimise transportation, storage, and handling costs. These pellets also allow for standardised sizes and compositions, which makes consumption in domestic and industrial furnaces easier and relatively safe (Monge et al. 2014), and also burn cleaner and reduce air pollution with the idea of neutral carbon (Arifudin et al. 2021).

Biofuel pellet generation from biomass including wood resources (sawdust, bark etc.) has been reported previously by researchers. Wood sawdust is among the most common raw materials used to make biofuel pellet. Li et al. (2012) studied the characteristics of pellet produced from wood sawdust. However, several challenges must be overcome especially those related to production aspects such as creation of fines powders, and debris during storage and transportation. Other crucial alternative biomass for biofuel pellet is from non-woody biomass such as coconut husks (Fu et al. 2020), pineapple leaves (da Silva et al. 2021) and banana leaves (Singh et al. 2020). Due to its abundance, low cost and significance in sustaining a green and circular economy, repurposing agricultural wastes as byproducts makes this type of biomass potentially very useful. However, agropellets are of lower quality than forest pellets, with low bulk density, high ash content, and low CV being the main drawbacks. Mixing woody and non-woody biomass is one potential solution to improve the quality of the pellets (Picchio et al. 2020).

Thus, plantations of *Metroxylon sagu*, commonly known as sago palm and *Acacia mangium* have been identified as potential areas for the growth of sustainable resources for future biomass-based industry in Malaysia. Biomass generated from both plantations can be utilised as various value-added bioenergy products such as heat and electricity generation, biofuel pellets, and wood-based products like medium density fibreboard (MDF). Thus, this biomass supply chain contributes to the transition from linear economy to circular economy.

In Malaysia, the largest sago producer is Sarawak. Sago palm is capable of growing up to the height of 15 m and on elevation of up to 1000 m. It is also well-known that the palm species has high survival rate in salinity and acidic soils. In 2023, the total of sago planted areas were 33,900 hectares. It is projected that more than 60,000 hectares will be planted in the near future, with the overall sago palm mill production of 133,900 tonnes which will be able to produce about 90% of the sago starch. Generally, sago biomass is generated through two distinct activities. Firstly, during the harvesting of sago logs at the plantation, about 53,500 tonnes of fronds are produced. Secondly, at the sago mill processing centers, waste materials such as barks (147,300 tonnes), residues (147,000 tonnes), and sago mill effluent (8,034,600 tonnes) are generated during the starch extraction process (National Biomass Action Plan, 2023). According to Chong et al. (2014), the underutilisation of sago bark is a result of both ignorance and technology. On the other hand, the estimated quantity of forest residues (bark, stumps, tops, branches, broken logs) in Malaysia for 2021 is 1,492,300 tonnes from the annual log production of 7,043,000 m^3 (National Biomass Action Plan, 2023). It is stated that over 70% of plantation land in certain areas are being dedicated to *A. mangium*.

Nevertheless, due to sago having a low cellulose and hemicellulose content, pelletising its biomass alone is not a sustainable biofuel. By blending non-wood material of sago bark with wood material of *A. mangium* as a feasible pellet product, it is expected to improve its physical, chemical, and combustion properties. This research attempted to explore the processing of sago and *A. mangium* into biomass pellets as an alternative energy source and expedite the densification process due to their high CV. The objectives of this study are to produce the biofuel pellet at varying mass ratios, characterisation and assessment of the suitability and potential of blending sago with *A. mangium* to produce biofuel pellet to ensure that the quality meets both end-user requirements and international standards. Thus, a thorough evaluation of its energy, physical, proximate, ultimate, and elemental qualities was conducted.

MATERIALS AND METHODS

Raw materials sourcing and preparation

Two types of biomasses were used for pellet production: bark of sago (*Metroxylon sagu*) and logs of *Acacia mangium* which showed density values of 470 and 540 kg m^{-3}, respectively. Both biomasses were supplied by Sarawak Timber Industry Development Corporation (STIDC) as raw materials for biofuel pellet production. In the first stage, the biomass samples were chopped into small pieces and air dried for 3 to 4 days or until the moisture content reduced from 30–40% to about 12–15%. Subsequently, the fraction was ground to 2–5 mm particle size prior to pelletisation. Contaminants such as dust, fine sand, clay and dirt were removed from the raw biomass samples through sieving process. A total of five pellet types were produced using five different sago-*A. mangium* compositions: 100% *A. mangium* (A100), 30% sago:70% *A. mangium*: (S30:A70), 50% sago:50% *A. mangium* (S50:A50), 70% sago:30% *A. mangium* (S70:A30) and 100% sago (S100). Figure 1 illustrates the biofuel pellet production process flow.

Production of biofuel pellet

All biomass and their mixtures were pelletised using a lab-scale pelletiser machine with a 100 kg h^{-1} capacity and revolving roller-cylinders (Figure 2). Pellets with a diameter of 8 mm were chosen in this study because these pellets are the most common commercially available pellet size.

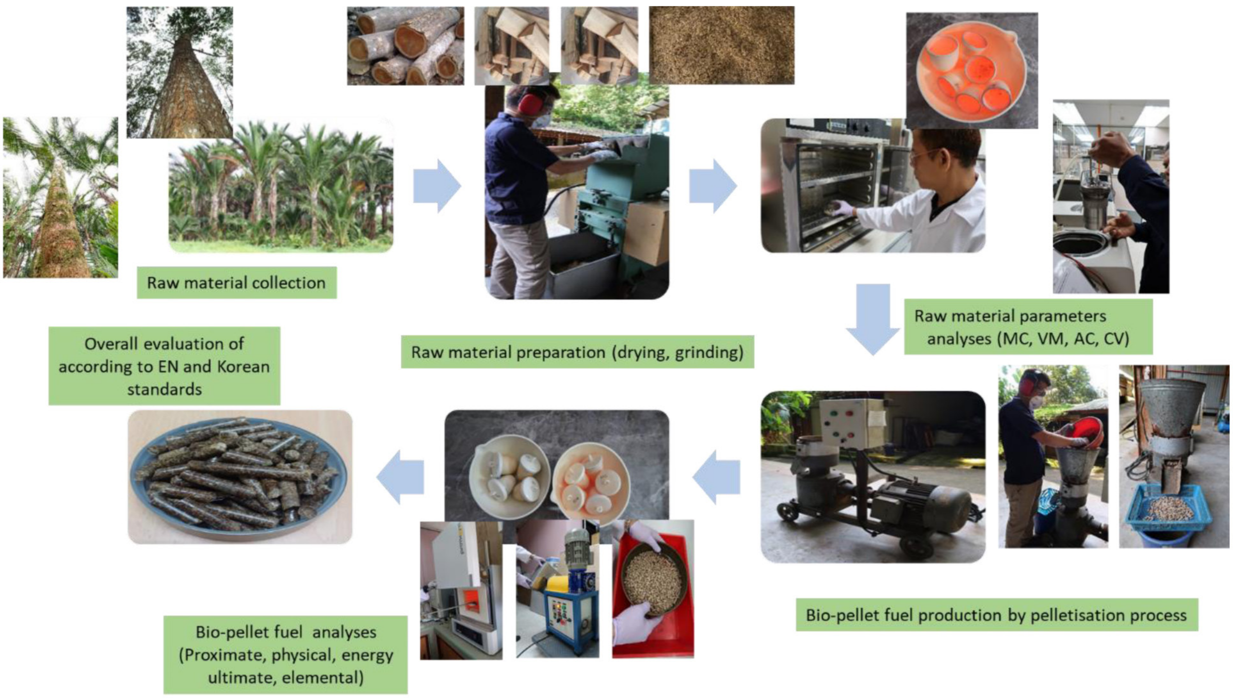


Figure 1 Process flow for sago-*Acacia mangium* biofuel pellet production

Figure 2 Pelletiser machine of a capacity of 100 kg h^{-1} equipped with rotating roller-cylinders

The pelletiser machine was fixed-dies type and made up of multiple components, including a gearbox, hopper, roller, cutting knife, electrical motor, and fixed dies. Dusty biomass material was gathered multiple times at the hopper. After the materials were dropped out of the hopper, the materials were pressed and drilled using a roller. Then, the dies were pressed when the roller produced friction force by centrifugal rotation. Pelletisation of each biomass types were carried out without adding the binding additives. The temperature was increased to 50–60 °C during the high-pressure pressing process. As the pellet cools, the lignin in the biomass acts as an organic binder to maintain its cohesiveness.

Physicochemical, mechanical and thermal analysis of biofuel pellet

The analysis of physical, mechanical, thermal and chemical properties of biofuel pellet is crucial to make sure the quality is comparable with international standard such as European (EN) and Korean standards. Both standards define quality and safety requirements for commercial solid biofuel pellets for industrial heating processes (Table 1). To check if the produced biofuel pellet fulfilled the EN and Korean standard requirements, the physical (diameter, length, bulk density, fines), chemical (proximate, ultimate and elemental), mechanical (durability) and thermal (calorific value) properties of the obtained biofuel pellet samples were extensively characterised using the following procedures.

Physical properties

The physical properties of biofuel pellet samples comprising of dimensions (diameter and shape), length, bulk density, fines and durability, were properly characterised. Random pellet samples with minimum weight of 100 g were collected for diameter and length tests. Both diameter and length were measured three times using a vernier calliper. Pellet diameter is the result of the die-hole dimension, while pellet length is from the distance between the plate and knife placed down the dish (Artemio et al. 2018). Pellet bulk density was determined by the ratio of mass to volume of the pellet (Equation 1). The weight of pellets was measured by using a digital analytical balance with an accuracy of 0.01 g and the volume was measured using a graduated cylinder. The quality of pellet in term of bulk density, was evaluated based on the EN and Korean standards.

Table 1 Guiding Value Grade 1 (European /Korean standard) for sago-*Acacia mangium* pellet properties

Properties	Guiding Value Grade 1 (European standard)	Guiding Value Grade 1 (Korean standard)
Bulk density (kg m^{-3})	≥600	≥640
Diameter (mm)	8±1	6–8
Length (mm)	≤40	≤32
Durability (%)	≥97.5	≥97.5
Fines content (%)	≤1.0	<1
Calorific Value (MJ kg^{-1})	16.5–19	-
Calorific Value (kCal kg^{-1})	-	≥4300
Moisture Content (%)	<10	<10
Volatile matter (%)	-	
Ash content (%)	≤0.7	≤0.7
Fixed carbon (%)	-	
Carbon (%)	-	
Hydrogen (%)	-	
Oxygen (%)	-	
Nitrogen (%)	≤0.30	<0.3
Sulphur (%)	≤0.03	<0.05
Arsenic (As) (mg kg^{-1})	≤ 1	≤ 1
Cadmium (Cd) (mg kg^{-1})	≤0.5	≤0.5
Chromium (Cr) (mg kg^{-1})	≤10	≤10
Copper (Cu) (mg kg^{-1})	≤10	≤10
Mercury (Hg) (mg kg^{-1})	≤0.1	≤0.05
Nickel (Ni) (mg kg^{-1})	≤10	
Lead (Pb) (mg kg^{-1})	≤10	
Zinc (Zn) (mg kg^{-1})	≤100	
Chlorine (Cl) (%)	≤0.02	<0.05

$$Pellet\ bulk\ density\ (kg/m^3) = \frac{Weight\ (kg)}{Volume\ (m^3)}$$ ...Eq. 1

$$Amount\ of\ fines(\%) = \frac{Mass\ of\ amount\ of\ fines\ (g)}{Mass\ of\ sample\ (g)} \times\ 100\ \%$$ ...Eq. 2

Fines and durability tests are important to study the ability of pellet to withstand abrasion during storage and transportation. To determine the amount of fines, pellet samples were shaken lightly and continuously for 10 min to simulate the loading and unloading of pellets during transportation. The pellets were then separated from its fines. The produced fines were measured using a digital analytical balance with an accuracy of 0.01 g. The percentage amount of fines in the sample was determined by using Equation 2.

Mechanical properties

The durability of pellet was determined in accordance to the EN 15210 standard. A total of 500 g of pellets was put in a cylinder drum with an oscillating box mounted on a shaft. The cylinder drum was rotated by a motor at 35 rpm for 10

$$Ash\ content\ (\%) = \frac{Weight\ of\ ash\ (g)}{Initial\ weight\ of\ dried\ sample\ (g)} \times\ 100\%$$
...Eq. 3

$$Moisture\ content\ (dry\ basis)(\%) = \frac{Wet\ weight\ (g) - Dry\ Weight\ (g)}{Wet\ weight\ (g)} \times\ 100\%$$
...Eq. 4

min. After rotation the pellets were removed and weighed to calculate the pellet durability. The durability is calculated by dividing the weight after rotation with weight before rotation then multiply by 100 (Brunerová et al. 2018).

Thermal properties

The calorific value (CV) of biofuel pellet samples was characterised using a bomb calorimeter (LECO Instrument). The CV of fuel (heat of combustion or heating value or heat value) is defined as the energy released per unit mass of fuel in complete combustion with oxygen. The experimental setup involved burning of the pellet (about 0.5 to 1 g) in the bomb calorimeter under constant oxygen. Then, the CV obtained is referred to as the gross calorific value (GCV). The GCV of biofuel pellet is measured at constant volume on a dry basis based on the British Standard EN 14918:2009. The CV is important to determine the energy content of samples. This test determines the total heat released by the pellets when complete combustion occurs. The CV of pellet is automatically measured and calculated by the machine.

Chemical properties

Proximate analysis was carried out to determine moisture content (MC), volatile matter, ash and fixed carbon contents in the pellet samples based on the British Standards BS EN 14774-2:2009, EN 15148:2009 and EN 14775:2009, respectively. The MC of pellet samples was determined using oven-drying method where the biofuel pellet weight was measured using a digital analytical balance with an accuracy of 0.01 g, before and after drying at 80 °C for 24 h. While the content of ash produced was expressed as percentage of residues remaining after combustion at 700 °C in an oven for about 4 h. The measurement of MC and ash content were carried out using Equations 3 and 4.

The ultimate analysis to determine carbon, hydrogen, nitrogen, and sulphur contents in the sago-*A. mangium* biofuel pellet samples was performed using a CHNS analyser (LECO Instrument Model 628). The elemental analysis was conducted using an inductive couple plasma spectrophotometer (ICP-OES, Perkin Elmer, Avio 500). Eight elements were tested, i.e. arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), and zinc (Zn).

RESULTS AND DISCUSSION

Physical and mechanical characteristics

The physical and mechanical properties of sago-*A. mangium* biofuel pellet samples were shown in Figure 3. The results obtained in Figure 3(a) indicated that the bulk density of sago-*A. mangium* biofuel pellets were comparable with the EN and Korean standards requirement, which is above 600 kg m^{-3} (Table 1). As shown in Figure 3(a), biofuel pellet produced using 100% *A. mangium* has the highest bulk density of 637 kg m^{-3}, while the lowest bulk density is recorded for biofuel pellet produced using 100% sago bark (607 kg m^{-3}). The addition of *A. mangium* sawdust to sago bark at a mass ratio of 70:30, 50:50 and 30:70 exhibited biofuel pellet with high bulk density of 631 kg m^{-3}, 621 kg m^{-3} and 620 kg m^{-3}. This is due to the particles of *A. mangium* which bonded better with the existence of sago bark, thus enhanced excellent mechanical properties of the biofuel pellet obtained (Rahman et al. 2013). A higher bulk density is desired since the more compact the pellet, the lower the storage and transportation costs (Picchio et al. 2020, Liu

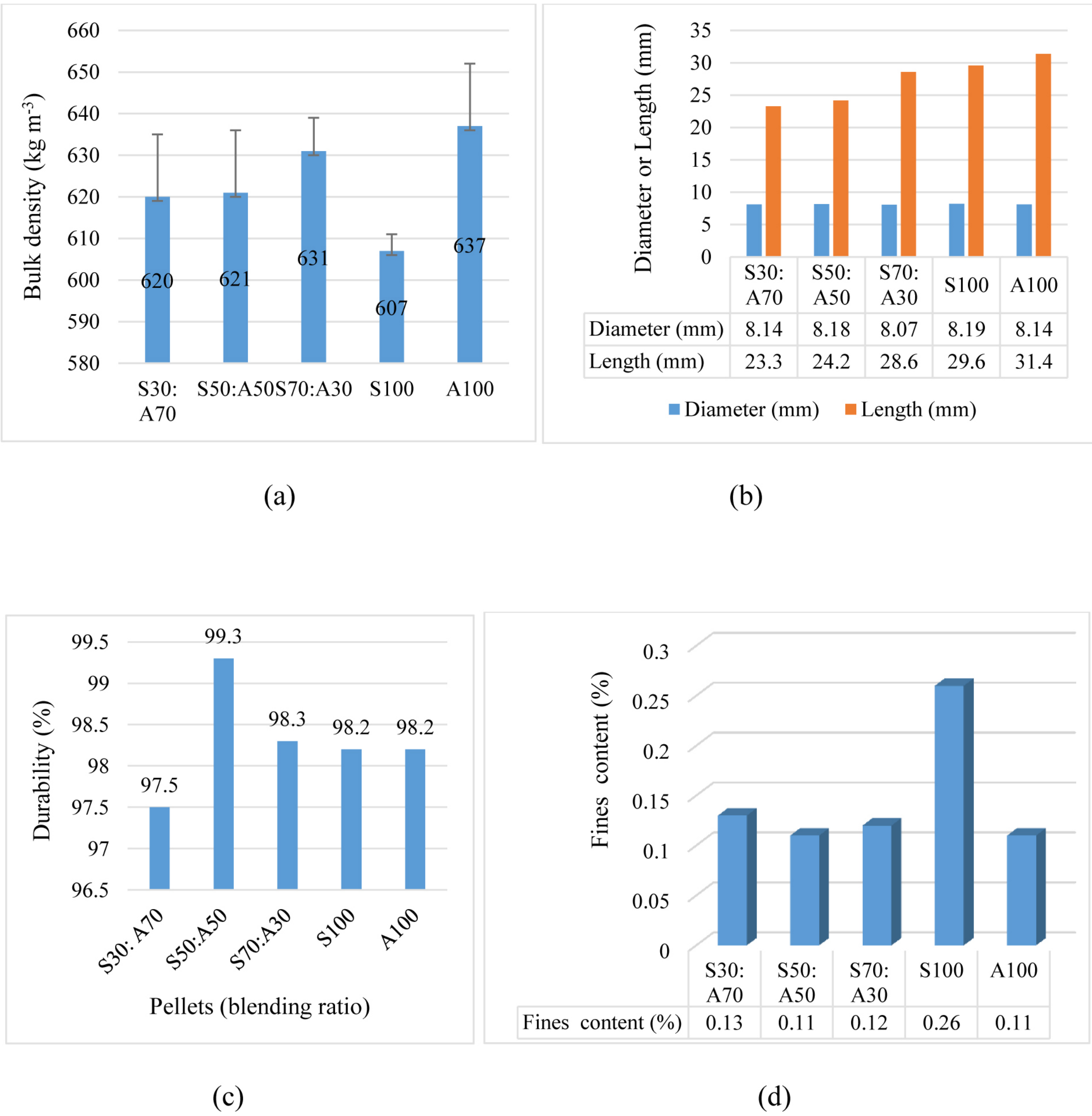


Figure 3 Physical properties of sago-*Acacia mangium* pellet (a) bulk density, (b) diameter and length, (c) durability, and (d) fines (A = *A. mangium*, S = sago bark)

et al. 2016, Artemio et al. 2018). Bulk density also influences the combustion behavior, where denser pellet has longer burnt time (Unpinit et al. 2015).

Parameters such as diameter and length of the biofuel pellet produced from sago bark and *A. mangium* sawdust were given in Figure 3(b). The visual inspections of the biofuel pellets exhibited uniform diameter and length. The diameter of biofuel pellets was in the range of 8.07–8.19 mm, whereas the length was 23.3–31.4 mm. The results obtained were comparable with the EN and Korean standards requirement. The pellet dimension and length were affected by the processing temperature. According to Ilic et al. (2018), the higher the temperature, the shorter was pellet length. This shows that the sago-*A. mangium* biofuel pellet is suitable and practical to be used by industry due to the fast-feeding rate during the combustion process. It can prevent the problem of slow feeding rate and produce less heat, thus providing less surface area exposed for biofuel pellet burning if the biofuel pellet is in longer size (Artemio et al. 2018). Therefore, the sago-*A. mangium* biofuel pellet is suitable for combustion in boilers and furnace with pneumatic feeding systems because of its length which is short enough to prevent

Figure 4 Sago-*Acacia mangium* biofuel pellet, 8 mm diameter (a) S100, (b) S70:A30, (c) S50:A50, (d) S30:A70, and (e) A100 (A = *A. mangium*, S = sago bark)

blockage in the mechanism, allowing easy flow, handling and feeding.

Durability of biofuel pellet is another important parameter for product quality assessment (Said et al. 2015). Biofuel pellet with low durability breaks more rapidly, creating problems during the processing in combustion chamber and boiler conveyors (Carroll & Finnan 2012). For unmixed biofuel pellet (Figure 3c), the durability was 98.2% for both 100% *A. mangium* and 100% sago bark pellets. For mixed biofuel pellet, combination of 50% sago bark and 50% *A. mangium* sawdust produced pellet with the highest durability (99.3%). While, addition of 70% and 30% sago bark produced pellet with 98.3% and 97.5% durability, respectively. The durability results were in good agreement with Figures 3(c) and 4 which showed that the biofuel pellet with 50% sago (the optimum blending ratio) demonstrated better particle bonding and structure, forming a good physical and durable biofuel pellet. In addition, the result showed that the amount of fines produced by all mixture of sago-*A. mangium* biofuel pellet was lower than that of the biofuel pellet produced from 100% sago. The fines of all biofuel pellet shown in Figure 3(d) were below 1% (0.11–0.26 mm), which is acceptable based on the European standard. The addition of sago bark reduced the amount of fines significantly (Rahman et al. 2013). This is also supported by the benefits of the rotation force applied to the fixed dies in pelletiser machine, where the material was ground finer and solidified. It provided a boost and pressed the material into the dies hole, and heat was produced at the dies from the rotation of the rollers (rpm), eliminating the need for an additional heater in the pelletiser (Renjani & Wulandani 2019).

Thermal properties

Figure 5 summarised the CV of sago-*A. mangium* biofuel pellet (n=3). The CV or the energy

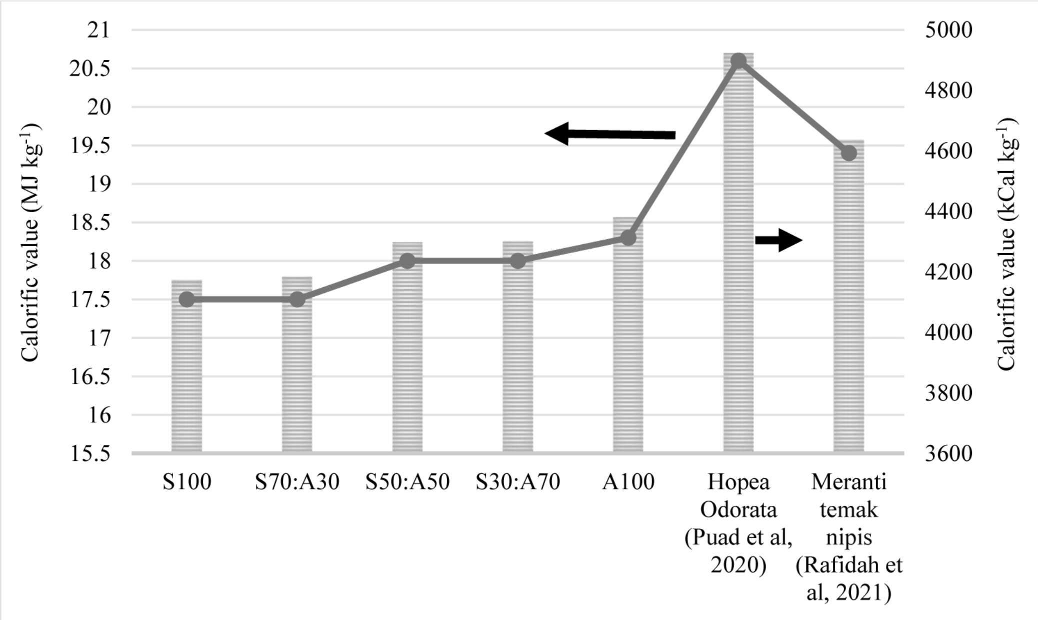


Figure 5 Calorific value of sago-*Acacia mangium* pellet in MJ kg-1 and kCal kg-1 (A = *A. mangium*, S = sago bark)

content of biofuel pellet was analysed to study the highest energy potential of biofuel pellet products (Lee 2015).

The MC of raw materials is one of the most important parameters to determine the pellet CV (Amirta et al. 2018, Artemio et al. 2018). Figure 5 showed that the 100% *A. mangium* biofuel pellet has the highest CV of 18.3 MJ kg^{-1}. The addition of sago bark in the biofuel pellet composition reduced the CV. This is due to the higher MC in sago as recorded in the proximate analysis. High MC in biofuel pellets can indeed reduce the CV, potentially due to the lower density of the raw material. This lower density can impact the overall energy density of the pellet, affecting its combustion efficiency and energy output (Artemio et al. 2018). The CV of biofuel pellet produced in this study was lower compared to the CV of wood pellet (*A. mangium*). This is because of the combination of raw materials between wood and non-wood materials such as sago is higher in MC, thus possibly affecting the amount of energy emitted during the combustion of the biofuel pellet. However, all produced pellets in this study exhibited slightly higher CV compared to the oil palm fibre pellet produced by Rahman et al. (2013), but approximately 10% lower than the normal wood pellet. This is due to the combination of raw materials between wood and non-wood which is higher in MC, thus the possibility of affecting the amount of energy emitted during combustion of biofuel pellet. The average CV ranged from 17.5–18.3 MJ kg^{-1} were within the minimum value required by the EN and Korean standards (>16.5–19 MJ kg^{-1} and >4300 kCal kg^{-1}, respectively). This indicated that the sago-*A. mangium* biofuel pellets produced are suitable for sustainable fuel sources.

Chemical properties

The proximate analysis determined the MC, ash content, volatile matter, and fixed carbon in biofuel pellet samples. Figure 6 showed that the average MC value of the sago-*A. mangium* biofuel pellet ranged from 7.23–8.77%. This indicated that the MC of biofuel pellet reduced after the pelletising process (<10%), which met the standard requirement for pellet. The results showed that the addition of sago bark into the composition of pellet stabilised and increased the MC of the pellets. This is because the sago used in this study was in the wet bark form, which had a very high MC. As such, it can be concluded that the addition of wet sago bark promoted the well-blending and increased the MC of the pellet (Rahman et al. 2013).

Traditionally, the quality of wood pellets is classified according to their ash residues which varied upon the type of biomass and production

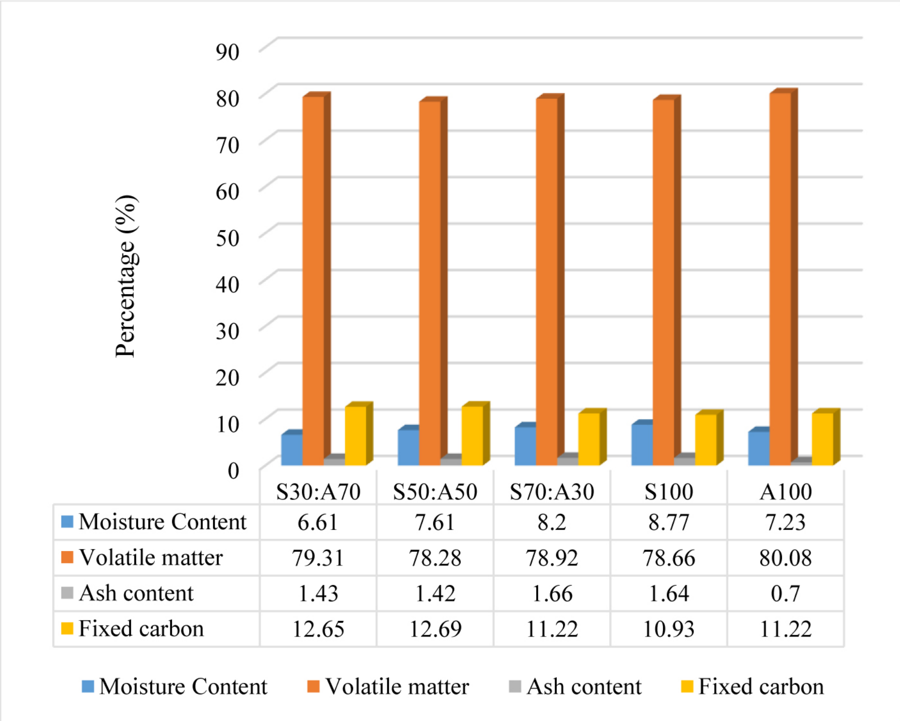
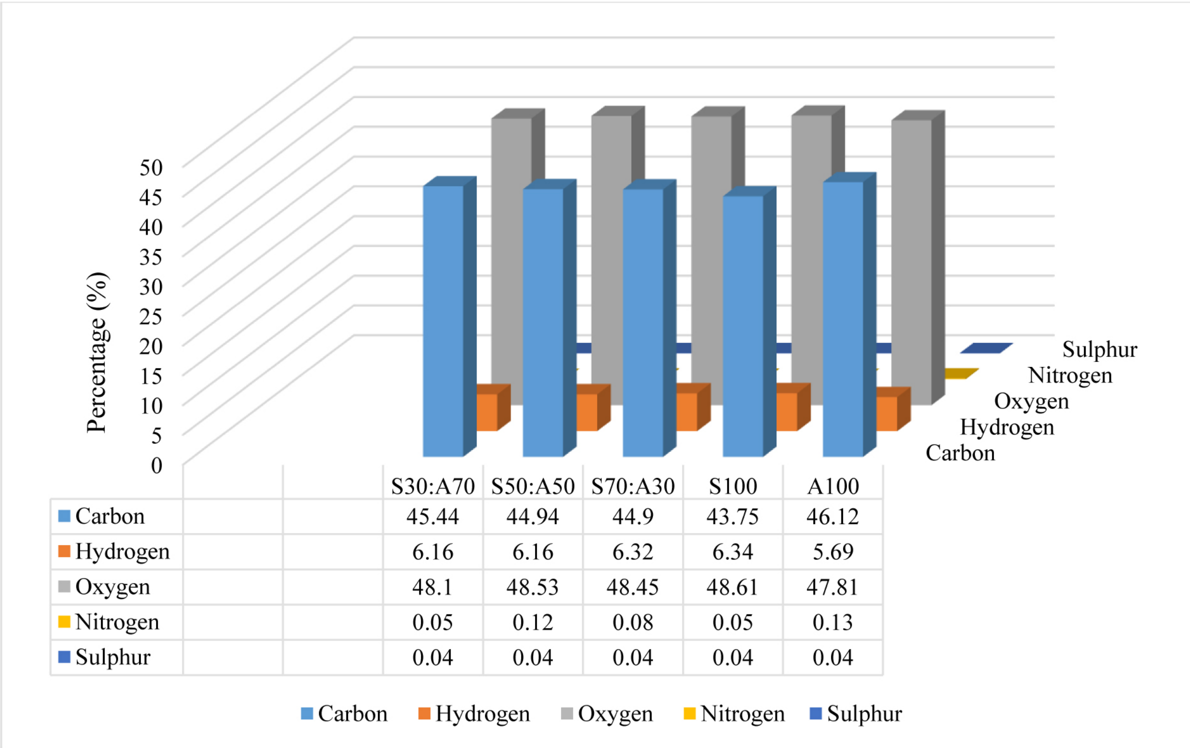


Figure 6 Proximate analysis of sago-*Acacia mangium* pellet (A = *A. mangium*, S = sago bark)

process (Senila et al. 2020). In this study, the addition of sago to the biofuel pellet composition increased the ash content of pellets compared to wood *A. mangium* biofuel pellet. The addition of 30–70% sago by weight increased the ash content produced by almost 50–60%. The ash percentage produced by all types of sago-*A. mangium* biofuel pellet produced in this study was between 1.42–1.66%. According to the EN standard requirement, these pellets are graded from A2 to B. Generally, the ash content of wood pellets typically ranged between 0.2–3%. The wood pellets can be classified into three classes according to their ash content: (1) Grade A1 (ash content of less than 0.7%), (2) Grade A2 (ash content of lower than 1.5%), and (3) Grade B (ash content of less than 3%). Grade A1 and A2 biomass pellets can be used for commercial or residential purpose, with no harm to the boilers. However, Grade B pellet is only sold for industrial applications (Anonymous 2023).

The results showed that ash content decreased as the *A. mangium* percentage increased. High ash content is not suitable for thermal conversion due to issues associated with ash removal, slagging, and deposit formation in furnace. The pellet produced was more brittle in structure because the ash content was higher in value (Hamzah et al. 2018). The higher ash content of pellet was due to silica, the minor element commonly found in tropical climatic plants. Silica is one of the ash compounds other than potassium, calcium, and magnesium. In terms of the effect of bark on the quality of biofuel, it is also reported that the presence of bark in solid biofuels increases the tendency of sintering during combustion, which may lead to combustion issues. As far as the increment of ash content is concerned, it will lower the heating value of the biofuel, posing the risk of sintering and adverse impacts on the processing equipment (Amirta et al. 2018).

The volatile matter of the pellet samples ranged from 78.28–80.08%. The volatile matter content influenced the combustion behavior of pellet. Pellets with high volatile matter content are considered suitable fuel for thermal conversion, which also can cause fast burning (Artemio et al. 2018). This is important so that combustion processes involving oxygen can occur, as volatile materials are combustible due to the decomposition of the compounds consisting of methane, hydrocarbons, hydrogen, and nitrogen and are readily ignited at high temperatures (Yuningsih et al. 2023, Luo & Zhou, 2021, Acda & Devera 2014). Research has



	S30:A70	S50:A50	S70:A30	S100	A100
Carbon	45.44	44.94	44.9	43.75	46.12
Hydrogen	6.16	6.16	6.32	6.34	5.69
Oxygen	48.1	48.53	48.45	48.61	47.81
Nitrogen	0.05	0.12	0.08	0.05	0.13
Sulphur	0.04	0.04	0.04	0.04	0.04

Figure 7 Ultimate analysis of sago-*Acacia mangium* pellet (A = *A. mangium*, S = sago bark)

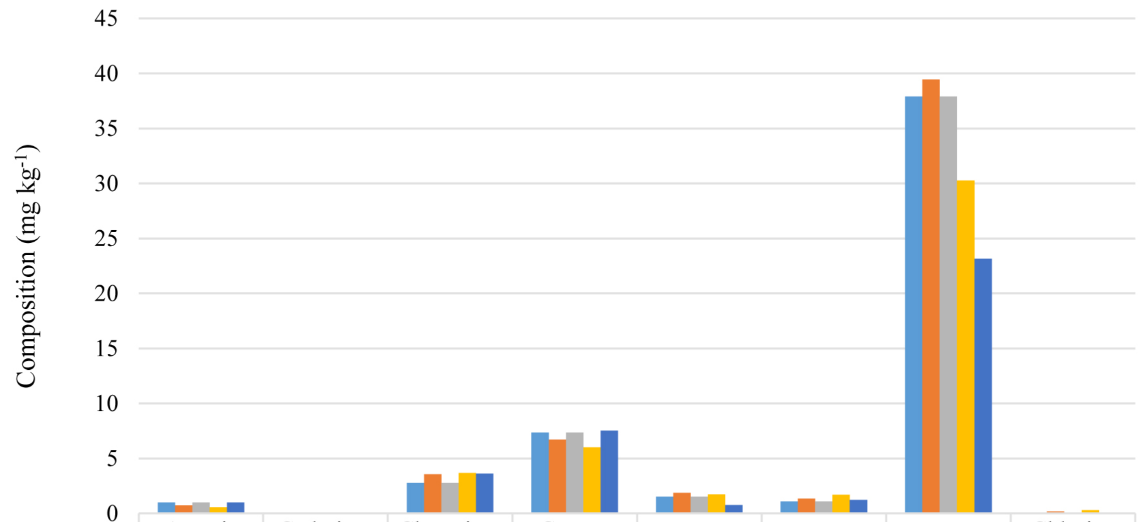
shown that biomass is a good fuel for thermal conversion when it contains high amounts of volatile materials (Artemio et al. 2018).

Fixed carbon content of sago-*A. mangium* biofuel pellet ranged from 10.93–12.69%. The biofuel pellet of sago mixture at 50% and less recorded a higher fixed carbon content of more than 12%. Studies revealed that the fixed carbon content is influenced by factors such as ash and volatile matter (Wibowo et al. 2021, Yuningsih et al. 2023). Higher fixed carbon levels of raw materials lead to a decrease in moisture content and volatile matter in the pellets. This ultimately affects the calorific values, indicating of a high value, thus highlighting the importance of fixed carbon in determining fuel quality (Amirta et al. 2018, Wibowo et al. 2021, Yuningsih et al. 2023)

Figure 7 showed the ultimate analysis results of sago-*A. mangium* biofuel pellet to determine carbon, hydrogen, oxygen, nitrogen, sulphur, and chlorine contents in the pellet samples. Pellets with high carbon and hydrogen contents, low oxygen and ash contents, and low amount of nitrogen are desirable to avoid environmental pollution. The nitrogen content of sago-*A. mangium* biofuel pellet samples ranged from 0.05–0.12%. This value is in accordance with the nitrogen concentration limit of the EN and Korean standards which is less than 0.30%. Pellets with low nitrogen content are preferred because it can avoid or reduce the potential of nitrogen oxides (NO_x) emission. Pellets produced using crop-based biomass materials could have higher nitrogen content. This is due to the amount of fertilisers used during growth of the crops. High nitrogen content in pellet products could be converted into NO_x, which will subsequently contribute to the formation of acid rain after the combustion of pellets (De Souza et al. 2020).

Carbon and hydrogen are considered important and desirable parameters in the production of pellets. These elements contribute to better combustion and help in the release of energy either in the form of carbon dioxide (CO_2) and water (H_2O). The carbon content in sago-*A. mangium* pellet samples ranged from 43.75% (100% sago pellet) to 46.12% (100% *A. mangium* pellet). The result was in good agreement with the values reported by De Souza et al. (2020) and the standards. However, the hydrogen content for 100% *A. mangium* biofuel pellet showed lower results with a difference of about 8.6% from the standard value.

The potential of sulphur released from sago-*A.*



	Arsenic (As)	Cadmium (Cd)	Chromium (Cr)	Copper (Cu)	Nickel (Ni)	Lead (Pb)	Zinc (Zn)	Chlorine (Cl) (%)
S30:A70	1.01	0.02	2.77	7.35	1.52	1.07	37.9	0.08
S50:A50	0.74	0.02	3.57	6.71	1.86	1.34	39.45	0.17
S70:A30	1.01	0.02	2.77	7.35	1.52	1.07	37.9	0.08
S100	0.55	0.02	3.69	6.02	1.73	1.69	30.28	0.29
A100	1	0.02	3.61	7.54	0.75	1.24	23.15	0.02

S30:A70 S50:A50 S70:A30 S100 A100

Figure 8 Elemental analysis of sago-*Acacia mangium* pellet (A = *A. mangium*, S = sago bark)

mangium biofuel pellet was also measured. The existence of sulphur will influence the formation and disposal of ash. Figure 7 showed the sulphur content which remained constant at 0.04% when the mass ratio of *A. mangium* to sago increased. The minimum sulphur content allowed by the EN and Korean standards should be less than 0.03% and 0.05%, respectively. The results indicated that the sago-*A. mangium* biofuel pellets met the standard requirements of commercial pellet as stated in the EN or Korean standards.

High sulphur content in pellet will increase the emission rate of NO_x which is dangerous and polluting to the environment (Amirta et al. 2018). It also reduces the combustion ability. Thus, the concentration of sulphur should be below the limit. In addition, high amount of sulphur, hydrochloric acid (HCl), and sulphur oxides (SO_x) emissions can cause problems such as deposit formation and corrosion. Sulphur values of above 0.1% are related to the oxidation of the equipment used in biomass combustion due to the alkaline salts present in the feedstock. Values above 0.2% are also related to the significant emissions of SO_x (De Souza et al. 2020).

Figure 8 summarised the elemental analysis of sago-*A. mangium* biofuel pellet and showed that the concentrations of As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn in sago-*A. mangium* biofuel pellet were below the EN and Korean standards limit (Table 1). Generally, low level of heavy metals in pellets is important because it has strong impact on ash quality, particulate emissions, ash recycling and disposal. Therefore, the content should be below the limit value particularly for usage in small scale systems which are usually not equipped with dust precipitation devices.

On the other hand, the chlorine (Cl) content in pellet was higher for samples mixed with 50–70% sago (0-17–0.27%). The higher the percentage of sago, the higher the Cl content in the pellet. However, only 100% *A. mangium* pellet recorded a Cl content of within the range of standard commercial pellet based on the EN and Korean standards limit (≤0.02 and <0.05, respectively). The increased concentrations of chlorine and sulphur can be the result of chemical contamination by insecticides, adhesives, glues or wood preservatives in the raw materials and additives usage (Hamzah et al. 2018).

Statistical analysis of variance (ANOVA) was carried out to determine whether there was a significant effect between the physical and trace element analysis in different composition of sago-*A. mangium* biofuel pellet samples. The ANOVA results of physical and trace element analysis showed that the p-value was less than α value of 0.05, with F_{value} (12603.69) > F_{crit} (2.45) and F_{value} (116.05) > F_{crit} (2.12), respectively. This indicated that the composition of sago and *A. mangium* have a significant effect on the physical properties and trace element content of sago-*A. mangium* pellet.

CONCLUSION

This study concluded that sago bark and *A. mangium* biomass was potentially used as the alternative feedstock for fuel pellet production. Successful production of fuel pellets from sago and *A. mangium* biomass was achieved for all combinations studied. The addition of sago into *A. mangium* prior to co-pelletisation process was observed to improve the physical characteristics of pellets. The best pellet containing optimum sago mixture of 50% and less, had lower ash (1.42–1.43%) and chlorine (0.08–0.17%) contents. It also recorded the highest CV of 18MJ kg^{-1}. Higher the sago content, higher were the chlorine and ash contents in the pellet. Excessive addition of sago bark increased pellet MC. High MC reduced the combustion characteristics of the pellets especially on the reduction of CV and the increase of ash content. Generally, the quality of fuel pellet produced from mix of sago bark waste biomass and *A. mangium* was satisfying and met the international standard quality of fuel pellet based on EN and Korean standards.

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