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Proximate Characterization of Sarawak Waste Biomass for Sustainable Bioenergy Applications

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Abstract **— This study investigates the proximate analysis of waste biomass sourced from Sarawak, Malaysia, focusing on their composition and energy properties as part of a broader initiative towards sustainable bioenergy utilization. Proximate analysis was performed according to the Japanese Industrial Standards (JIS) on four biomass types: *Acacia mangium* bark, oil palm kernel, Nipah palm frond, and bamboo waste from *Bambusa vulgaris* species, measuring moisture content, ash content, volatile matter, and fixed carbon content. The results indicate low moisture content across all samples (0.347–0.485%), enhancing energy efficiency, while variations in ash content suggest differing suitability for energy applications. Notably, bamboo waste demonstrated the highest volatile matter content at 93.239%, supporting efficient combustion characteristics, while Nipah palm frond exhibited the highest fixed carbon content (10.301%), indicating strong potential for sustained energy output. The higher heating values estimated revealed that Nipah palm frond offers the highest energy content (17.35 MJ/kg), followed by oil palm kernel (16.21 MJ/kg), with bamboo and *Acacia mangium* bark at 14.53 MJ/kg and 14.36 MJ/kg, respectively. Although these values are lower than those of charcoal, but they are comparable with other waste biomass, and they position these biomass types as viable candidates for biofuel production given its advantages with its abundance.**

Keywords—Ash content, Fixed carbon content, Volatile matter content, Higher heating value, Biofuel.

I. INTRODUCTION

Sarawak, one of Malaysia's largest states, possesses a rich and diverse forest and agricultural resource base that generates substantial quantities of wood and non-wood biomass wastes. These residues represent an underutilized renewable resource with significant potential for energy recovery and material valorization. In the context of escalating global environmental challenges and the urgent need to transition from fossil fuels, biomass utilization has gained attention as a sustainable pathway for renewable energy generation. This aligns closely with Sarawak's strategic commitment to advancing green energy initiatives and promoting environmentally responsible resource management [1].

Biofuels derived from biomass wastes offer a viable and sustainable alternative to conventional fossil fuels, particularly due to the abundant lignocellulosic residues produced by forestry and agricultural activities [2]. These biomass materials can be converted into useful energy carriers through thermochemical conversion processes, which employ high temperatures, typically between 450 °C to 1200 °C, to transform solid biomass into energy and value-added chemical products [3]. Among thermochemical technologies, combustion remains the most widely adopted method, owing to its technical maturity, operational simplicity, and commercial readiness.

Thermochemical conversion of biomass is fundamentally governed by the pyrolysis process, which serves as the initial stage in most conversion pathways, including combustion. Biomass combustion involves a sequence of exothermic reactions between the fuel and an oxidizing agent, resulting in the release of heat and the transformation of chemical species. During the combustion of lignocellulosic biomass, energy is generated primarily through oxidation reactions involving carbon, hydrogen, and oxygen,

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with minor contributions from combustible sulphur and nitrogen compounds present in the biomass matrix [4]. Direct combustion accounts for approximately 90% of the energy derived from biomass and contributes more than 97% of global bioenergy production, highlighting its dominant role in current bioenergy systems [5]. The combustion process generally proceeds through three main stages: drying, pyrolysis and reduction, and the combustion of volatile gases and solid char [6].

The efficiency, stability, and environmental performance of biomass combustion are strongly influenced by the intrinsic properties of the fuel. Proximate analysis is therefore a critical tool for assessing biomass suitability for combustion applications, as it determines the relative proportions of moisture, volatile matter, fixed carbon, and ash content. These parameters directly affect ignition behaviour, heat release characteristics, combustion efficiency, and ash-related operational issues in boilers. Biomass materials with high moisture content require additional energy input prior to ignition, which can reduce overall combustion efficiency and make them less favourable for direct combustion. Such materials may instead be better suited for alternative biofuel conversion pathways [5]. Consequently, proximate analysis provides essential baseline information for understanding combustion behaviour and guiding appropriate biomass utilization strategies.

Despite the recognized importance of biomass characterization, the energy potential of many locally available biomass wastes in Sarawak remains insufficiently explored. The absence of systematic and comparative data on locally sourced feedstocks limits informed decision-making regarding their optimal use in bioenergy systems. This knowledge gap is particularly evident for underutilized biomass resources that are readily available but largely discarded or inefficiently managed. Addressing this gap is essential to unlock Sarawak's untapped biomass potential, support regional green energy development, and advance circular economy practices.

Among the locally abundant biomass wastes in Sarawak are plantation-derived residues such as *Acacia mangium* bark and oil palm by-products, as well as naturally occurring plants including Nipah palm (*Nypa fruticans*) and bamboo. *Acacia mangium*, a fast-growing species widely cultivated for timber production, generates substantial bark waste with potential energy value. Previous studies on oak bark by Ruiz-Aquino *et al.* [7] have demonstrated high heating values (HHV) and favorable fuel characteristics, suggesting comparable potential for *Acacia mangium* bark. The oil palm (*Elaeis guineensis*) industry is another major contributor to biomass waste in Sarawak, where more than 79% of the total biomass produced per plant consists of residues such as empty fruit bunches, palm pressed fiber, and palm kernel [8]. Meanwhile, Nipah palm (*Nypa fruticans*) fronds, although traditionally used in limited applications, remain largely unexplored for energy utilization [9]. Bamboo, increasingly promoted as an alternative plantation resource, also generates significant waste and is known for its high cellulose and lignin content, which is favourable for energy and material applications [10].

While numerous studies have reported proximate and energy analyses of biomass resources worldwide, comparative assessments of diverse, locally available biomass wastes in Sarawak remain scarce. Furthermore, direct determination of HHV through bomb calorimetry is often constrained by high cost and operational complexity, limiting its routine application. To address these challenges, this study conducts a systematic comparative proximate analysis of four locally sourced biomass wastes in Sarawak—*Acacia mangium* bark, oil palm kernel, Nipah palm frond, and bamboo species from *Bambusa vulgaris*. By leveraging established correlation models to confirm the relationship between proximate composition and energy potential, this work provides a practical and cost-effective approach for evaluating biomass combustion suitability. The findings contribute valuable baseline data for local bioenergy development, support waste-to-resource strategies, and reinforce Sarawak's commitment to sustainable energy and green technology advancement.

It is important to note that this work does not attempt to exhaustively represent all biomass variability in Sarawak, but rather to establish indicative thermochemical profiles for key biomass classes. The objective is therefore to evaluate relative combustion suitability under controlled conditions, rather than to generalize absolute performance across all geographical and environmental contexts.

II. METHODOLOGY

A. Raw Material Collection

Fig. 1. The three different biomasses used in this study (a) *Acacia mangium* bark; (b) *Elaeis guineensis* kernel; (c) *Nypa fructicans* frond; (d) *Bambusa vulgaris*.

The materials for this study were sourced locally from Sarawak. *Acacia mangium* bark (AMB) (Figure 1a) and *Elaeis guineensis* kernel (EGK) (Figure 1b) were obtained from the local processing plant at Tanjung Manis, Mukah. *Nypa fruticans* fronds (NFF) were collected from Pulau Bruit in the Daro district of Sarawak (Figure 1c). Finally, the matured (3 years old) *Bambusa vulgaris* (BV) (Figure 1d), was collected from a local processing plant in Sibu.

The geographical differences among the samples collected may influence biomass properties, including ash composition and moisture retention. Therefore, to minimize variability, all samples were subjected to standardized preprocessing conditions, including oven-drying. This approach is to ensures that the reported differences primarily reflect material characteristics rather than the external environmental variations.

B. Proximate Analysis

Proximate analysis was conducted to determine the moisture content (MC), ash content (AC), volatile matter content (VMC), and fixed carbon content (FCC) of the samples, following the procedures outlined in the Japanese Industrial Standard (JIS M 8812:2004). The analysis utilized 60-mesh carbonized powder to ensure consistency and accuracy. Each parameter was measured six times for each sample to minimize experimental error and enhance data reliability.

The Japanese Industrial Standard (JIS M 8812:2004) was selected due to its wide applicability in biomass and solid fuel characterization, particularly in Asian research contexts. JIS provides well-defined thermal conditions and reproducible procedures, ensuring consistency across measurements.

C. Determination of Moisture Content

The MC was measured from 1 g of samples. The crucible with sample was weighed before and after drying in an oven at 105±3°C for 60 minutes. Prior to being weighed, the oven-dried samples were placed in a desiccator for 1 hour. The moisture content was calculated using the Eq. (1) below,

$$\text{Moisture content (\%)} = \frac{w_1 - w_2}{w_2}\ x\ 100 \quad (1)$$

, where w_1 is the weight of the crucible and sample before drying (g) and w_2 is the weight of the crucible and sample after drying (g).

D. Determination of Ash Content

The ash content was measured from 1 g of sample. The sample was placed in a crucible that had been previously weight, and the crucible and samples were weighed. The samples in the crucible were incinerated in a furnace at 815°C for 150 minutes. After cooling to room temperature, the samples were removed and placed in a desiccator for 2 hours before their weight is measured. The ash content was calculated using Eq. (2) below,

$$\text{Ash content (\%)} = \frac{M_3 - M_1}{M_2}\ x\ 100 \quad (2)$$

, where M_1 is the weight of the crucible (g), M_2 is the weight of sample (g) and M_3 is the weight of the crucible and sample after incineration (g).

E. Determination of Volatile Matter

The volatile matter was measured from 1 g of sample. The sample was placed in a crucible that had been previously weight, and the crucible and samples were weighed. The samples in the crucible were incinerated in a furnace at 900°C for 7 minutes. The samples were then placed in a desiccator and weight. The volatile matter was calculated using Eq. (3) below,

$$\text{Volatile matter (\%)} = \frac{M_2 - M_3}{M_2 - M_1}\ x\ 100 \quad (3)$$

, where M_1 is the weight of crucible before incineration (g), M_2 is the weight of the crucible and sample before incineration (g), M_3 is the weight of the crucible and sample after incineration (g).

F. Determination of Fixed Carbon

The fixed carbon is the portion of charcoal that remains after deduction of moisture content, ash content and volatile matter as presented in the following Eq. (4),

Fixed carbon (%) = 100 – (Moisture content + Ash content + Volatile matter) (4)

G. Statistical Analysis

One-way analysis of variance (ANOVA) was employed to determine whether statistically significant differences exist among the biomass samples. ANOVA is suitable for comparing multiple group means simultaneously while controlling Type I error.

Following ANOVA, Duncan's Multiple Range Test (DMRT) was used as a post-hoc analysis to identify homogeneous subsets among sample means. DMRT is particularly suitable for biomass studies due to its higher sensitivity in detecting differences between groups, especially when sample sizes are relatively small (n = 6).

H. Limitations of Study

While proximate analysis provides essential insight into combustion-related properties, it has inherent limitations when used as a standalone tool. Specifically, it does not capture the elemental composition (C, H, O, N, S) of biomass, which is critical for accurately determining energy content and emission characteristics.

Although HHV was estimated using established correlations , direct calorimetric measurements would provide more precise validation. Furthermore, ultimate analysis and thermogravimetric analysis (TGA) are necessary to fully understand combustion kinetics and reaction mechanisms.

Therefore, the conclusions of this study should be interpreted as preliminary indicators of bioenergy suitability, and future work should integrate complementary analyses for a more comprehensive evaluation.

III. RESULTS AND DISCUSSION

A. *Proximate Value of Four Different Biomass*

The proximate analysis of the four biomass samples—AMB, EGK, NFF, and BV—revealed noticeable differences in MC, AC, VMC, and FCC, all of which are directly relevant to their combustion behavior, as presented in Fig. 2 and Table I.

Overall, VMC dominates the composition of all samples. This observation is consistent with the study by Sivabalan *et al.* [5], which reported VMC as the largest fraction in raw biomass materials. During thermal decomposition, VMC releases hydrogen, light hydrocarbons, tar, water, carbon monoxide, and carbon dioxide. The presence of these flammable gases initiates the combustion process; however, a high concentration of volatiles can limit heat buildup and hinder the attainment of high combustion temperatures [11].

Among the samples, BV exhibits the highest VMC (93.239 ± 0.782%), followed closely by AMB (92.381 ± 1.054%) and EGK (91.587 ± 1.344%), while NFF records a noticeably lower VMC (78.731 ± 1.406%). In contrast, FCC is highest in NFF (10.301 ± 2.196%) and lowest in BV (4.910 ± 1.879%). Fixed carbon represents the carbon fraction that remains after the release of volatile matter [12], and higher FCC is generally desirable for producing higher-energy biofuels.

AC varies significantly among the samples, with NFF showing a markedly higher ash fraction (10.482 ± 1.212%) compared to the other biomass wastes, which contain relatively low ash levels (approximately 1–2%). Lower ash content is advantageous, as it reduces slagging and fouling tendencies in biomass boilers that could otherwise negatively impact operational efficiency [12].

Finally, MC remains low and comparable across all samples (0.347–0.485%), indicating minimal energy loss during ignition. High MC is a major disadvantage in combustion processes because, although combustion reactions are exothermic, water evaporation is endothermic. As MC increases, both the higher heating value (HHV) and lower heating value (LHV) of biomass decrease [4].

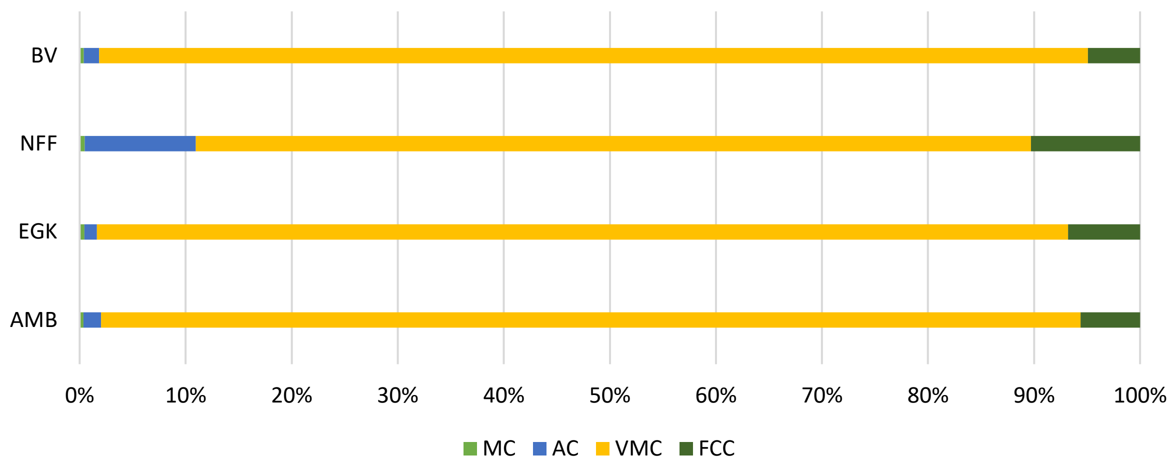

Fig. 2. The proximate analysis composition for the four different wastes.

Table I. The average values of moisture content, ash content, volatile matter content and fixed carbon content in four different wastes.

Sample	MC	AC	VMC	FCC
AMB	0.347 ± 0.080	1.667 ± 1.191	92.381 ± 1.054	5.606 ± 2.644
EGK	0.462 ± 0.096	1.167 ± 1.169	91.587 ± 1.344	6.785 ± 1.705
NFF	0.485 ± 0.050	10.482 ± 1.212	78.731 ± 1.406	10.301 ± 2.196
BV	0.378 ± 0.077	1.473 ± 1.191	93.239 ± 0.782	4.910 ± 1.879

Compared with the biomass samples reported by Sivabalan *et al.* [5] (Table II), the four Sarawak biomass wastes investigated in this study exhibit distinctly different proximate characteristics, particularly in terms of MC, VMC and AC.

Overall, the MC of the present samples (0.347–0.485%) is substantially lower than those reported in the previous study, where MC values range from 4.5% (sugarcane bagasse) to 13.4% (sawdust and coconut husk). This indicates that the Sarawak biomasses require significantly less energy for drying prior to combustion, which is advantageous for direct thermal utilization.

In terms of VMC, the present samples—especially BV, AMB, and EGK—exhibit exceptionally high values (91.6–93.2%), far exceeding in values (56.7–77.1%) in the study by Sivabalan *et al.* [5]. Such high VMC suggests superior ignition characteristics and more rapid devolatilization during combustion compared to conventional agricultural residues.

Conversely, the FCC of the Sarawak samples (4.9–10.3%) is generally lower than that of the biomasses reported by Sivabalan *et al.* [5] which range from 12.7% to 27.5%. This implies a comparatively shorter char combustion phase but aligns with the dominance of volatile-driven combustion behavior.

With respect to AC, most of the Sarawak samples (AMB, EGK, and BV) exhibit very low ash levels (approximately 1–2%), comparable to or lower than sawdust, groundnut shell, coconut husk, and sugarcane bagasse, and markedly lower than rice husk (16.4%) and jatropha cake (8.3%). However, NFF shows a relatively high ash content (10.482%), approaching that of rice husk, which may pose greater challenges related to ash handling and fouling.

Table II. The six different types of biomasses with their proximate analysis (*Source*: Sivabalan *et al.* [5]).

Sample	MC	AC	VMC	FCC
Sawdust	13.4	0.6	72.9	12.7
Groundnut shell	10.1	2.8	68.0	19.1
Coconut husk	13.4	2.4	56.7	27.5
Rice husk	7.2	16.4	61.8	14.6
Sugarcane bagasse	4.5	2.4	77.1	16.0
Jatropha cake	7.3	8.3	65.1	19.3

B. *Moisture Content*

MC influences combustion efficiency, as high moisture levels require more energy for evaporation before combustion can occur. It is found that the MC of all samples are relatively low which average between 0.347 to 0.485%. This low MC is due to the oven-dried samples used in this study.

The oven drying is a process where wood particles or fibers are exposed to controlled high temperatures for extended periods to reduce MC. This method is particularly effective for achieving extremely low moisture levels. During this process, the bound water within the wood structure is thoroughly evaporated, resulting in moisture contents that can fall below 1% [13]. In addition, after the oven-drying, the samples were kept in low-humidity environments in which to prevent reabsorption of moisture from the surrounding air causing low MC.

According to the ANOVA test, the MC for samples is statistically different for different species. Table III shows the Duncan multiple tests for each species.

Table III. Duncan multiple tests for the moisture content.

Sample	N	Subset for alpha = 0.05		
		1	2	3
AMB	6	0.347		
BV	6	0.378	0.378	
EGK	6		0.462	0.462
NFF	6			0.485
Sig.		0.494	0.078	0.601

The Duncan test results reveal three homogeneous subsets. In Subset 1, AMB has the lowest mean MC, setting it apart from the other samples as the least moisture retentive. Meanwhile, Subset 2 includes both BV and EGK in which these groups exhibit statistically similar moisture content, indicating that the materials have moderate moisture levels. Finally, Subset 3 is represented solely by NFF, with the highest mean MC value.

Although the MC for all samples are statistically significant, the low MC recorded for all samples makes them are equally advantageous for biofuel application because low MC enhances the stability and efficiency of these biomass materials. Low MC reduces the energy required for drying, making the materials more energy-efficient when used as fuel [14]. In biofuel applications, lower MC contributes to a higher calorific value, ensuring more efficient combustion and energy release [15]. Therefore, the low MC of these samples makes them well-suited for applications in biofuel production.

C. *Ash Content*

AC determines the non-combustible residue left after biomass combustion, with lower values preferred to minimize contamination and it is one of the important properties if material to be used for fuel [16]. EGK showed the lowest AC (1.167 ± 1.169%), followed closely by BV (1.473 ± 1.191%) and AMB (1.667 ± 1.862%). In contrast, NFF had a significantly higher AC (10.482 ± 1.212%), which may pose challenges.

According to the ANOVA test, the AC for samples is statistically different for different species. Table IV shows the Duncan multiple tests for each species.

Table IV. Duncan multiple tests for the ash content.

Sample	N	Subset for alpha = 0.05	
		1	2
EGK	6	1.167	
BV	6	1.473	
AMB	6	1.667	
NFF	6		10.482
Sig.		0.563	1.000

The Duncan test results reveal distinct groupings in mean values and these samples fall into two homogeneous subsets. Subset 1 includes EGK, BV and AMB which suggest that these three samples share similar MC and do not significantly differ from each other at an alpha level of 0.05. Meanwhile, Subset 2 comprises only NFF, with a substantially higher mean value which is statistically different from other samples in Subset 1.

The AC of waste significantly influences their suitability for biofuel applications, as higher AC can reduce combustion efficiency and increase residue after burning. Among the materials tested, EGK, BV and AMB which exhibited the low AC are advantageous for energy applications due to its minimal impact on combustion efficiency. This is based on the previous studies by Senila *et al.* [17], suggesting that lower AC contributes to higher energetic value and more efficient burning processes. In addition, these values fall within acceptable limits for biofuel, adhering to standard requirements and suggesting these materials would produce less ash residue and fewer clumps when burned, enhancing their energy output and reducing maintenance in combustion systems.

In contrast, the AC of NFF was significantly higher, which may present challenges in biofuel applications. To overcome this limitation, NFF may be more suited for lower-temperature processes or for blending with lower-ash materials to optimize its energy output and minimize issues related to ash deposits [18].

D. Volatile Matter Content

VMC reflects the ease of ignition and the release of combustible gases during combustion. The typical volatile matter range for general biomass is 65 to 85% and 76 to 86% for woody biomass. BV recorded the highest VMC (93.239 ± 0.782%), indicating excellent ignition properties and fast combustion, which is advantageous for use as an alternative fuel. EGK (91.587 ± 1.344%) and AMB (92.381 ± 1.054%) also demonstrated high VMC. NFF, however, exhibited the lowest VMC (78.731 ± 1.406%), which could result in slower ignition and combustion, limiting its performance as a biofuel unless mixed with other biomass sources.

According to the ANOVA test, the VMC for samples are statistically different for different species. Table V shows the Duncan multiple tests for each species.

Table V. Duncan multiple tests for the volatile matter content.

Sample	N	Subset for alpha = 0.05		
		1	2	3
NFF	6	78.731		
EGK	6		91.587	
AMB	6		92.381	92.381
BV	6			93.239
Sig.		1.000	0.255	0.219

The Duncan test results reveal three distinct homogeneous subsets for the samples analyzed at a significance level of 0.05. NFF is categorized in the first subset, suggesting that it holds a statistically distinct, lower mean compared to the other samples. EGK and AMB both fall into the second subset in which these two samples do not exhibit statistically significant differences from each other, indicating similar performance within the context of this analysis. Finally, BV, with the highest mean value is placed in the third subset, marking it as significantly different from other waste and indicating the highest level of the measured characteristic.

The limit of VMC to avoid ignition of the fuel with smoky flame is about 40%. All samples in this study have significantly higher VMC than the defined limit. Consequently, the samples will ignite easily but produce smoke during ignition. However, if the air supply is sufficient, combustion can take place with smoke production. The higher the VMC, the more reactive and easily it ignited [19].

E. Fixed Carbon Content

FCC indicates the amount of solid carbon available for combustion after the volatile matter is released. High FCC values suggest prolonged and stable combustion, making the fuel suitable for sustaining high kiln temperatures. In addition, high FCC is indicative of high HHV (Seah *et al.*, 2024). NFF had the highest FCC (10.301 ± 2.196%), which suggests good long-term combustion potential. EGK (6.785 ± 1.705%) and AMB (5.606 ± 2.644%) exhibited moderate FCC values, balancing ignition speed with sustained combustion. BV recorded the lowest FCC (4.910 ± 1.879%), indicating a faster burn rate but shorter combustion duration, making it suitable for processes requiring rapid heat generation.

According to the ANOVA test, the FCC for samples is statistically different for different species. Table VI shows the Duncan multiple tests for each species.

Table VI. Duncan multiple tests for the fixed carbon content.

Sample	N	Subset for alpha = 0.05	
		1	2
BV	6	4.910	
AMB	6	5.606	
EGK	6	6.785	
NFF	6		10.301
Sig.		0.165	1.000

The Duncan test results provide insight into the differences in mean values across four samples. In Subset 1, BV, AMB, and EGK show no statistically significant differences among each other, with a significance value of 0.165. This suggests that these three samples have comparable mean values, falling within a similar range. Meanwhile Subset 2 includes only NFF, which has a considerably higher mean of 10.301. Overall, these results suggest that while BV, AMB, and EGK share similar mean values, NFF stands out with a significantly higher mean, likely reflecting a distinct property or characteristic that sets it apart from the other samples.

F. Higher Heating Value Estimation

According to Nhuchhen and Abdul Salam [20], the HHV of biomass can be effectively estimated using a linear correlation based on the data from proximate analysis. This correlation offers a practical alternative to analytical measurement which is more complex and costly. The validity of this estimation is well-supported, as the correlation has shown consistent accuracy across various biomass types. This makes it a useful tool for preliminary evaluations in biofuel research, where HHV is essential for comparing the energy potential of different materials. Based on their paper, the linear correlation for estimating HHVs of biomass is:

Higher heating value (MJ/kg) = 19.2880 – 0.2135 x VMC/FCC + 0.0234 x FCC/AC – 1.9584 x AC/VMC

The HHV of waste biomass in this study using the linear correlation estimation are indicated in Fig. 3.

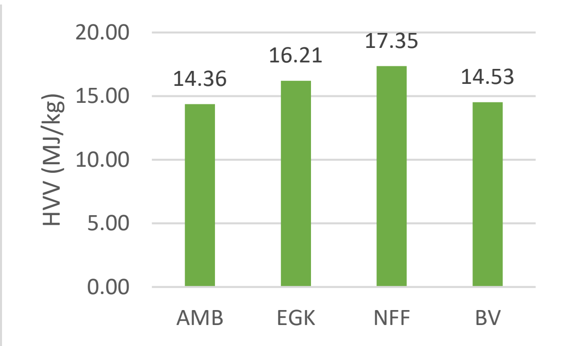

Fig. 3. The HHV for the four different wastes.

According to Fig. 3, NFF exhibits the highest HHV at 17.35 MJ/kg, indicating its superior energy content compared to the other biomass sources. EGK follows with an HHV of 16.21 MJ/kg. BV and AMB show lower values, at 14.53 MJ/kg and 14.36 MJ/kg, respectively. This data suggests that NFF may be the most promising biomass for biofuel production in terms of energy potential. Although these estimated values are lower than charcoal (29-33 MJ/kg), it is comparable with other agriculture biomass such as coconut husk (15.9 MJ/kg) [21], banana peel (17.4 MJ/kg) [5] and risk husk (15.1 MJ/kg) [22].

G. Influence of Intra-Sample Variability

Biomass properties are known to vary due to factors such as harvesting season, plant maturity, and preprocessing conditions. For example, moisture content is strongly influenced by environmental humidity and drying history, while ash content may vary depending on soil contamination and mineral uptake.

In this study, variability was minimized through controlled experimental procedures, including uniform drying, particle size standardization, and repeated measurements (n = 6). Nevertheless, the reported values should be interpreted as laboratory-standardized results, and natural variability under field conditions may lead to broader ranges.

Future studies should incorporate seasonal sampling and multi-location datasets to better quantify variability and improve the representativeness of biomass characterization.

IV. CONCLUSION

The proximate analysis of various biomass samples from Sarawak reveals key differences in their combustion-related properties. MC in all samples is low, likely due to oven-drying and storage in low-humidity environments. This low moisture level is advantageous as it enhances energy efficiency and stability, reducing the energy required for drying during combustion. AC also varies significantly among the samples with EGK, BV, and AMB have relatively low AC, making them more suitable for energy applications due to minimal residue and higher combustion efficiency. VMC is important as it affects ignition and combustion rates. BV exhibits the highest VMC indicating rapid ignition and efficient combustion, followed by EGK and AMB with similarly high VMC values. Finally, NFF records the highest FCC (10.301%), which suggests good long-term combustion potential, making it favorable for applications requiring steady heat output.

Based on the proximate analysis value, HHV estimation suggests that NFF has the highest energy content, followed by EGK, BV and AMB. Although these values are less than charcoal's energy density, they are comparable with other agricultural biomass types, making them viable candidates for biofuel production. In particular, NFF demonstrates the highest energy potential, indicating promise for biofuel applications despite its high AC, which could be managed through specific usage strategies. EGK, AMB, and BV also present viable options, each with unique attributes that could be tailored to different energy applications based on specific requirements for combustion efficiency and residue management.

This study provides a controlled comparative assessment of selected biomass wastes under standardized laboratory conditions. While the findings highlight the promising energy potential of these materials, particularly Nipah palm frond, it is emphasized that real-world performance may vary due to geographical and environmental factors.

Therefore, the results should be considered as baseline reference data, and further investigation incorporating multi-location sampling, ultimate analysis, and direct calorimetric measurements is recommended to support large-scale bioenergy applications.

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AUTHOR CONTRIBUTIONS

Ros Syazmini Mohd Ghani: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing–Original Draft Preparation;
Sofiyah Mohd Razali: Validation;
Mohamad Saiful Sulaiman: Conceptualization, Methodology, Validation;
Madihan Yusof: Formal Analysis, Investigation, Methodology, Validation;
Mohammad Shahril Osman: Supervision.

CONFLICT OF INTERESTS

No conflict of interests was disclosed.

ETHICS STATEMENTS

Our publication ethics follow The Committee of Publication Ethics (COPE) guideline. https://publicationethics.org/

DATA AVAILABILITY STATEMENT

Not available.

REFERENCES

[1] A. B. M. Abdul Malek, M. Hasanuzzaman and N. A. Rahim, "Prospects, Progress, Challenges and Policies for Clean Power Generation from Biomass Resources," *Clean Technol. Environ. Policy*, vol. 22, no. 6, pp. 1229–1253, 2020.

[2] L. Cherwoo *et al.*, "Biofuels An Alternative to Traditional Fossil Fuels: A Comprehensive Review," *Sustain. Ener. Technol. and Assess.*, vol. 60, pp. 103503, 2023.

[3] J. J. Zhang and X. Zhang, "The Thermochemical Conversion of Biomass into Biofuels," *Biomass, Biopolymer-Based Materials, and Bioenergy*, pp. 327–368, Duxford, 2019.

[4] T. Bhaskar *et al.*, "Thermochemical Conversion of Biomass to Biofuels," *Biofuels*, Academic Press, pp. 51–77, 2011.

[5] K. Sivabalan, S. Hassan, H. Ya and J. Pasupuleti, "A Review on The Characteristic of Biomass and Classification of Bioenergy Through Direct Combustion and Gasification as An Alternative Power Supply," *J. Phys. Conf. Ser.*, vol. 1831, no. 1, pp. 012033, 2021.

[6] A. Demirbas, "Combustion Characteristics of Different Biomass Fuels," *Prog. Ener. Combust. Sci.*, vol. 30, no. 2, pp. 219–230, 2004.

[7] F. Ruiz-Aquino, M. M. González-Peña, J. I. Valdez-Hernández, U. S. Revilla and A. Romero-Manzanares, "Chemical Characterization and Fuel Properties of Wood and Bark of Two Oaks From Oaxaca, Mexico," *Ind. Crops Prod.*, vol. 65, pp. 90–95, 2015.

[8] Z. X. Ooi, Y. P. Teoh, B. Kunasundari and S. H. Shuit, "Oil Palm Frond as A Sustainable and Promising Biomass Source in Malaysia: A Review," *Environ. Prog. Sustain. Ener.*, vol. 36, no. 6, pp. 1864–1874, 2017.

[9] R. S. Mohd Ghani, M. S. Osman and A. I. Abdul Rani, "Exploring The Potential of Nipah Palm Frond as Sustainable Raw Material for Eco-Friendly Particleboard Production," *Clean. and Circul. Bioecon.*, vol. 8, pp. 100092, 2024.

[10] M. Perumal *et al.*, "Survivorship and Field Growth Characteristics of Four Selected Bamboo Species for The Development of Bamboo Industry in Sarawak, Malaysian Borneo," *Malaysian Appl. Biol.*, vol. 52, no. 5, pp. 155–162, 2023.

[11] D. A. da Silva *et al.*, "Volatile Matter Values Change According to The Standard Utilized?," *Res., Soc. and Develop.*, vol. 10, no. 12, pp. e291101220476, 2021.

[12] D. Racero-Galaraga, J. D. Rhenals-Julio, S. Sofan-German, J. M. Mendoza and A. Bula-Silvera, "Proximate Analysis in Biomass: Standards, Applications and Key Characteristics," *Results Chem.*, vol. 12, pp. 101886, 2024.

[13] A. Hermawan, T. Priadi, T. Murano, H. Sakagami and N. Fujimoto, "High-temperature Drying: A Review of Fundamental Research and Development in Wood Drying," *Drying Technol.*, vol. 42, no. 16, pp. 2282–2298, 2024.

[14] M. Ståhl and J. Berghel, "Energy Efficient Pilot-Scale Production of Wood Fuel Pellets Made from A Raw Material Mix Including Sawdust and Rapeseed Cake," *Biomass Bioener.*, vol. 35, no. 12, pp. 4849–4854, 2011.

[15] P. McKendry, "Energy Production from Biomass (Part 1): Overview of Biomass," *Bioresour. Technol.*, vol. 83, no. 1, pp. 37–46, 2002.

[16] B. Klašnja, S. Orlović and Z. Galić, "Comparison of Different Wood Species as Raw Materials for Bioenergy," *South-east Europ. Forest.*, vol. 4, no. 2, pp. 81–88, 2013.

[17] L. Senila *et al.*, "Sustainable Biomass Pellets Production using Vineyard Wastes," *Agriculture*, vol. 10, no. 11, pp. 501, 2020.

[18] T. Zeng, A. Pollex, N. Weller, V. Lenz and M. Nelles, "Blended Biomass Pellets as Fuel for Small Scale Combustion Appliances: Effect of Blending on Slag Formation in The Bottom Ash and Pre-Evaluation Options," *Fuel*, vol. 212, pp. 108–116, 2018.

[19] P. L. W. Kamga *et al.*, "Physical and Energetic Characteristics of Pellets Produced from Movingui Sawdust, Corn Spathes, and Coconut Shells," *Ener. Rep.*, vol. 11, pp. 1291–1301, 2024.

[20] D. R. Nhuchhen and P. Abdul Salam, "Estimation of Higher Heating Value of Biomass from Proximate Analysis: A New Approach," *Fuel*, vol. 99, pp. 55–63, 2012.

[21] B. Patel, "Biomass Characterization and Its Use as Solid Fuel for Combustion," *Iranica J. Ener. & Environ.*, vol. 3, no. 2, pp. 123-128, 2012.

[22] B. Patro, "Efficiency Studies of Combination Tube Boilers," *Alexandria Eng. J.*, vol. 55, no. 1, pp. 193–202, 2016.