Advanced and Sustainable Technologies
ASET
E-ISSN 2976-2294

Volume 4, No 1, June 2025 [75-83]

Building Stronger Biomass: How Particle Size Affects the Physical and Mechanical Properties of *Khaya senegalensis* Fuel Pellets

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Received 3 February 2025, Revised 27 February 2025, Accepted 5 March 2025

ABSTRACT

Biomass has gained significant attention as a renewable energy source due to its potential to reduce dependency on fossil fuels and lower carbon emissions. Among various biomass-derived fuels, pelletized biomass offers enhanced energy density, improved combustion efficiency, and ease of handling and storage. Khaya senegalensis, a fast-growing tree that thrives in suboptimal conditions, requires regular pruning, leading to significant biomass waste. This study examines the influence of feedstock particle size on the mechanical properties of Khaya senegalensis fuel pellets. Biomass trimmings from Khaya tree branches were collected, processed into wood chips, and ground into five particle sizes (0.1, 0.3, 0.5, 1, and 2 mm) before pelletization. The pellets were produced under constant moisture content, pressure, temperature, and binder percentage. A one-factor-at-a-time (OFAT) approach was employed, with each process repeated three times to ensure consistency. The mechanical properties analyzed include unit density, durability, axial compressive strength, and diametral compressive strength. Experimental data are analyzed using analysis of variance (ANOVA) to examine correlations between feedstock particle sizes and mechanical properties. This study establishes that particle size plays a crucial role in determining the physical and mechanical properties of Khaya senegalensis wood pellets. The results indicate that finer particles (0.15 mm) contribute to higher unit density and durability, whereas coarser particles (1.00 mm) enhance compressive strength.

Keywords: Biomass, *Khaya senegalensis*, Energy pellet, Feedstock particle size, Renewable energy.

1. INTRODUCTION

The growing demand for renewable energy sources has driven extensive research into biomass as a sustainable alternative to fossil fuels [1]. Biomass-derived fuels have gained significant attention due to their potential to reduce fossil fuel dependence [2], lower carbon emissions, and contribute to a more sustainable energy landscape. Among various biomass fuel forms, pelletized biomass stands out for its higher energy density, improved combustion efficiency, and ease of storage and handling, making it a viable option for renewable energy production.

Khaya senegalensis, a fast-growing tree that thrives in less-than-ideal conditions, is widely cultivated for timber, landscaping, and reforestation. However, the frequent pruning required for its maintenance generates substantial biomass waste, presenting a waste management challenge. Instead of discarding or burning this waste, repurposing it into high-quality energy pellets provides an eco-friendly and efficient alternative for both waste reduction and bioenergy generation.

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The production quality of biomass pellets is highly dependent on various factors, including feedstock particle size, moisture content, pressure, temperature, and binder percentage. Among these, feedstock particle size plays a crucial role in determining the physical and mechanical properties of fuel pellets, influencing unit density, durability, and compressive strength. Understanding these relationships is essential for optimizing biomass pellet production and enhancing fuel performance.

This study investigates the effects of feedstock particle size on the mechanical properties of *Khaya senegalensis* wood pellets. Biomass trimmings from Khaya tree branches were processed into wood chips and ground into five particle sizes (0.1, 0.3, 0.5, 1, and 2 mm) before pelletization under controlled moisture content, pressure, temperature, and binder percentage conditions. A one-factor-at-a-time (OFAT) approach was employed, with each process repeated three times to ensure reliability. The mechanical properties, including unit density, durability, axial compressive strength, and diametral compressive strength, were analyzed using analysis of variance (ANOVA) to assess the correlation between particle size and pellet quality.

By identifying the optimal feedstock particle size for superior mechanical performance, this study aims to provide valuable insights into *Khaya senegalensis* biomass utilization for sustainable energy production. The findings will contribute to improved biomass pellet manufacturing practices, promoting efficiency in renewable energy applications.

2. MATERIAL AND METHODS

The raw material was collected at Padang Besar, Perlis. The leaves were removed from the fronds, and it was then allowed to dry naturally in open, atmospheric air. The feedstock was then cut into smaller parts before being subjected to a woodchipper to produce wood chips. The raw material was ground to smaller particle sizes using a hammer mill. The ground oil palm fronds were randomly selected for the pelleting process.

2.1 Pellet Production Process

The pelletization process begins with harvesting or collecting biomass resources. Khaya tree branch trimmings were gathered, and the leaves were removed. The branches were then cut into smaller parts and processed through a wood chipper to produce wood chips. These chips were further ground using a micro-fine grinder before being pelletized into energy pellets. In this experiment, ground biomass was classified into different particle sizes using a sieve shaker and then pelletized under constant moisture content, pressure, temperature, and binder percentage. Next, the mold was compressed in the chamber, and 3 tonnes of pressure were applied to the material. After a while, the air was let out, and the mold exited the chamber. The bottom of the mold was removed, and then the material was pushed out of the mold. The process was repeated three times using the one-factor-at-a-time (OFAT) approach. The equipment involved in this experiment is depicted in Figure 1, while Figure 2 illustrates the stages of fuel pellet production, starting from *Khaya senegalensis* tree trimmings to the final pelletized product.

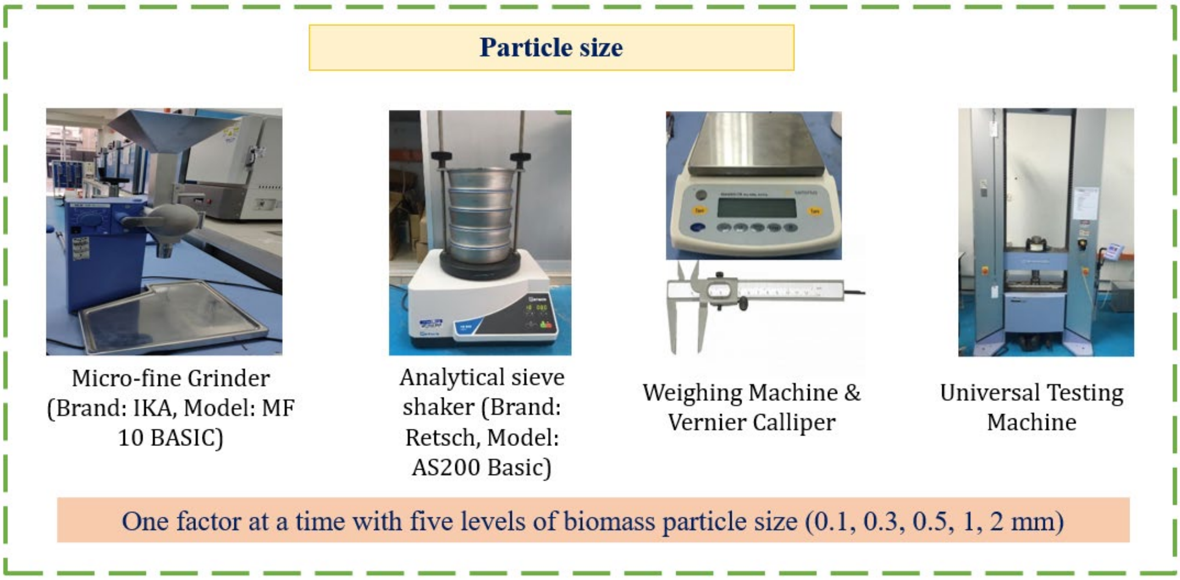

Figure 1: The flow chart of the study.

Figure 2: Progression from *Khaya senegalensis* tree trimmings to the final fuel pellets.

2.2 Determination of the effects of feedstock particle size on physical and mechanical properties of Khaya senegalensis wood fuel pellets via parametric study.

The mechanical durability of *Khaya senegalensis* fuel pellets was tested according to CEN/TC 335 EN 15210-1:2009. The process involved weighing the pellets before and after testing. Initially, the pellet mass was measured using a weighing balance. The pellets were then shaken in a sieve shaker at 50 rpm for 10 minutes. After the test, the remaining intact pellets were weighed to determine their final mass. To measure pellet density, the mass of untested pellets was recorded, and their diameter and length were measured to calculate volume.

Pellet strength refers to the maximum stress a pellet can withstand before breaking. Compression strength was tested using a Shimadzu Autograph AGS-X series 250 kN Universal Testing Machine (UTM). Before testing, each pellet's diameter and length were measured. A single pellet was placed between two parallel plates, with the top plate applying perpendicular pressure at 1 mm/min until the pellet cracked or broke. The final strength value was reported as an average of three tests. The pellets were tested by placing them between two plates, ensuring the applied load was evenly distributed. The test automatically stopped when the top plate moved 7 mm downward, and the maximum force recorded during deformation was noted as the pellet's compressive strength. In the axial test, the pellet was positioned perpendicular to the platen surface, while in the diametral test, it was placed parallel to the platen surface.

3. RESULTS AND DISCUSSION

3.1 Pellet Unit Density

The particle size of the material used to produce energy pellets can significantly impact the density of the pellets. In general, smaller particle sizes tend to result in higher pellet densities. In this case, the effect of *Khaya senegalensis* feedstock particle size on biofuel pellet unit density was investigated. The results of the *Khaya senegalensis* pellets unit density from various feedstock particle sizes are presented in Figure 3. The results showed that the unit density of the pellets decreased as the particle size increased. The highest unit density of 1225.21 kg/m^3 was obtained with the smallest particle size of 0.15 mm. The lowest unit density of 1073.02 kg/m^3 was obtained with the largest particle size of 1 mm with 13.24 % difference. The unit density for the 0.3 mm, 0.5 mm, and 2 mm particle sizes are 1182.62 kg/m^3, 1158.19 kg/m^3, and 1100.43 kg/m^3, respectively. This suggests that smaller particle sizes result in higher unit density, which is desirable for biofuel pellets. This is because smaller particles can pack more tightly together, reducing the space between particles and increasing the overall density of the material. When the material is compressed into pellets, this increased density translates into a higher pellet density. In reviewing the literature, it was found that smaller particles are more likely to come into contact with one another and form bonds or solid bridges as a result of the compaction process [3].

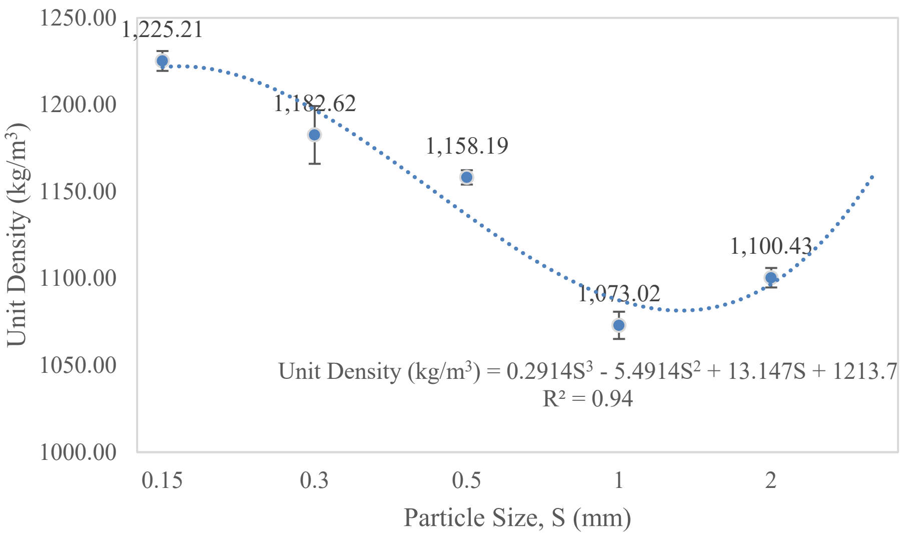

Figure 3: The effect of particle size on the Khaya senegalensis biofuel pellets' unit density.

The findings of this study suggest that using smaller particle sizes in the production of *Khaya senegalensis* biofuel pellets can result in higher unit density, better quality, and improved performance. This is supported by a researcher [4], who stated that pellets with low unit density will yield high fine content, which is undesirable for fuel pellets. The unit density of the pellets is an important quality parameter because it affects their durability and combustion efficiency. In addition, the decreased value in unit density with an increment of feedstock particle size in this study corroborates the earlier findings from [5] that finer particles produced more compact pellets. Higher unit density pellets tend to be more durable and have better combustion efficiency because they have a higher packing density and lower air content. Additionally, pellets with high unit density have a smaller volume and weight, which eases transportation.

Additionally, there is no overlap in the error bars presented in Figure 3, signifying a significant difference. Therefore, it is essential to conduct the appropriate statistical tests to determine whether the difference between the means is statistically significant. Based on the ANOVA: Single factor statistical analysis, the ANOVA analysis has determined a statistically significant difference between the particle size and pellet unit density. The p-value of 5.74 × 10−34 (<< 0) is much less than the typical significance level of 0.05, indicating strong evidence to reject the null hypothesis that there is no difference between the groups. In summary, the statistical analysis has provided strong evidence to support the conclusion that there is a significant difference between the feedstock particle size and pellet unit density.

3.2 Durability

The influence of pressure on the mechanical durability of the *Khaya senegalensis* biofuel pellets is shown in Figure 4. Pellet durability is an important property of biomass pellets that indicates their resistance to breakage during handling and transportation. The results suggest that the pellet durability varies slightly depending on the particle size of the biomass feedstock used to produce the pellets. Based on the figure, it can be seen that the highest pellet durability of 99.64 % was obtained with a 0.15 mm particle size, while the lowest pellet durability of 99.52 % was obtained with a 0.3 mm particle size. The other particle sizes tested had pellet durability values that fell within this range, with 99.58 % for 0.5 mm, 99.62 % for 1 mm, and 99.6 % for 2 mm particle sizes.

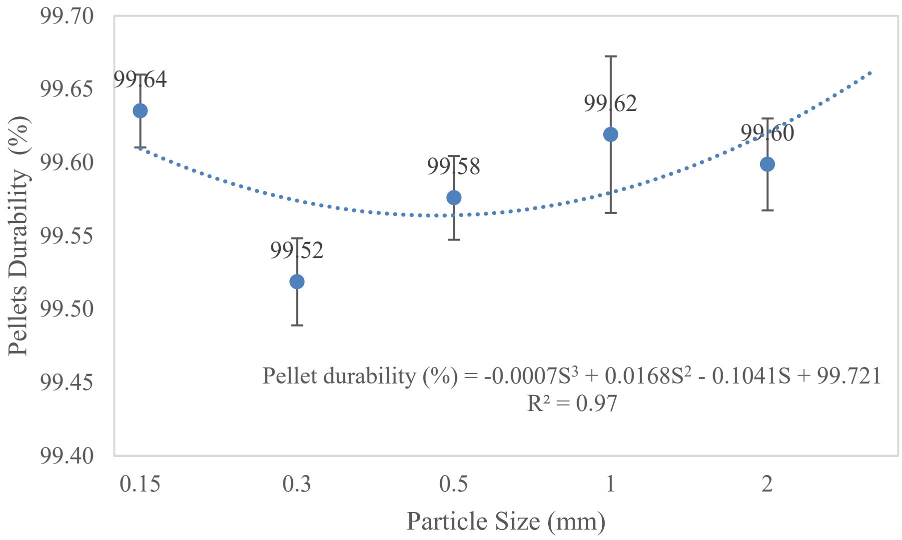

Figure 4: The influence of particle size on the Khaya senegalensis biofuel pellets' mechanical durability.

These findings further support the idea of Ishii and Furuichi [6], who advocate that due to the huge surface area available for binding, a small particle size is often recommended for producing wood pellets. In another study, it was stated that pellet durability is significantly influenced by the particle size of the pellet feed, and one of the crucial elements in boosting the density and hardness of pellets is the reduction of biomass particle size [7]. Nonetheless, the considerable variety in the data may result from natural fluctuation caused by biological or environmental factors; thus, the results were not as anticipated. It is important to note that the differences in pellet durability between the different particle sizes are relatively small. However, these results could help determine the optimal particle size range for a specific type of biomass feedstock to maximize pellet durability and minimize production costs. While it is true that fine particles contribute to the production of more durable pellets, the process of fine grinding is considered unfavorable due to its associated drawbacks, such as increased production time and cost.

The presence of overlap between the error bars could suggest a non-significant difference. Error bars are graphical representations of the variability in a data set, and they typically show the standard deviation, standard error, or confidence interval of the data. However, it is crucial to note that the presence of overlap between error bars does not necessarily mean that there is no significant difference between the means of the two groups. Statistical significance is determined by the size of the difference between the means, as well as the sample size and variability in the data. Therefore, it is important to perform appropriate statistical tests to determine whether the difference between the means is significant. In a single ANOVA test, the p-value is significant at $6.73 \times 10{-}58$ (<< 0), which is much less than the typical significance level of 0.05). The alternative hypothesis is, therefore, accepted if the null hypothesis is rejected.

3.3 Axial compressive strength

The axial compressive strength of biomass pellets is an important characteristic that determines the durability and handling properties of the pellets during transportation and storage. It is vital to ensure that biomass pellets have adequate axial compressive strength to withstand handling and transport stresses without breaking or degrading. This can help to minimize pellet dust and fines, improve the efficiency of pellet combustion, and reduce the risk of damage to pellet storage and transportation equipment. This test involves placing the pellet between two flat plates and applying a compressive load until the pellet fractures. The maximum load required to fracture the pellet is then recorded as the compressive strength. The khaya pellets' axial compressive strength resulting from particle sizes is depicted in Figure 5. From this data, it can be seen that 0.3 mm particle size resulted in the lowest value of axial compressive strength (47.1 MPa). The maximum axial compressive strength was recorded at 78.81 MPa from 1 mm particle size. Larger particles are more able to transmit and distribute loads, resulting in a higher compressive strength.

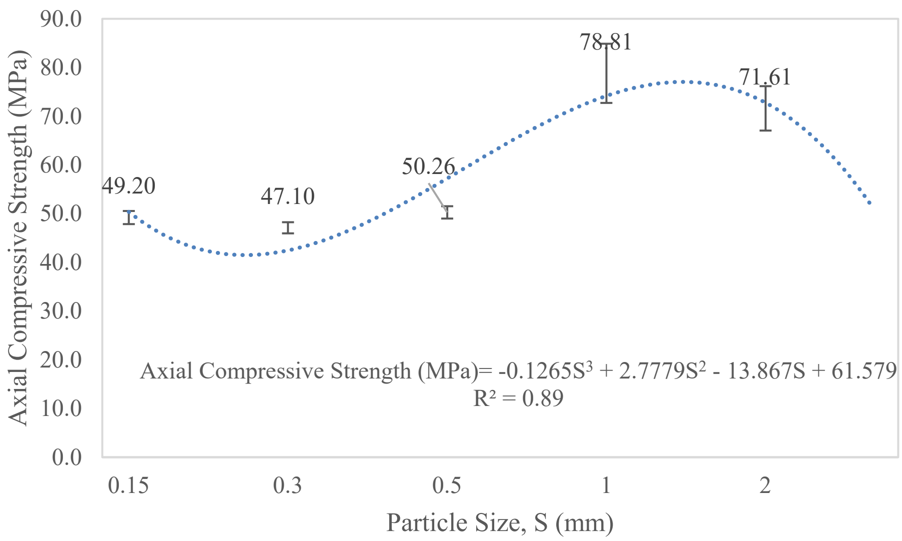

Figure 5: Khaya senegalensis biofuel pellets' axial compressive strength vs. particle size.

In contrast, the smaller particles may tend to move around or become displaced under load, which could lead to a lower compressive strength. These results are in accord with recent studies indicating that the results of compressive tests indicate that larger particles helped particle interlocking and led to the development of durable and dense pellets [8]. Another possible explanation is that the larger particles may have a more uniform and consistent shape, which can contribute to a more regular packing structure and result in a higher compressive strength [9]. It is also possible that material composition and defects or cracks affect the compressive strength [10]. Further statistical tests have revealed a significant result with a p-value of $2.55 \times 10{-}15$ (<< 0). It means that the result is highly unlikely to have occurred by chance. This suggests a real and significant difference or relationship between the particle size and the pellet axial compressive strength.

3.4 Diametral compressive strength

The diametral compression test is a standard method to determine the compressive strength of small, cylindrical samples. The test involves applying a load perpendicular to the diameter of the sample and measuring the force required to break it. The strength of the material is then calculated as the maximum load divided by the cross-sectional area of the sample. Figure 6 presents the experimental data on *Khaya senegalensis* pellets' diametral compressive strength from particle sizes.

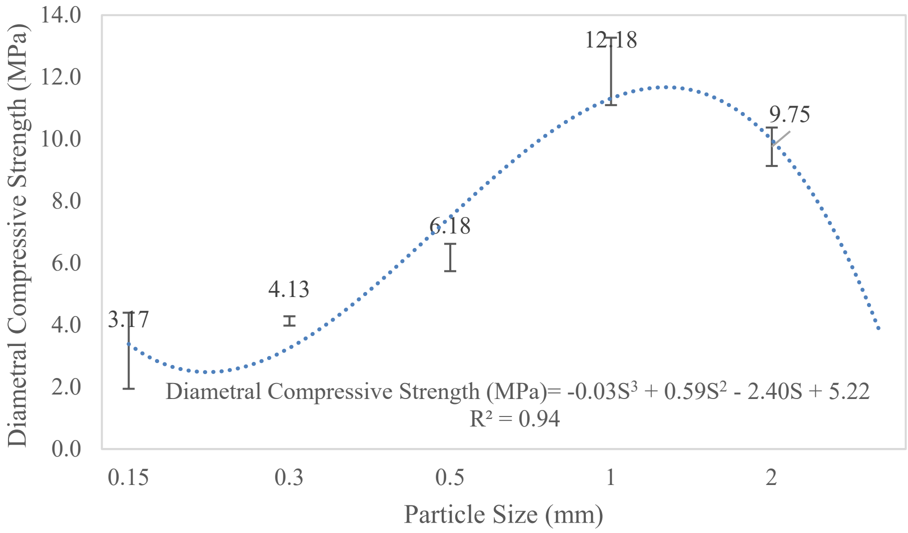

Figure 6: Khaya senegalensis biofuel pellets' diametral compressive strength vs. particle size.

The maximum diametral compressive strength of 12.18 MPa was observed in samples made of 1 mm particles, while the minimum diametral compressive strength of 3.17 MPa was observed in samples of the smallest 0.15 mm particles. Smaller particles tend to have more defects, such as voids, cracks, and impurities, which can weaken the material and reduce its strength [11]. This is because smaller particles have a larger surface area-to-volume ratio, which makes them more susceptible to surface effects and chemical reactions [12]. In addition, smaller particles may also have a lower packing density, which can lead to higher porosity and reduced interparticle bonding. This can result in weaker, more porous samples more prone to fracture under load. On the other hand, larger particles tend to have fewer defects and a higher packing density, which can improve interparticle bonding and increase the strength of the material. This is because larger particles have a smaller surface area-to-volume ratio, reducing surface effects and chemical reactions.

This result is significant at the p-value of $5.59 \times 10-7$ (<< 0), which indicates strong statistical significance. It suggests that the probability of observing the result by chance alone is very low, typically less than 0.05 or 5 %. In other words, if the null hypothesis (i.e., the hypothesis that there is no significant difference between two groups or conditions) were true, the probability of obtaining a result as extreme or more extreme than the one observed would be less than $5.59 \times 10-7$. This suggests strong evidence against the null hypothesis and in favor of the alternative hypothesis.

4. CONCLUSION

From the thorough investigation, it became evident that the particle size parameter played an essential role, resulting in statistically significant outcomes for all responses. Table 1 presents the response analysis summary for *Khaya senegalensis* wood pellet characteristics under different feedstock particle sizes. The results show that the highest unit density (1225.21 kg/m^3) and durability (99.64%) were achieved at a particle size of 0.15 mm, with R^2 values of 0.94 and 0.97, respectively. In contrast, the highest axial compressive strength (78.81 MPa) and diametral compressive strength (12.18 MPa) were observed at a particle size of 1.00 mm, with an R^2 value of 0.89 for axial strength. This study confirms that particle size is a critical factor influencing the physical and mechanical properties of *Khaya senegalensis* wood pellets. The findings reveal that smaller particle sizes (0.15 mm) enhance unit density and durability, while larger particle sizes (1.00 mm) improve compressive strength. The high R^2 values indicate strong correlations between particle size and pellet performance, validating the significance of this parameter in optimizing pellet quality.

Table 1: Summary of Response Analysis for *Khaya senegalensis* Wood Pellet Characteristics Under Varied Feedstock Particle Sizes.

Response	Optimal Particle Size (mm)	Maximum Value	R^2
Unit Density (kg/m^3)	0.15	1225.21	0.94
Durability (%)	0.15	99.64	0.97
Axial Compressive Strength (MPa)	1.00	78.81	0.89
Diametral Compressive Strength (MPa)	1.00	12.18	0.94

ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude for the financial assistance provided by the Higher Education Ministry of Malaysia (FRGS), research grant number FRGS/1/2020/TK0/UNIMAP/03/22. Additionally, we would like to express our sincere gratitude for the assistance provided by colleagues and technical experts and the support from the Faculty of Mechanical Engineering & Technology, Universiti Malaysia Perlis (UniMAP).

REFERENCES

[1] Simanjuntak, J. P., Tambunan, B. H., & Sihombing, J. L. Potential of Pyrolytic Oil from Plastic Waste as an Alternative Fuel Through Thermal Cracking in Indonesia: A Mini Review to Fill the Gap of the Future Research. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, vol 102, issue 2 (2023) pp. 196-207.

[2] Dey, S., Reang, N. M., Das, P. K., & Deb, M. A comprehensive study on prospects of economy, environment, and efficiency of palm oil biodiesel as a renewable fuel. Journal of cleaner production, vol 286, (2021) p. 124981.

[3] Pampuro, N., Bagagiolo, G., & Cavallo, E. Energy requirements for wood chip compaction and transportation. Fuel, vol 262, (2020) p. 116618.

[4] Lu, D., Tabil, L. G., Wang, D., Wang, G., & Emami, S. Experimental trials to make wheat straw pellets with wood residue and binders. Biomass and Bioenergy, vol 69, (2014) pp. 287-296.

[5] Abedi, A., & Dalai, A. K. Study on the quality of oat hull fuel pellets using bio-additives. Biomass and Bioenergy, vol 106, (2017) pp. 166-175.

[6] Ishii, K., & Furuichi, T. Influence of moisture content, particle size and forming temperature on productivity and quality of rice straw pellets. Waste management, vol 34, issue 12 (2014) pp. 2621-2626.

[7] Zaini, I. N., Novianti, S., Nurdiawati, A., Irhamna, A. R., Aziz, M., & Yoshikawa, K. Investigation of the physical characteristics of washed hydrochar pellets made from empty fruit bunch. Fuel Processing Technology, vol 160, (2017) pp. 109-120.

[8] Rezaei, H., Yazdanpanah, F., Lim, C. J., & Sokhansanj, S. Pelletization properties of refuse-derived fuel-Effects of particle size and moisture content. Fuel Processing Technology, vol 205, (2020) p. 106437.

[9] Chaloupkova, V., Ivanova, T., & Havrland, B. Sieve analysis of biomass: accurate method for determination of particle size distribution. In Proceedings of the 15th International Scientific Conference on Engineering for Rural Development, Jelgava, (2016, May) pp. 25-27.

[10] Ungureanu, N., Vladut, V., Voicu, G., Dinca, M. N., & Zabava, B. S. Influence of biomass moisture content on pellet properties–review. Engineering for rural development, vol 17, (2018) pp. 1876-1883.

[11] Silva, G. J. B., Santana, V. P., & Wójcik, M. Investigation on mechanical and microstructural properties of alkali-activated materials made of wood biomass ash and glass powder. Powder Technology, vol 377, (2021) pp. 900-912.

[12] Das, S., Sarkar, P. K., & Mahapatra, S. Single particle combustion studies of coal/biomass fuel mixtures. Energy, vol 217, (2021)p.119329.

Conflict of interest statement: The authors declare no conflict of interest.

Author contributions statement: Conceptualization, Ras Izzati Ismail & Chu Yee Khor; Methodology, Ras Izzati Ismail; Formal Analysis, Ras Izzati Ismail, Chu Yee Khor & Alina Rahayu Mohamed; Investigation, Ras Izzati Ismail & Alina Rahayu Mohamed; Writing & Editing, Ras Izzati Ismail & Chu Yee Khor.