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Mechanical and Physical Properties Characterization of the Pelletization Pressure and Binder Percentages Effects on the *Muntingia calabura* Solid Biofuel Pellets

Ras Izzati Ismail[1*], Muhammad Haziq Hamirul Md Yatin[1], Nur Lailina Makhtar[1], Mohd Hafif Basha Mohamad Jamel Basha[1], Lee Yit Leng[1], and Norawanis Abdul Razak[1]

[1]Faculty of Mechanical Engineering & Technology, Universiti Malaysia Perlis, Pauh Putra Main Campus, 02600 Arau, Perlis, Malaysia.

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ABSTRACT

Renewable energy sources, like biomass, provide a sustainable alternative to fossil fuels, and biomass derived from organic waste, such as the Muntingia calabura tree, holds significant potential as a renewable energy option. This study investigated how pelletization pressure and binder amounts influence the quality of biofuel pellets made from Muntingia calabura. The research tested varying pressures and binder levels to evaluate key properties such as density, axial compressive strength, diametral compressive strength, pellets durability, and impact resistance. Physically, the findings revealed that higher pressures significantly enhanced pellet density and strength while reducing moisture. Mechanically, compressive strength improved with greater pressure, and pellets without binders performed especially well at higher pressures due to natural compaction. Impact resistance, which measures durability, was highest in pellets with a 4% binder, showing they could withstand handling and transportation more effectively. The best overall results were achieved with 2% binder and a pressure of 31.4 MPa, balancing durability and energy efficiency. These findings demonstrate the strong potential of Muntingia calabura as a renewable energy source, offering a sustainable biofuel solution when combined with optimized pelletization processes. This approach not only enhances the usability of agricultural waste but also contributes to addressing environmental challenges by providing cleaner and more sustainable energy alternatives.

Keywords: Biomass Pellet, Fossil Fuels Replacement, *Muntingia calabura*, Renewable Energy.

1. INTRODUCTION

Biomass energy is a renewable form of energy produced from biomass resources using traditional and non-traditional techniques. Biomass energy is renewable and is available in large quantities and therefore it can be considered as a source of energy. Biomass is a renewable resource that has the potential to be used as an alternative to fossil fuels for energy [1]. Since there is a large availability of biomass resources, it becomes possible to manufacture pellets from biomass for conventional power plants as a co-firing fuel. It is considered environmentally friendly because it does not release large amounts of CO2, NOx, and SO2 emissions compared to fossil fuels [2]. Figure 1 illustrates the various approaches to biomass energy use in Malaysia [3]. The traditional approach to biomass use involves combusting raw biomass to produce heat and power, while the modern technologies include the production of liquid biofuels, production of biogas by means of anaerobic digestion, and running biorefineries.

*Corresponding author: rasizzati@unimap.edu.my

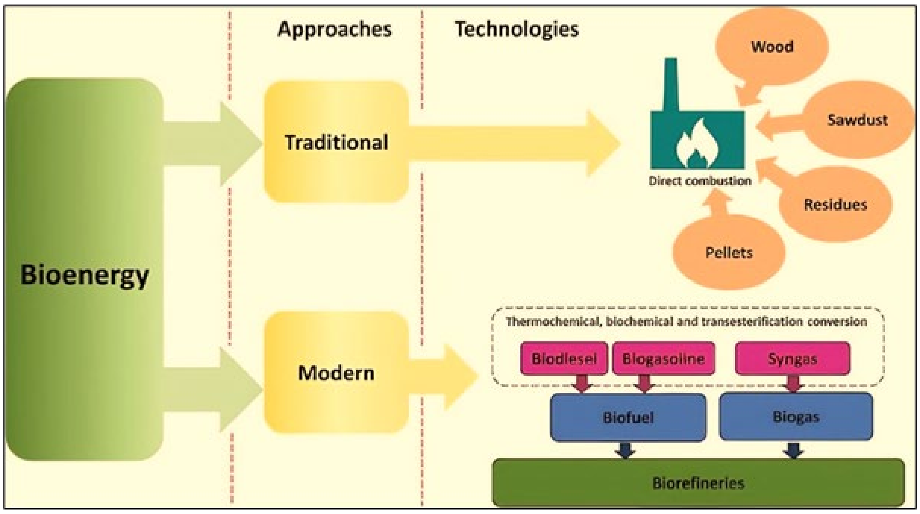

Figure 1: Biomass energy in Malaysia [3].

However, previous research showed that biomass fuels have low density and low energy content when compared to fossil fuels. To address this issue, pelletization is necessary to enhance material handling, minimize dust, and facilitate automated processes. Pellets are denser and have consistent quality, which helps with controlled release in pharmaceuticals and agriculture, as well as efficient combustion in biofuels. From an economic standpoint, pelletization reduces expenses associated with transportation and increases the worth of the product [4]. It helps the environment by reusing waste and creating safer work environments.

1.1 Biomass

Biomass, a naturally occurring combustible substance of organic origin that contains inherent chemical energy, has the potential for a permanent resolution of the problem of fossil fuel emissions as well as a viable candidate for the replacement of the latter. As stated, biomass sources include agricultural, forestry, and urban waste products, which include wood, crop residues, sawdust, straw, manure paper, urban waste and wastewater [3,5]. These materials can be efficiently burnt to produce heat or electricity and can also be transformed into liquid biofuels, which makes biomass suitable for all energy purposes and for processing in biorefineries. Besides, another researcher mentioned that biomass can be converted to bioenergy that includes solid, liquid and also gaseous fuels which can be used to produce heat, cooling and also electric energy [6]. Biomass is an important energy source in Southeast Asia due to the importance of agriculture and forest presence, through agricultural and forest residues being produced at over 500 million tons per year with potential biomass energy of over 8000 million gigajoules [7]. In the same paper, the author also mentioned that based on improved technology, research and development (R&D), expanded energy markets, technology transfer from developed countries, and knowledge application in biomass energy development, it is expected that biomass energy will provide significant environmental and economic benefits to the region's energy sector in the near future.

While biomass has a high potential to act as the source of renewable thermal energy, there are problems with its low calorific value, low density and high moisture content which makes further usage and storage difficult [8]. However, the use of solid fuel pellets that have been derived from biomass is possible.

1.1.1 *Muntingia Calabura*

Muntingia calabura has proven useful in traditional medicine to manage various illnesses in Southeast Asia and tropical America [9]. *Muntingia calabura*, known as 'kerukup siam' or 'ceri kampung' by the Malays, is not traditionally used in Malay traditional medicine for its medical properties. However, it has been incorporated into conventional medicine in other regions of Southeast Asia and tropical America. This tree has the characteristic of fast growing and can grow in a variety of soil conditions. They include treatment of gastric ulcer, headache, cold, stomachache, measles, as well as pimples. Besides, the tree can grow to be 7-12 meters tall and has a wide spreading crown [10]. Its leaves are simple, arranged oppositely, and have an elliptic oval shape with a serrated margin. It bears small white stars like flowers and small round Berries, either red or yellow, of 1-1. 5 cm in diameter. Besides, each part of the tree has been used in traditional medicine due to its potential possession of anti-inflammatory, antiseptic, and analgesic effects [11].

In this study, the *Muntingia calabura* tree was chosen as the main material for producing pellets. Figure 2 depicts the biomass of *Muntingia calabura* collected from Kampung Tanjung Besar, Temerloh, Pahang, at the coordinates 3°27'59.2 "N and 102°28'11.9 "E. Initially, the stems of *Muntingia calabura* were cut with a machete and collected in large quantities. The raw material was then naturally dried in sunlight. Once dried, it was chopped into smaller pieces to make it easier to feed into a grinder or pellet machine.

Figure 2: *Muntinga calabura* tree.

2. MATERIAL AND METHODS

The process involved gathering raw material, specifically, the stems of *Muntingia calabura*. Before grinding, the stems were cut into smaller sections. These sections were then fed into a grinder to break them into small pieces. To facilitate the production of high-quality pellets, a particle size of 0.5 mm was used. The samples consisted of binding agents in varying percentages of corn starch, 0%, 2%, and 4% with a constant moisture content of 12% and pressures of 18.8 MPa, 25.1 MPa, and 31.4 MPa. A single hydraulic press, SPECAC model GS1501, was used to generate pellets, producing 27 pellets for each sample. To ensure accuracy, replication was employed to verify that the results were consistent and not due to random chance. Figure 2 shows the manual hydraulic pellet press used in the experiment.

Figure 3: Manual hydraulic pellet press.

The pellet properties test was conducted to assess various mechanical characteristics. This process involved analyzing various parameters, including density, durability, compressive strength, and impact resistance.

Density was determined by dividing the mass by the volume of a material substance. A weighing scale was used to measure the mass of the raw material. On top of that, a vernier caliper was utilized to measure the height and length of the pellet during production to calculate its volume and finally, the density of the pellets.

The compressive strength, or hardness, of a pellet was measured by its ability to withstand pressure without breaking. The crushing resistance test was employed to evaluate the pellet quality. The strength of the pellets was tested by compressing them between two plates using a universal testing machine with a compression jig. The sample was compressed at a rate of 1 mm/min until it cracked. The compression strength was determined by the force required to deform the material to its maximum. The compressive strength was determined using the Shimadzu Autograph AGS-X 50 kN Universal Testing Machine.

Next, the impact resistance test was performed by drop a pellet sample from a height of about 1.5 m. The pellet, which stayed intact, was weighed. The impact resistance was determined by taking the difference between the end weight and the original weight and multiplying it by 100.

3. RESULTS AND DISCUSSION

This section explores how changes in pellet pressure and the addition of corn starch as a binder influence the properties of the pellets. The pressures tested were set at 18.8 MPa, 25.1 MPa, and 31.4 MPa, while the binder was added in amounts of 0%, 2%, and 4%. Mechanical properties, including compressive strength and impact resistance, were examined. The aim is to understand how these factors work together to create stronger, higher-quality pellets.

3.1 Density

Density measures how much matter is packed into a given space. It is an important property used to identify and classify materials [12]. Simply put, density shows how tightly packed a material is. In pellet production, density is a key factor. It refers to how compact the material becomes when crushed into pellets. The density of the raw material is also significant, as denser materials can be crushed more effectively, resulting in pellets with higher strength and energy content. Table 1 illustrates the percentage of binder and raw material weight distribution.

Table 1: The percentage of binder and weight of raw material *Muntingia Calabura.*

Percentages of corn starch (%)	Weight of corn starch (g)	Percentages of *Muntingia calabura* (%)	Weight of *Muntingia calabura* (g)
0%	0	100	1
2%	0.02	98	0.98
4%	0.04	96	0.96

The impacts of pelletization pressure and binder percentage on the density of biofuel pellets produced from *Muntingia calabura* are shown in Figure 4. Based on this figure, it can be seen that pellets without binder reached the maximum density of 0.82 g/cm^3 at the lowest pressure of 18.8 MPa, followed by pellets with 2% binder, 0.76 g/cm^3, then 4% binder, 0.74 g/cm^3. For all binder percentages, the pellets' density rises at 25.1 MPa. Whereas pellets with 2% and 4% binder both have a density of 0.79 g/cm^3, pellets without binder have a density of 0.80 g/cm^3. Comparatively to 18.8 MPa, the variation in density across binder percentages decreases less, which suggests that higher pressure lessens the effect of binder on compaction. The effect of pressure on raw density was studied by a researcher in 2024, showing that this is an important factor to be investigated when manufacturing biomass fuel pellets [13].

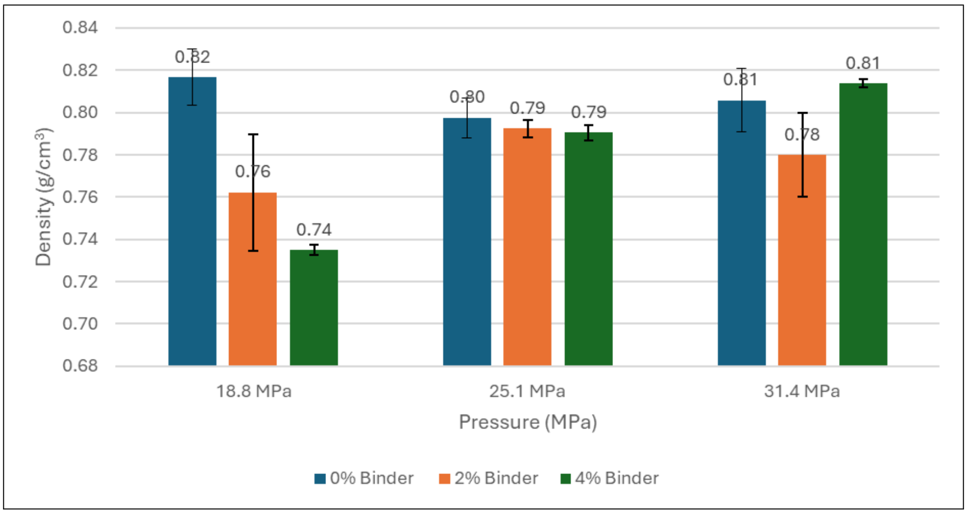

Figure 4: Pellet density at different pressures and different percentages of binder.

At the highest pressure of 31.4 MPa, all pellets attain their maximum densities. While 2% binder pellets are somewhat lower at 0.78 g/cm^3, 0% and 4% binder pellets have the same density of 0.81 g/cm^3. This indicates that the compaction force is powerful enough at extremely high pressure to overcome the limiting effects of the binder, therefore enabling even pellets with greater binder content to attain comparable densities to those without binder.

In addition, an ANOVA analysis in Table 2 shows the p-value of 0.03389, which indicates that it has a significant impact on the density, as it is below the standard threshold of 0.05. Similarly, the binder percentage has a p-value of 0.04911, which is just below the threshold, indicating statistically significant results. The interaction between pressure and binder percentage also plays an important role, with a p-value of 0.02972, confirming that the combination of these two factors significantly affects the density. This is supported by research in 2023, whereby the pelletization of biomass feedstock was investigated in relation to adhesives and binder [14].

Table 2: ANOVA analysis for pellet density at different pressures and different binder percentages.

Source of Variation	SS	Df	MS	F	P-value	F crit
Sample	0.004625	2	0.002312	4.109068	0.033887	3.554557
Columns	0.004029	2	0.002015	3.579727	0.049107	3.554557
Interaction	0.007731	4	0.001933	3.434655	0.029716	2.927744
Within	0.01013	18	0.000563			
Total	0.026515	26				

3.2 Compressive Strength

The compressive strength of a pellet reflects its ability to resist crushing under pressure, which is a key property for determining its durability during handling, transportation, and storage [15,16]. This strength was tested by applying a compressive load and measuring the maximum force the pellet can withstand before breaking or deforming. Figure 5 illustrates how the axial compressive strength was affected by various pelletization pressures and binder percentages. In this figure, it can be collected that pellets exhibit higher strength in axial tests due to the larger surface area absorbing the load, while diametral tests tend to result in lower values as the pressure is focused on the weaker cylindrical diameter. By combining these two approaches, a clearer picture of the pellet's mechanical properties is formed, ensuring its reliability for real-world applications.

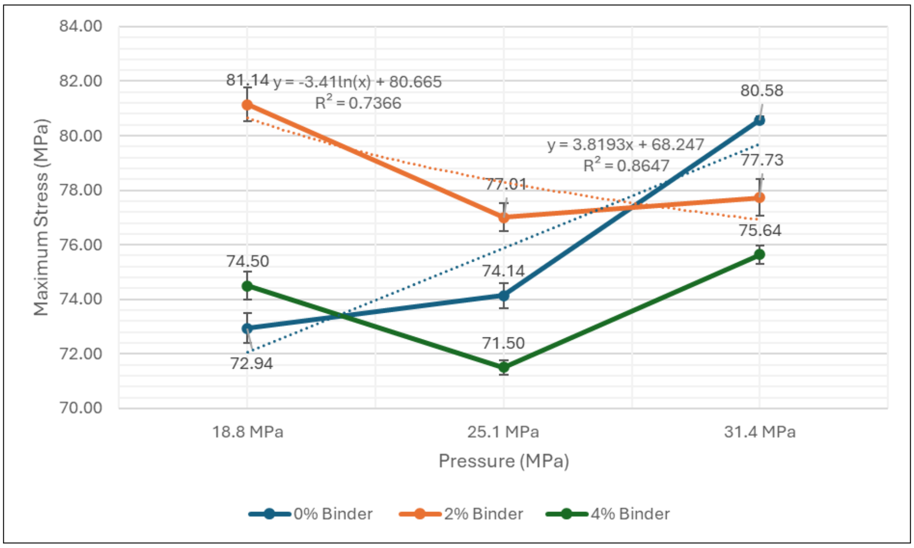

Figure 5: The maximum stress at different pressures and different binder percentages in axial compressive strength.

As the pressure goes up from 18.8 MPa to 31.4 MPa, the compressive strength gets better at all binder levels. Higher pressure helps bond the particles more closely together, which leads to stronger connections and better structural integrity. At a lower pressure of 18.8 MPa, pellets with 2% binder reach their peak strength, hitting 81.14 MPa. This indicates that a little binder does a great job of filling in gaps and enhancing particle cohesion while still allowing for effective compaction. As the pressure builds, the importance of binders tends to decrease. At the highest pressure of 31.4 MPa, pellets without any binder show the best compressive strength at 80.58 MPa, surpassing those with 2% and 4% binder. This shows that when pressures are higher, the natural bonding of biomass particles can create strong pellets on their own, without needing any extra binder. The lowest values of axial compressive strength are observed under certain conditions, showing some limitations in pressure and binder interactions. At 18.8 MPa with 0%

binder, the axial compressive strength is 72.94 MPa, which is the lowest among all data points at this pressure level. This low value happens because, without a binder, the compaction force is the only factor helping the particles stick together. With this low pressure, the force is not strong enough to tightly pack the biomass particles, leading to weak inter-particle bonding and less durable pellets.

In a previous study in 2023 by Ismail et al. [17], it was found that Khaya senegalensis pellets had their lowest axial compressive strength of 50.26 MPa at a pressure of 18.8 MPa. This study shows that *Muntingia calabura* pellets perform significantly better, with the lowest strength recorded at 72.94 MPa under the same pressure. This notable difference showcases the excellent mechanical properties of *Muntingia calabura* as a material for pelletization. The improved performance might be thanks to its natural makeup, like a higher lignin content, which helps hold particles together more effectively when under pressure. Also, the structure, particle size, and moisture content of *Muntingia calabura* probably help create stronger bonding and enhance durability [1,19,20]. These results indicate that *Muntingia calabura* is a dependable choice for creating durable pellets, even with lower compression, making it an excellent option for biofuel production.

An Analysis of Variance (ANOVA) test shown in Table 3 revealed a p-value of 4.26×10^{-8} for binder percentage, 1.33×10^{-6} for compaction pressure, and 6.88×10^{-8} for interaction, which significantly affects the axial compressive strength of the pellets.

Table 3: ANOVA analysis for pellet durability manufactured at different pressures and different binder percentages.

Source of Variation	SS	Df	MS	F	P-value	F crit
Sample	102.204	2	51.102	50.316	4.26×10^{-8}	3.554557
Columns	63.946	2	31.973	31.481	1.33×10^{-6}	3.554557
Interaction	93.958	4	23.490	23.128	6.88×10^{-7}	2.927744
Within	18.281	18	1.016			
Total	278.389	26				

On the other hand, the data obtained on diametral compressive strength shown in Figure 6 demonstrates that varying binder percentages and compaction pressures influence the mechanical strength of the pellets. At the lowest pressure of 18.8 MPa, pellets with 2% binder show the highest compressive strength at 6.74 MPa, followed by those with 4% binder at 4.48 MPa, and pellets with 0% binder at 4.04 MPa. This indicates that using a little binder at lower pressures helps particles stick together better, leading to stronger pellets. As the pressure rises to 25.1 MPa and 31.4 MPa, a decrease in the diametral compressive strength at all binder levels was observed. At 31.4 MPa, the strength decreases noticeably, showing values of 2.00 MPa for pellets without any binder, 1.74 MPa for those with 2% binder, and 1.35 MPa for pellets with 4% binder. The decrease in strength at higher pressures might be linked to over-compaction, which can lower elasticity and lead to tiny cracks in the pellet structure. Also, higher pressures could lead to thermal degradation of the binder, which may lessen its effectiveness in boosting pellet strength. At 18.8 MPa, the 2% binder offers a wonderful balance between cohesion and compaction, leading to the highest diametral compressive strength. At higher pressures, pellets without any binder do a better job than those with binders. This might be because not using a binder allows the particles to fit together more tightly. In contrast, having a high binder content, like in the 4% binder, can act as a filler, reducing direct bonding between particles and making the structure weaker. Overall, pellets with 2% binder perform well at lower pressure, while pellets without any binder perform better at higher pressures due to the advantages of natural compaction.

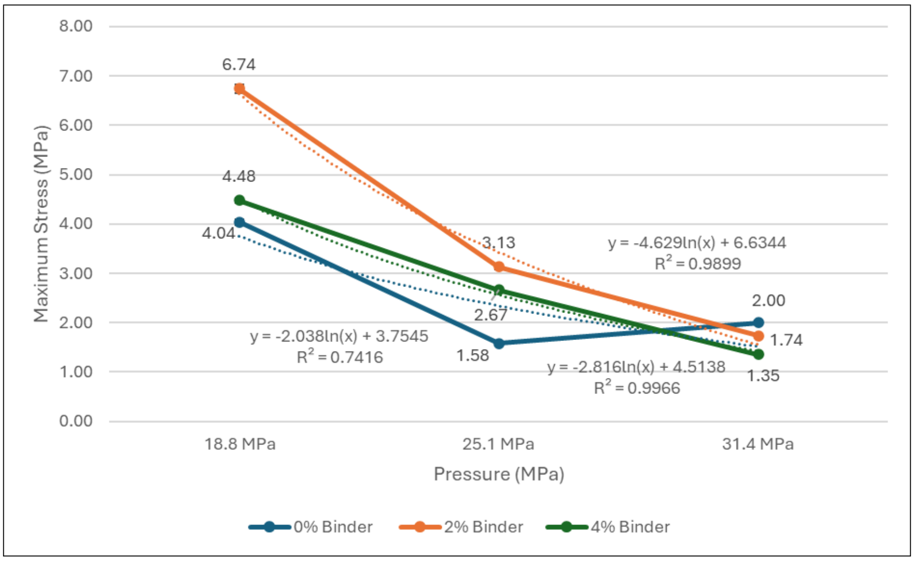

Figure 6: The maximum stress at different pressure and different binder percentages in diametral compressive strength.

3.3 Impact Resistance

Impact resistance is the ability of a material to endure sudden forces or impacts without breaking or losing its structure. For biofuel pellets, this property is essential as it reflects their durability during handling, transportation, and storage [18]. Pellets with good impact resistance remain intact when subjected to physical stress, such as being dropped or colliding with other objects, minimizing the risk of breakage and reducing waste. The data shown in Figure 7 illustrates how the impact resistance of biofuel pellets is affected by different pressures and binder percentages. Overall, as the pressure increases, the impact of resistance improves for all binder levels.

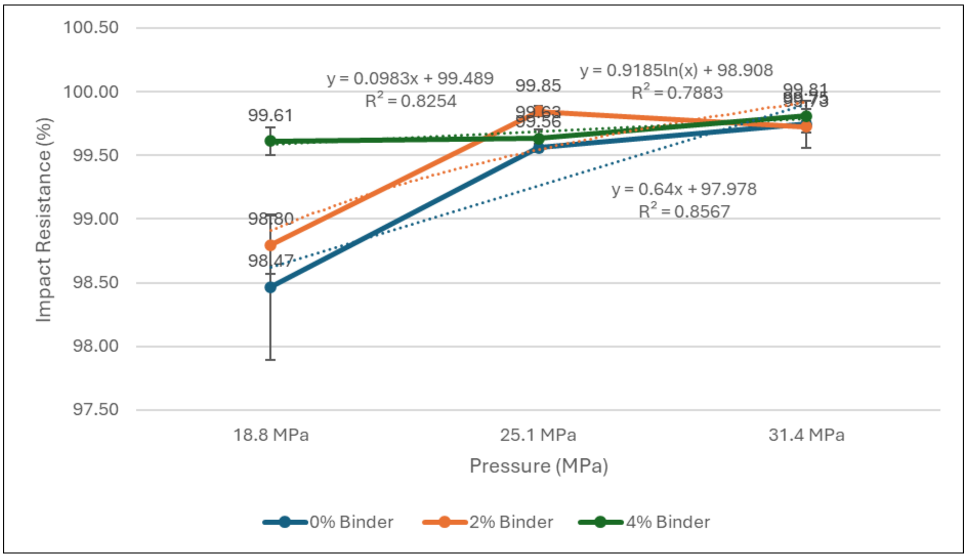

Figure 7: The impact resistance at different pressures and different binder percentages.

This suggests that higher compaction during pellet formation makes the pellets more durable and better able to withstand physical stress. At 18.8 MPa, pellets with 4% binder achieve the highest impact resistance at 99.61%, while those with no binder have the lowest at 98.47%. In summary, the highest impact resistance is observed in pellets with 4% binder at 31.4 MPa, while the lowest occurs in pellets with no binder at 18.8 MPa. This demonstrates the importance of optimizing both pressure and binder levels to produce strong and durable biofuel pellets. In a previous study conducted by [16], the impact resistance of biomass pellets made from a mix of sawdust and farm waste achieved 98.76% impact resistance, by using 5% starch binder and a pressure of 30 MPa. While their pellets were strong, the *Muntingia calabura* pellets in this study performed even better, reaching 99.81% impact resistance with only 4% of binder. This means *Muntingia calabura* may have natural binding properties, which help make the pellets strong without needing too much binder.

Table 4 indicates the ANOVA results that show how different factors affect the impact resistance of the pellets. The sample factor, which compares different groups, does not have a significant impact because its p-value is above 0.05, which is 0.08482. However, the columns factor, which looks at how pressure and binder percentages influence the pellets, has a significant effect, as indicated by its very small p-value of 0.00047. The interaction between pressure and binder percentage does not have a noticeable effect, since the p-value is higher 0.08562 than 0.05. In simple terms, pressure and binder percentages affect the pellets' resistance, but their combination does not significantly change the results.

Table 4: ANOVA analysis for pellets' impact resistance at different pressures and different binder percentages.

Source of Variation	SS	df	MS	F	P-value	F crit
Sample	0.825	2	0.412	2.838	0.08482	3.555
Columns	3.510	2	1.755	12.081	0.00047	3.555
Interaction	1.410	4	0.353	2.427	0.08562	2.928
Within	2.615	18	0.145			
Total	8.361	26				

4. CONCLUSION

In summary, this study successfully achieved its objectives by exploring the effects of varying binder percentages and pelletization pressures on the mechanical and chemical qualities of biomass pellets derived from *Muntingia calabura*. Physically, higher pressures resulted in denser pellets, while moisture content decreased as pressure increased. Chemically, adding binders and increasing pressure helped retain more volatile matter and reduced ash content, making the pellets more efficient for combustion. However, pellets without binders had the highest fixed carbon content, which is crucial for energy efficiency. Mechanically, compressive strength improved with greater pressure, and pellets without binders performed especially well at higher pressures due to natural compaction. Impact resistance, which measures durability, was highest in pellets with a 4% binder, showing they could withstand handling and transportation more effectively.

This study highlights the potential of *Muntingia calabura* as a sustainable biofuel source. By optimizing the pelletization process, it is possible to create high-quality pellets that meet energy needs while addressing environmental challenges. This research demonstrates that with the right balance of pressure and binder, *Muntingia calabura* can be transformed into a reliable renewable energy solution, contributing to a greener and more sustainable future.

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