International journal of science, engineering, and information technology
Volume 10, Issue 01, December 2025
Journal homepage: https://journal.trunojoyo.ac.id/ijseit

Effects of Particle Size and Compaction Pressure on the Physical and Energy-Related Properties of Biopellets from Casuarina Equisetifolia

Khamdi Mubarok, Teguh Prasetyo, M. Abdul Ghoni

Department of Industrial and Mechanical Engineering, University of Trunojoyo Madura, Bangkalan, Indonesia

A B S T R A C T

The increasing demand for renewable energy requires alternative resources to reduce fossil fuel dependency and mitigate climate change. Biomass has emerged as a promising solution due to its wide availability and favorable combustion characteristics. Casuarina equisetifolia, a fast-growing coastal species abundant in Indonesia, remains underutilized despite its potential as a bioenergy feedstock. This study investigates the effects of particle size variation (20, 40, and 60 mesh) and compaction pressure (2, 3, and 4 tonf) on the quality of biopellets produced from Casuarina equisetifolia. Biomass powder was mixed with 10% tapioca binder, compacted using a hydraulic press with a cylindrical mold, and oven-dried at 150 °C for 30 minutes. Pellet quality was evaluated through moisture content, density, and calorific value following SNI standards. The data were statistically analyzed using two-way ANOVA. The ANOVA results confirmed that both particle size and compaction pressure had significant effects ($p < 0.05$) on all response variables. Moisture content decreased with finer particles and higher pressure, with the lowest value of 5.27% obtained at 60 mesh and 4 tonf. Density increased under the same conditions, reaching 1.191 g/cm³. Calorific value also varied significantly, with the maximum of 4697 cal/g observed at 20 mesh and 4 tonf. These findings demonstrate that optimization of particle size and compaction pressure is essential to improve both physical and energy-related properties of biopellets. The results highlight the potential of Casuarina equisetifolia as a sustainable biomass feedstock to support Indonesia's Net Zero Emission 2060 target.

Keywords: Biopellets, Casuarina Equisetifolia, Moisture Content, Density, Calorific value.

Article History
Received 22 September 2025 Received in revised form 07 October 2025 Accepted 15 December 2025

1. Introduction

The transition toward renewable energy is a global strategy to reduce greenhouse gas emissions and achieve long-term sustainability. Indonesia has committed to Net Zero Emission (NZE) by 2060, requiring diversification of energy sources and reduced reliance on fossil fuels [1]. Biomass is a key contributor in this effort due to its renewability, availability, and ability to mitigate environmental impacts [2]. Unlike previous studies focusing on agricultural residues such as rice husks or palm waste, this study provides the first systematic investigation on Casuarina equisetifolia, a coastal wood species with unique anatomical and lignocellulosic characteristics relevant to Indonesia's renewable energy context

Among solid biofuels, pellets are considered advantageous because of their uniformity, higher energy density, and easier storage compared to raw biomass [3]. Pellet quality, however, is strongly influenced by raw material properties and processing parameters such as particle size, compaction pressure, and drying conditions. Standards including SNI 8021:2020 for wood pellets and SNI 8951:2020 for biomass pellets provide reference values for density, moisture content, and calorific value that define pellet quality [4], [5].

Casuarina equisetifolia, a fast-growing coastal species, represents an abundant yet underutilized biomass resource. Previous studies have reported its high calorific potential, making it suitable for renewable energy applications [6]. Nevertheless, research on its pelletization remains limited compared with other biomass sources such as palm oil residues [7], rice husks [8], and coffee waste [9].

Pellet performance is generally assessed by physical and energy-related properties, especially moisture content, density, and calorific value. Smaller particle sizes and higher compaction pressures are known to improve densification, while coarser particles may enhance combustion characteristics [10]–[12]. Therefore, optimization of these factors is essential to produce high-quality pellets. This study investigates the effects of particle size and compaction pressure on the quality of biopellets derived from Casuarina equisetifolia, providing insights into its potential as a renewable energy feedstock in support of Indonesia's NZE 2060 target.

* *Corresponding author.*
E-mail address: khamdi.mubarok@trunojoyo.ac.id

E-ISSN 2548-4214

2. Research Methodology

This study employed an experimental approach to investigate the influence of particle size variation and compaction pressure on the quality performance of biopellets produced from Casuarina Equisetifolia. The experimental workflow encompassed sequential steps, including raw material conditioning, controlled drying and particle size classification, preparation of biomass formulations, pelletization under different compaction pressures, and subsequent laboratory characterization of the produced pellets. All experimental procedures were conducted at the Energy Conversion Laboratory, Department of Mechanical Engineering, University of Trunojoyo Madura.

2.1. Biomass Pretreatment

Branches and twigs of Casuarina equisetifolia were selected as the sole feedstock to ensure material uniformity throughout the experiments. The raw material was initially reduced in size using a rotary chopper operating at approximately 2700 rpm, producing small chips suitable for milling. These chips were subsequently ground with a disk mill (motor 1400 rpm; disk shaft 2800 rpm) until a fine powder was obtained, with oversized particles automatically recirculated into the hopper to maintain consistency. The milled powder was then classified using a stack of sieves into three narrow particle size fractions, namely 20 mesh, 40 mesh, and 60 mesh. Each fraction was collected by combining two sieve sizes, whereby material that passed through the coarser sieve but was retained on the finer sieve was used for subsequent processing.

To improve pellet cohesion, tapioca starch was added as a binder at a fixed proportion of 10% (w/w). A 10 % (w/w) tapioca starch binder was selected based on prior studies reporting that concentrations between 8–12 % effectively improve pellet integrity while maintaining acceptable calorific value for lignocellulosic biomass in tropical regions [9,10,11]. The raw material and binder were carefully weighed with a digital balance (accuracy ±0.01 g) to ensure consistent composition in each batch. At this stage, no pre-drying treatment was performed; instead, moisture reduction was carried out during the post-compaction drying step. This pretreatment procedure was applied uniformly, with only the particle size fraction and later compaction force varied according to the experimental design.

2.2. Biopellets Densification

The densification stage was carried out using a custom-made cylindrical steel mold (pellet die) and a hydraulic shop press as the main forming equipment. The die was designed with four cylindrical cavities, each with a diameter of 8 mm and a height of approximately 30 mm, to produce uniform pellets across all treatments. Its construction in three detachable parts (upper plate, lower plate, and locking system) allowed for easy loading of biomass powder and removal of pellets after pressing (Figure 1).

The hydraulic shop press employed in this study had a maximum capacity of 12 tonf with a stroke length of 135 mm and dimensions of 1320 × 220 × 210 mm, enabling the application of precise compaction loads. Three compaction levels were tested: 2 tonf (≈97.5 MPa), 3 tonf (≈146.3 MPa), and 4 tonf (≈195.1 MPa), calculated based on the effective cross-sectional area of the mold cavity. During operation, the sieved biomass powder—premixed with 10% tapioca starch binder—was loaded into the mold and subjected to the designated pressure using the hydraulic press. Once the targeted pressure was reached, the mold was locked to maintain compaction.

Immediately after pressing, the pellets were dried in an electric oven at 150 °C for 30 minutes while still confined in the mold. This simultaneous compaction–drying approach minimized cracking and improved pellet dimensional stability by reducing residual moisture. Each treatment combination of particle size and compaction force was repeated three times, ensuring reproducibility of the densification process. The final product shown on Figure 2.



Figure 1. Pellet die



Figure 2. The final products

2.3. Experimental Design

The experiment was structured as a two-factor factorial design to evaluate the combined effects of particle size and compaction pressure on bio-pellet quality. Two independent variables were considered: (i) particle size, with three levels (20, 40, and 60 mesh), and (ii) compaction pressure, with three levels (2, 3, and 4 tonf, equivalent to 97.5, 146.3, and 195.1 MPa, respectively). This resulted in nine treatment combinations (3 × 3), each of which was replicated three times to ensure statistical robustness.

The response variables measured included moisture content, density, and calorific value, following the relevant SNI standards. Moisture content was determined using the oven-drying method (SNI 06-3730-1995), density was calculated based on mass-to-volume ratio (SNI 8021:2020), and calorific value was measured with a bomb calorimeter (SNI 01-6235-2000). Each test was conducted on multiple specimens per batch to reduce measurement error.

The experimental workflow was designed to control extraneous variables. All pellets were produced under the same drying conditions (150 °C for 30 minutes) and with a constant binder proportion of 10% tapioca starch. Environmental factors such as ambient temperature and humidity were not varied and assumed constant during testing. The design matrix for the factorial experiment is summarized in Table 1, where M denotes the mesh size and F denotes the compaction pressure.

Table 1. Factorial design for particle size and compaction pressure.

No	Code	Particle size (mesh)	Pressure (Tonf)	Pressure (MPa)
1	M1F1	20	2	97.5
2	M1F2	20	3	146.3
3	M1F3	20	4	195.1
4	M2F1	40	2	97.5
5	M2F2	40	3	146.3
6	M2F3	40	4	195.1
7	M3F1	60	2	97.5
8	M3F2	60	3	146.3
9	M3F3	60	4	195.1

3. Results and Discussion

The performance of the fabricated biopellets was evaluated using three key indicators: moisture content, density, and calorific value. Together, these properties define the suitability of pellets for use as standardized renewable solid fuels in accordance with SNI 8951:2020 requirements. A two-way ANOVA was applied to statistically examine the individual and interactive effects of the independent variables, namely particle size and compaction pressure. The analysis demonstrated that both parameters significantly affected the physical integrity and energy characteristics of the pellets, with the magnitude of their influence differing across the evaluated properties.

3.1. Data Collection

Biopellets were successfully produced from Casuarina equisetifolia using three particle size classes in mesh (20, 40, and 60 mesh) and three compaction pressures in ton-force (2, 3, and 4 tonf). Each treatment combination was replicated three times, resulting in 27 specimens. The pellets were cylindrical, with an average diameter of 8 mm and a height ranging from 28 to 34 mm depending on compaction level.

The quality evaluation of Casuarina equisetifolia biopellets was carried out based on three primary parameters: moisture content, density, and calorific value, all of which are essential indicators of pellet performance according to SNI standards. Table 2 presents the complete experimental results for nine treatment combinations of particle size (20, 40, and 60 mesh) and compaction pressure (2, 3, and 4 tonf).

Table 2. Moisture content, density, and calorific value of biopellets under various particle size and pressure combinations.

No	Code	Moisture content (%)	Density (gr/cm^3)	Calorific value (cal/gr)
1	M1F1	6.39	0.947	3282
2	M1F2	5.65	1.048	4190
3	M1F3	5.27	1.124	4697
4	M2F1	7.56	1.015	2383
5	M2F2	6.77	1.096	3711
6	M2F3	5.65	1.141	1852
7	M3F1	9.49	1.079	4302
8	M3F2	8.31	1.121	4175
9	M3F3	7.15	1.191	4115

Moisture content values ranged from 5.27% to 9.49%, all below the maximum 10% set by SNI 8021:2020. Pellet density varied between 0.947 g/cm³ and 1.191 g/cm³, consistently exceeding the minimum standard of 0.5 g/cm³. Calorific values showed wider variation, from 1851.67 cal/g to 4697.33 cal/g. Only pellets produced under 60 mesh at 4 tonf (4302.67 cal/g) met the SNI 8951:2020 requirement of 4300 cal/g. These results suggest that the quality of pellets strongly depends on both particle size and compaction pressure.

3.2. Data Interpretation

Moisture content decreased with increasing compaction pressure (Figure 3). The lowest average (5.27%) was observed in 20-mesh pellets pressed at 4 tonf, indicating that higher pressure effectively reduced porosity and entrapped water. Conversely, finer particles (60 mesh) tended to retain more moisture when pressed at lower pressures, with the highest moisture content (9.49%) recorded at 60 mesh and 2 tonf. This behavior reflects the larger surface area of fine particles, which promotes water absorption unless adequately compacted. Although several treatments yielded calorific values below the SNI 8951:2020 limit, this variation can be attributed to compositional differences within Casuarina equisetifolia biomass and the influence of binder distribution during compaction. These findings indicate that feedstock homogenization and controlled mixing could enhance reproducibility in future work.

Compared with pellets from rice husks and palm residues [7, 8], Casuarina equisetifolia exhibited comparable density and moisture characteristics but slightly lower calorific stability, emphasizing the need for further optimization of feedstock uniformity.

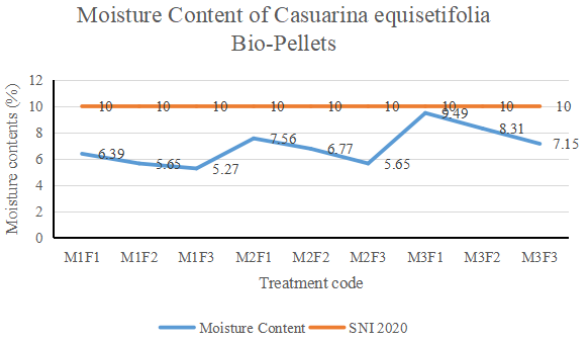


Figure 3. Variation of moisture content with compaction pressure across different particle sizes

Pellet density was positively correlated with both decreasing particle size and increasing compaction pressure (Figure 4). The highest density (1.191 g/cm³) was achieved at 60 mesh with 4 tonf, almost double the minimum SNI requirement, demonstrating the effectiveness of densification. In contrast, coarser particles (20 mesh) resulted in lower

density (0.947 g/cm³), even under higher pressure, due to larger voids between particles.

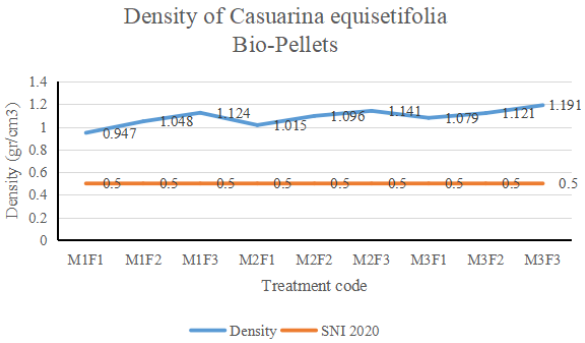


Figure 4. Trend on density as a function of compaction pressure and particle size.

Calorific value exhibited a different trend (Figure 5). The maximum (4697.33 cal/g) was obtained at 20 mesh with 4 tonf, indicating that coarser particles retained structural integrity favorable for combustion. Finer particles (40–60 mesh) generally produced lower calorific values, with several treatments (e.g., 40 mesh at 4 tonf; 60 mesh at 2 tonf) yielding values far below the SNI standard. This suggests that excessive fineness may cause incomplete combustion or higher ash formation, reducing energy release.

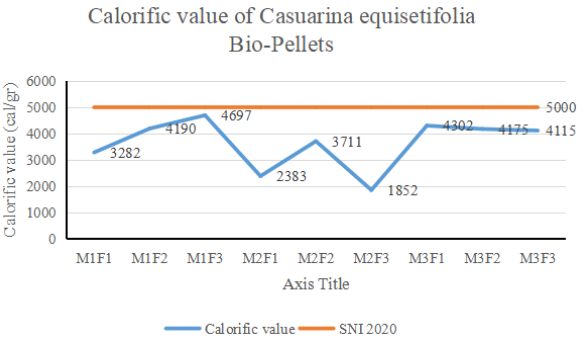


Figure 5. Trend on calorific value as a function of compaction pressure and particle size.

Overall, the optimal balance between density, moisture, and calorific value was achieved at 20 mesh with 4 tonf and at 60 mesh with 4 tonf. The former produced the highest calorific value, while the latter yielded the highest density and acceptable calorific value.

3.3. Statistical Analysis

Two-way ANOVA was conducted to evaluate the influence of particle size, compaction pressure, and their interaction on pellet properties. The results showed that moisture content was significantly affected by both particle size ($p = 0.002$) and compaction pressure ($p = 0.007$), with particle size contributing 65.7% and pressure 31.5% of the variance. Density was also significantly influenced by both factors ($p = 0.005$), with particle size (48.9%) and compaction pressure (47.4%) contributing almost equally. Calorific value exhibited high variation but was not statistically significant at the 95% confidence level ($p > 0.05$). Particle size contributed 60.4% of the variance, while compaction pressure contributed only 10.6%. This indicates that the energy content of Casuarina equisetifolia is primarily governed by its intrinsic chemical composition rather than particle size or compaction pressure.

These findings confirm that moisture content and density can be effectively controlled by adjusting particle size and compaction pressure, whereas calorific value is less predictable under the tested conditions. The results are consistent with previous studies reporting that finer particles enhance density [10] and that higher compaction pressures reduce moisture content [11]. However, the negative impact of excessive fineness on calorific value aligns with observations in other biomass feedstocks [12].

4. Conclusion

This research confirmed that Casuarina equisetifolia wood residues can be utilized as feedstock for bio-pellet production, meeting several requirements of SNI standards. Particle size and compaction pressure significantly influenced moisture content and density, with finer particles and higher pressures yielding pellets of lower moisture and higher density. The optimum condition was obtained at 60 mesh with 4 tonf of pressure, producing pellets with a density of 1.191 g/cm³ and moisture content of 5.27%. Calorific value, however, was not significantly affected by these parameters, as it is largely governed by the inherent composition of the biomass. Even so, high energy values were recorded, with the maximum of 4697 cal/g at 20 mesh and 4 tonf. These results emphasize that processing parameters are effective in improving physicomechanical quality, while energy properties remain relatively stable. Future research should include mechanical durability, ash content, and combustion performance tests to establish a more comprehensive characterization of Casuarina equisetifolia pellets..

Acknowledgements

The authors gratefully acknowledge the support of the Institute for Research and Community Service (LPPM) at Universitas Trunojoyo Madura, which provided funding for this research through an independent research grant under the research group scheme, contract number 5779/UN46.4.1/PT.01.03/2023.

References

[1] Zahira, N. P., & Fadillah, D. P. (2022). Pemerintah Indonesia menuju target Net Zero Emission (NZE) tahun 2060 dengan variable renewable energy. Jurnal Ilmu Sosial, 2(2).
[2] Parinduri, L., et al. (2020). Konversi biomassa sebagai sumber energi terbarukan. Journal of Electrical Technology, 5(2).
[3] Goembira, F., Aristi, D. M., Nofriadi, D., & Putri, N. T. (2021). Analisis konsumsi bahan bakar biopelet sekam padi dan jerami pada kompor biomassa. Jurnal Ilmu Lingkungan, 19(2), 201–210.
[4] BSN. (2020a). SNI 8021:2020 Pelet Kayu. Badan Standardisasi Nasional.

[5] BSN. (2020b). SNI 8951:2020 Pelet Biomassa untuk Pembangkit Listrik. Badan Standardisasi Nasional.
[6] Arrlianda, Z. (2017). Strategi pengembangan energi biomassa dari cemara laut (Casuarina equisetifolia) berbasis pemberdayaan masyarakat. Jurnal Ketahanan Energi, 3(2).
[7] Zulfian, D., et al. (2015). Kualitas biopelet dari limbah batang kelapa sawit pada berbagai ukuran serbuk dan jenis perekat. Jurnal Hutan Lestari, 3(2), 208–216.
[8] Aljarwi, M. A., Pangga, D., & Ahzan, S. (2020). Uji laju pembakaran dan nilai kalor briket wafer sekam padi dengan variasi tekanan. Hasil Kajian, Inovasi, dan Aplikasi Pendidikan Fisika, 6(2).
[9] Muazzinah, M., Meriatna, M., Bahri, S., & Ibrahim, I. (2022). Pemanfaatan limbah ampas kopi menjadi biopelet sebagai sumber energi terbarukan. Chemical Engineering Journal Storage, 2(3), 85–94.
[10] Nuriana, W., Rokhayat, S., & Sudarno, R. T. (2022). Pengaruh variasi ukuran partikel bahan biopelet terhadap laju pembakaran dan kerapatan massa pada limbah kayu mahoni. Penelitian Ilmu-Ilmu Eksakta, 23(1), 11–15.
[11] Raudhatul Jannah, R., Sribudiani, E., & Somadona, S. (2022). Biopelet dari limbah serbuk rotan dan serbuk gergaji dengan perekat sagu. Wahana Forestra, 17(2), 147–161.
[12] González, J. F., Ledesma, B., Alkassir, A., & González, J. (2011). Study of the influence of the composition of several biomass pellets on the drying process. Biomass and Bioenergy, 35(10), 4399–4406.Sze S M 1969 Physics of Semiconductor Devices (New York: Wiley–Interscience)