

Effect of ball milling duration on the morphology and densification of pineapple pomace pellets

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ABSTRACT Pineapple pomace is an abundant processing residue with potential for conversion into compact pellets suitable for handling, storage and downstream utilization. This study investigated the effect of ball-milling duration on the morphology and densification of pineapple pomace pellets. The milling duration was varied to 0, 30, 60, and 90 min, and the samples were then compacted into pellets. The resulting pellets were characterized for thickness, density, Shore D hardness, surface morphology and color. Increasing milling duration reduced pellet thickness and increased pellet density by approximately 30% and 13%, respectively. Pellet hardness also increased with milling duration, indicating greater resistance to surface indentation. Surface morphology revealed progressive surface smoothing with increasing milling duration. Color analysis showed that increased milling durations improved the pellet color uniformity. These findings demonstrate that ball milling is an effective mechanical pretreatment approach for improving the densification of agricultural biomass residues.

KEYWORDS: Ball milling; Pellet; Pineapple pomace; Scanning electron microscopy.

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INTRODUCTION

Agricultural waste is a significant global sustainability challenge due to inefficient resource use and environmental degradation. The improper management of agricultural waste leads to various environmental hazards, including soil and water pollution, greenhouse gas emissions, and biodiversity loss (Kumar *et al.*, 2026; Saha *et al.*, 2024). In line with Sustainable Development Goal 12 (Responsible Consumption and Production), reducing food loss and promoting the valorization of food processing by-products are essential for improving resource efficiency and supporting circular economy practices. Therefore, sustainable processing approaches offer an effective pathway to minimize environmental impacts while enhancing the utilization of existing food resources.

Pineapple (*Ananas comosus*) is a widely cultivated tropical fruit, known not only for its flavour and nutritional profile but also as a source of various bioactive compounds, including antioxidants, vitamins, and dietary fibre. Pineapple processing generates significant amounts of by-products, with pineapple pomace being one of the most abundant residues produced by the juice industry. After juice extraction, pineapple pomace is often discarded or utilized in low-value applications despite its significant resource potential. Studies have shown that pineapple pomace contains high levels of dietary fiber (approximately 45–51%), substantial amounts of carbohydrates and bioactive compounds (Meena *et al.*, 2022; Selani *et al.*, 2014). This fiber-rich material has a heterogeneous fibrous structure, which can influence particle packing and consolidation during compaction. These compositional and structural characteristics make pineapple pomace a promising raw material for value-added applications, provided that suitable processing strategies are developed to enhance its handling, stability, and utilization.

Physical processing methods, particularly ball milling, have been widely used to modify biomass powders by reducing particle size and inducing morphological changes without chemical additives (Kıymaz *et al.*, 2025; Telidi & Salim, 2023). In biomass-related applications, ball milling has been

reported to improve handling, storage stability, and bulk properties of plant-based powders, facilitating downstream processing (An *et al.*, 2025; Rajaonarivony *et al.*, 2021). Ball milling operates through repeated collisions between milling balls and the material, in which mill rotation induces impact and attrition forces that fracture particles into finer sizes (Azam & Mupit, 2022). For fibrous biomass such as pineapple pomace, this fragmentation can progressively disrupt the fibrous structure, allowing for particle rearrangement during subsequent compaction. Finer particles facilitate densification by improving interparticle contact (Wang *et al.*, 2025). These milling-induced morphological changes may therefore influence the densification and physical characteristics of the resulting pellets. However, limited information is available on the influence of ball milling duration on the densification behavior of pineapple pomace during pellet formation. Therefore, this study investigates the effect of ball milling duration on the morphology and densification of pineapple pomace pellets.

METHODOLOGY

Sample Preparation

Pineapples (*Ananas comosus*) were collected from a local market in Kuala Nerus, Terengganu. The pineapples were rinsed with water, cut into small pieces, and juiced using a juice extractor (SJ-6, Russell Taylors, Malaysia). The collected pomace, with an initial moisture content of 87.5% (wet basis), as determined according to AOAC (2000), was dried in a hot-air oven at 65 °C for 24 h to a final moisture content of approximately 12.5% (wet basis), and then ground to a coarse powder using a laboratory grinder.

Ball Milling

The pomace powder was processed using high-energy ball milling equipment (BM40, POWTEQ Instrument, China). For each run, 10 g of pineapple pomace powder was placed in a stainless-steel jar, with a ball-to-powder ratio of 10:1 by weight. During milling, the balls were rotated horizontally at a constant speed of 300 rpm for 0, 30, 60, and 90 minutes at room temperature. The milled samples were stored in airtight containers before further processing.

Palletization

The milled samples were pelletised by uniaxial compaction using a hydraulic press (Specac, Kent, United Kingdom). For each milling duration, 0.5 g of powder was loaded into a 13-mm cylindrical uniaxial die at a load of 5 tons at room temperature. The load was maintained for 1 min, then gradually released to minimise structural disturbance to the formed pellets. The compacted pellets were carefully ejected from the die and stored in a desiccator before further characterisation.

Morphology Evaluation

The surface morphology of the milled powder and corresponding compacted pellets was examined using a scanning electron microscope (SEM) (TESCAN VEGA, Czech Republic). Powder samples were lightly dispersed onto conductive carbon tape, while compacted pellets were mounted on metal stubs. All samples were sputter-coated with a thin layer of gold to enhance electrical conductivity and minimise charging effects during imaging. Microstructural images were acquired under high-vacuum conditions at an accelerating voltage of 15 kV and a magnification of 100×.

Thickness, Density and Hardness Measurements

The thickness of the compacted pellets was measured using a digital micrometre. The density of the compacted pellets was determined using a densimeter (Biobase, Jinan, China). Thickness and density measurements were performed in triplicate. Pellet hardness was measured using a Shore D durometer following the method described by Megdoud *et al.* (2014). Shore D hardness was used as a comparative measure of the surface indentation resistance of pellets produced at different milling durations. The hardness reading was recorded after a penetration time of 3 s at three different locations on each pellet.

Color Measurement

The colour of the compacted pineapple pomace pellets was measured using a colorimeter (FRU WR18, China). The colour parameters were expressed in the *CIE Lab** colour space, where L^* represents lightness, a^* values represent the red-green axis and b^* values denote the yellow-blue axis. The total colour difference was determined using Equation 1 (Telidi & Salim, 2023):

$$\Delta E^* = \sqrt{(a^* - a_0^*)^2 + (b^* - b_0^*)^2 + (L^* - L_0^*)^2} \quad (1)$$

where L_0^* , a_0^* and b_0^* are the color coordinates of the unmilled (0 min) pellet sample.

Statistical Analysis

Statistical analysis was performed using one-way analysis of variance (ANOVA) followed by Duncan's multiple range test to compare mean differences at a significance level of $p < 0.05$.

RESULT AND DISCUSSION

Morphology Analysis

SEM images of pineapple pomace powder and the corresponding compacted pellets at different milling durations are shown in Figure 1. The images of the unmilled powder showed large, irregular fibrous particles with a rough surface texture. These coarse fibres were loosely entangled, resulting in poor surface contact and weak interparticle bonding during compaction, as evidenced by a rough-surface pellet with visible interparticle gaps. After 30 min, particle fragmentation occurred, producing more uniform particles while still retaining the fibrous morphology. This may have improved particle rearrangement and consolidation during compaction.

Further milling to 60 min enhanced fibre fragmentation, increasing the number of smaller particles. This facilitated closer interparticle contact with fewer voids, resulting in a smoother surface. At 90 min, increased fragmentation was observed due to extensive fibre breakage. The corresponding pellet exhibited the smoothest and most uniform surface among all samples, indicating a high degree of particle consolidation. These observations are consistent with previous studies in which smaller particles improve packing efficiency by reducing void spaces, thereby enhancing interparticle contact during compaction (Hanif & Majeedullah, 2022; Santl *et al.*, 2012). However, quantitative particle-size distribution was not determined in this study, and further instrumental analysis is required to establish the relationship between particle size and milling duration.

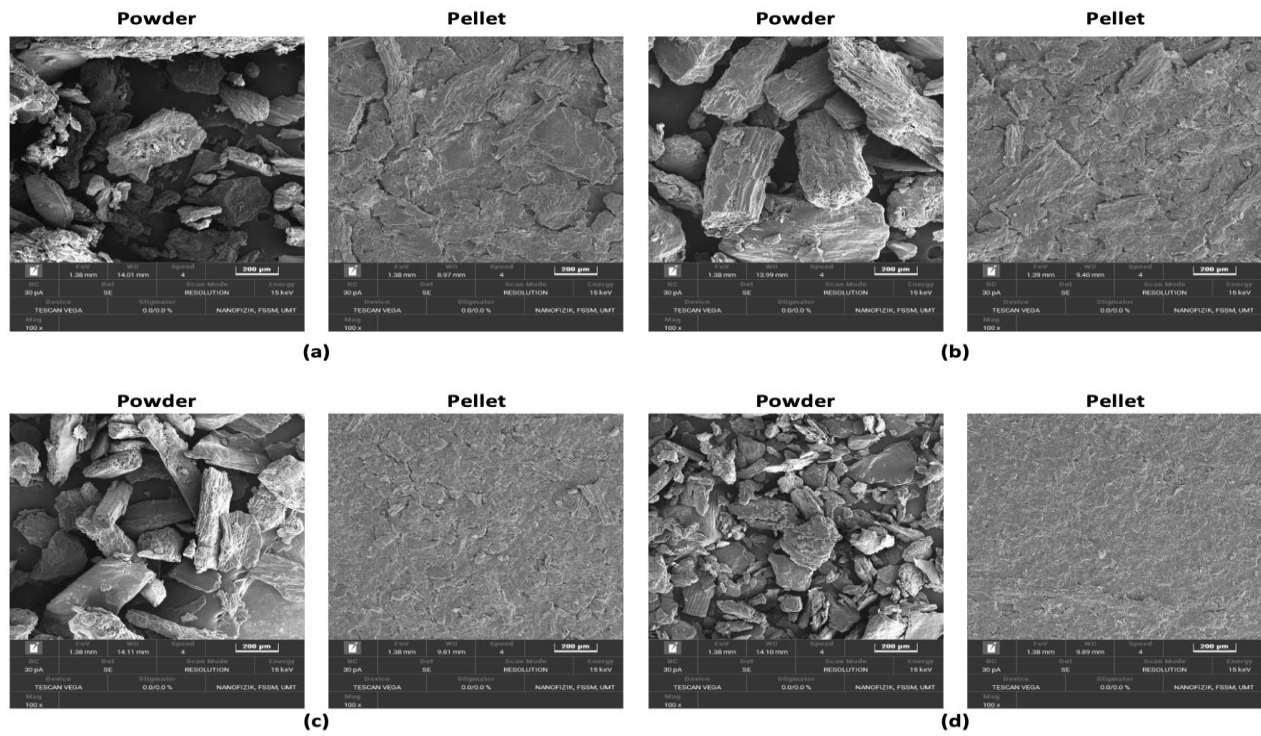


Figure 1. SEM images of pineapple pomace powder and after compaction at different milling durations: (a) 0 min, (b) 30 min, (c) 60 min and (d) 90 min.

Thickness, Density and Hardness

The thickness and density of pineapple pomace pellets at different milling durations are presented in Table 1. Increasing ball milling duration progressively reduced pellet thickness by up to 30% and increased pellet density by up to 13%, demonstrating enhanced densification of the compacted pomace. This result is supported by the corresponding SEM observations, in which the powder subjected to 90 min of milling exhibited greater fiber fragmentation, while the corresponding pellet showed a more uniform surface. These findings are consistent with previous studies showing that finer particles improve packing efficiency and increase pellet density in particulate systems (An *et al.*, 2025; Hong *et al.*, 2021). Pellet hardness increased with milling duration, reaching 33.2 Shore D after 90 min. This increase may be associated with progressive particles and fiber fragmentation during milling, which can promote closer particle contact and more effective consolidation during compaction. The resulting improvement in indentation resistance is consistent with previous studies showing that the Shore D hardness of compressed biomass materials is influenced by particle characteristics and processing conditions (González *et al.*, 2020; Megdoud *et al.*, 2014; Supramono *et al.*, 2015). From a process-efficiency perspective, prolonged milling involves greater processing time and energy requirements while enhancing pellet densification and hardness. Therefore, further evaluation based on energy consumption measurements is required to establish the practical efficiency of extended milling.

Table 1. Pellet thickness, density and hardness of pineapple pomace at different milling durations.

Milling Duration	Thickness (mm)	Density (g/cm ³)	Hardness (Shore D)
0 min	4.01 ± 0.03 ^a	1.186 ± 0.002 ^a	17.3 ± 0.8 ^a
30 min	3.39 ± 0.04 ^b	1.238 ± 0.002 ^b	26.8 ± 1.5 ^b
60 min	3.00 ± 0.02 ^c	1.290 ± 0.001 ^c	30.5 ± 1.3 ^c
90 min	2.80 ± 0.02 ^d	1.342 ± 0.005 ^d	33.2 ± 1.3 ^d

Note: Column-wise values followed by different superscript letters are significantly different ($p < 0.05$).

Color Analysis

The colour parameters (L^* , a^* , b^* , and ΔE) of pineapple pomace pellets are shown in Table 2. The L^* values increased after milling, indicating enhanced lightness, which may be associated with changes in particle morphology and surface uniformity, thereby influencing light reflection from the pellet surface (Gueli *et al.*, 2017). At longer milling durations (60–90 min), a slight decrease in L^* was observed, likely due to increased particle packing and surface smoothing, which reduces diffuse light scattering. The decrease in a^* values indicate reduced redness, whereas the increase in b^* values reflect enhanced yellowness of the pellets as milling duration increases. These changes are attributed to particle size reduction and improved surface homogeneity, which promote a more uniform color distribution and alter light–surface interactions. This is consistent with previous ball milling studies showing particle size–dependent changes in reflectivity and chromaticity (Liu *et al.*, 2021). The ΔE decreases with milling duration relative to the unmilled powder, reflecting an overall colour change induced by mechanical processing. However, the 60 min samples showed intermediate values that were not significantly different from either 30 or 90 min, indicating gradual color stabilization.

Table 2. The colour parameters of pineapple pomace pellet at different milling durations.

Milling Duration	L^*	a^*	b^*	ΔE
0 min	67.16 ± 0.57^a	9.32 ± 0.12^a	21.39 ± 0.14^a	-
30 min	72.46 ± 0.48^b	7.89 ± 0.16^b	23.63 ± 0.24^b	5.93 ± 0.68^a
60 min	71.02 ± 0.67^c	8.50 ± 0.22^c	24.64 ± 0.11^c	5.11 ± 0.55^{ab}
90 min	70.45 ± 0.40^c	8.37 ± 0.34^c	24.32 ± 0.27^c	4.52 ± 0.39^{bc}

Note: Column-wise values followed by different superscript letters are significantly different ($p < 0.05$).

CONCLUSION

This study demonstrated that ball milling is an effective mechanical pretreatment method for modifying the morphology of pineapple pomace, thereby enhancing pellet densification. Increasing milling time progressively fragmented the heterogeneous fibrous structure into finer particles, which may have facilitated particle rearrangement and closer interparticle contact during compaction. This was evidenced by a 30% decrease in pellet thickness and a 13% increase in pellet density after 90 min of milling, demonstrating the relationship between progressive fiber fragmentation and pellet densification. Pellet hardness also increased with milling duration, indicating greater resistance to surface indentation following compaction. Color analysis further indicated improved color uniformity with increasing milling duration. Taken together, these findings highlight the role of the fibrous morphology of pineapple pomace in its compaction behavior and demonstrate the potential of ball milling to produce a more densified intermediate form for subsequent biomass handling and processing. Further studies incorporating quantitative particle-size distribution analysis, compressive strength, friability, optimization of compaction conditions and energy consumption measurements are needed to better understand the compaction, mechanical behavior and processing efficiency of pineapple pomace pellets.

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REFERENCES

- [1] An, N.N., Li, D., Wang, L.J. & Wang, Y. 2025. Unlocking the potential of corn flour: A study on the multidimensional effects of ball milling. *Food and Bioprocess Technology*, 18(1), 573–587.
- [2] AOAC International. 2000. *Official Methods of Analysis of AOAC International* (17th edition). Gaithersburg, MD, USA: AOAC International.
- [3] Azam, M.A. & Mupit, M. 2022. Carbon nanomaterial-based sensor: Synthesis and characterization. In: Manjunatha, J.G. & Hussain, C.M. (eds.). *Carbon Nanomaterials-Based Sensors*. Elsevier. pp. 15–28.
- [4] González, W.A., López, D. & Pérez, J.F. 2020. Biofuel quality analysis of fallen leaf pellets: Effect of moisture and glycerol contents as binders. *Renewable Energy*, 147, 1139–1150.
- [5] Gueli, A.M., Bonfiglio, G., Pasquale, S. & Troja, S.O. 2017. Effect of particle size on pigments colour. *Color Research & Application*, 42(2), 236–243.
- [6] Hanif, F. & Majeedullah. 2022. Comminution. In: Khan, S.A. (eds). *Essentials of Industrial Pharmacy. AAPS Advances in the Pharmaceutical Sciences Series*, Vol. 46. Cham: Springer. pp. 27–44.
- [7] Hong, S.J., Das, P.R. & Eun, J.B. 2021. Effects of superfine grinding using ball-milling on the physical properties, chemical composition, and antioxidant properties of *Quercus salicina* (Blume) leaf powders. *Journal of the Science of Food and Agriculture*, 101(8), 3123–3131.
- [8] Kıymaz, B.M., Özmen, D., Moin, A., Çiçek, B., Toker, O.S. & Arici, M. 2025. Modification of taro starch using ball milling process. *International Journal of Biological Macromolecules*, 321, 146300.
- [9] Kumar, S., Divya, Thakur, S. & Kumar, R. 2026. The ecological toll: Biodiversity loss and habitat degradation caused by agricultural waste. In: Giri, A., Kumar, R., Dhull, S.B. & Acharya, S. (eds.). *Waste to Resources*. Academic Press. pp. 155–166.
- [10] Liu, M., Peng, Z., Wang, X., He, Y., Huang, S., Wan, J., Wang, B., Zhou, Y., Yang, H. & Zheng, H. 2021. The effect of high energy ball milling on the structure and properties of two greenish mineral pigments. *Dyes and Pigments*, 193, 109494.
- [11] Meena, L., Neog, R., Yashini, M. & Sunil, C. 2022. Pineapple pomace powder (freeze-dried): Effect on the texture and rheological properties of set-type yogurt. *Food Chemistry Advances*, 1, 100101.
- [12] Megdoud, D., Boudaa, M., Ouamrane, F. & Benamara, S. 2014. Influence of the compression force and powder particle size on some physical properties of date fruit (*Phoenix dactylifera*) tablets. *International Journal of Nutrition and Food Engineering*, 8(10), 1163–1167.
- [13] Rajaonarivony, K.R., Mayer-Laigle, C., Piriou, B. & Rouau, X. 2021. Comparative comminution efficiencies of rotary, stirred and vibrating ball-mills for the production of ultrafine biomass powders. *Energy*, 227, 120508.
- [14] Saha, B., Kumar, S., Verma, D.K., Nag, A., Bhattacharya, P., Dutta, S.K., Kumar, V., Kumari, S., Anjum, M., Kumari, S., Saha, S., Sahay, S., Sathyanarayana, K. & Vats, A.K. 2024. Microbial biodegradation of the agricultural wastes for environmental sustainability. In: Saha, S.P., Mazumdar, D., Roy, S. & Mathur, P. (eds.). *Agro-waste to Microbe Assisted Value Added Product: Challenges and Future Prospects*. Cham: Springer. pp. 157–174
- [15] Santl, M., Ilic, I., Vrečer, F. & Baumgartner, S. 2012. A compressibility and compactibility study of real tableting mixtures: The effect of granule particle size. *Acta Pharmaceutica*, 62(3), 325–340.
- [16] Selani, M.M., Brazaca, S.G.C., Dos Santos Dias, C.T., Ratnayake, W.S., Flores, R.A. & Bianchini, A. 2014. Characterisation and potential application of pineapple pomace in an extruded product for fibre enhancement. *Food Chemistry*, 163, 23–30.
- [17] Supramono, D., Devina, Y.M. & Tristantini, D. 2015. Effect of heating rate of torrefaction of sugarcane bagasse on its physical characteristics. *International Journal of Technology*, 6(7), 1084–1093.

- [18] Telidi, U.S.M. & Salim, N.S.M. 2023. Effect of ball milling time on structural properties and colour analysis of calamansi (*Citrus microcarpa*) peel powder. *Transactions on Science and Technology*, 10(3), 164–169.
- [19] Wang, X., Ma, T., Sun, J., Jiang, L., Liu, Y., Yu, B., Chen, Y., Zhai, M. & Zhou, H. 2025. Effects of pelletizing pressure and particle size on flame characteristics and potassium release in volatile combustion of biomass pellets. *Biomass and Bioenergy*, 199, 107916.