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Sustainable Briquette Production from Hazelnut Shell Waste: The Significance of Particle Size in Quality Enhancement

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ABSTRACT: Interest in biomass briquettes as a fossil fuel substitute has increased due to the growing need for sustainable energy sources. The impact of hazelnut shell charcoal particle size on briquette quality is examined in this study, with particular attention paid to important variables such bulk density, compressive strength, moisture content, ash content, volatile matter, and fixed carbon content. Three different particle size treatments (20 mesh, 40 mesh, and 60 mesh) were analyzed using a Completely Randomized Design (CRD) with five replications. The results indicated that finer particle sizes (60 mesh) significantly improved briquette quality, exhibiting higher bulk density (0.975 g/cm³), compressive strength (58.38 N/cm²), and fixed carbon content (68.25%), while reducing moisture content (7.13%), ash content (2.85%), and volatile matter (21.65%). These findings highlight the importance of optimizing particle size to enhance the physical and combustion properties of biomass briquettes. Briquette manufacture from hazelnut shell waste offers a viable sustainable bioenergy strategy that supports waste reduction and the growth of renewable energy sources.

KEYWORDS: biomass briquettes, combustion efficiency, hazelnut shell, particle size, renewable energy.

INTRODUCTION

A strong dependence on fossil fuels, which greatly contribute to greenhouse gas emissions and climate change, has resulted from the global increase in energy use, especially in nations like Indonesia. Despite the environmental challenges posed by fossil fuels, they continue to dominate energy sources due to their role in meeting electricity demand and supporting economic growth. This situation necessitates a transition towards renewable energy to mitigate environmental degradation and achieve sustainable development. Fossil fuels are linked to increased greenhouse gas emissions, exacerbating climate change (J. Wang & Azam, 2024). The reliance on fossil fuels in developing countries, including Indonesia, hinders progress towards global climate objectives (Rahman et al., 2024). Transitioning to renewable energy sources can significantly reduce carbon emissions and improve environmental quality (Rahman et al., 2024).

Studies indicate a positive correlation between renewable energy adoption and improved environmental conditions, emphasizing the need for policies promoting renewable energy (Zhang, 2024)(Aneja et al., 2023). Because of its availability and carbon-neutral qualities, biomass has emerged as a promising renewable energy source in the shift to sustainable energy systems. Biomass can be converted into various forms of energy, including solid, liquid, and gaseous fuels, which can significantly reduce greenhouse gas emissions and support energy sustainability. Pyrolysis and gasification are prominent methods for converting biomass into energy, enabling efficient waste utilization and reducing environmental impact (Polesek-Karczewska et al., 2024). Recent advancements in photocatalysis allow for the conversion of biomass into hydrogen and other fuels, utilizing light energy to enhance chemical reactions (Zhang et al., 2024). Biomass-to-hydrogen technologies, such as anaerobic digestion and gasification, show competitive production costs, making them attractive alternatives to fossil fuels (Rey et al., 2024). Decentralized Processing: Innovations in biomass logistics and processing can facilitate localized energy production, enhancing energy security and reducing transportation emissions (Blay-Roger et al., 2024).

A viable renewable energy source is biomass briquettes, especially in tropical areas like Indonesia where forestry and agriculture produce a lot of organic waste. By improving energy density and combustion efficiency, this biomass is transformed into briquettes, providing a sustainable substitute for fossil fuels. Briquettes have a calorific value that can reach up to 6728 kJ/kg, making them more efficient than raw biomass (Khan et al., 2023). Utilizing biomass reduces greenhouse gas emissions compared to conventional fossil fuels, contributing to a low-carbon energy system (Zhu et al., 2024). Briquettes repurpose agricultural waste, such as straw and sawdust, mitigating environmental pollution and waste disposal issues (Ibitoye et al., 2023; Zhu et al., 2024). The heterogeneity of

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biomass materials complicates the scaling of production from laboratory to industrial levels (Zhu et al., 2024). Various conversion methods, such as pyrolysis and gasification, have distinct advantages and limitations, affecting the overall efficiency and cost of briquette production (Ibitoye et al., 2023).

The underutilization of hazelnut shells in briquette production presents a significant opportunity for waste management and energy sustainability. These shells, often discarded or burned, can be transformed into valuable energy resources, contributing to a circular economy. Hazelnut shells possess high carbon content, making them suitable for energy production (Borkowska et al., 2024). The conversion process can mitigate greenhouse gas emissions compared to traditional waste disposal methods (McNeill et al., 2024). Utilizing hazelnut shells reduces environmental pollution associated with burning waste (Guo et al., 2024). The production of briquettes from these shells can decrease reliance on fossil fuels, promoting cleaner energy alternatives (Sikiru et al., 2024).

The quality of biomass briquettes is significantly influenced by particle size, which affects their physical, mechanical, and combustion properties (Abineno et al., 2024; Bunga et al., 2024; Jonson & Dethan, n.d.). Smaller particle sizes enhance briquette density and compressive strength, leading to improved interparticle bonding and more efficient combustion characteristics. This overview highlights the critical role of particle size in optimizing briquette quality (J. Dethan & Lalel, 2024; Makaborang et al., 2020). Smaller particles (less than 1.2 mm) yield higher apparent density and compressive strength, as demonstrated in coffee husk briquettes (Setter et al., 2021). In rice straw briquetting, reduced particle size resulted in lower energy consumption and increased product density and compressive strength (Y. Wang et al., 2018). Smaller particles facilitate the efficient release of volatile matter, contributing to higher fixed carbon content, essential for stable combustion (J. J. S. Dethan et al., 2024; Kette et al., 2024; Setter et al., 2021a). The combustion behavior of biomass refuse-derived fuel (BRDF) showed improved fixed carbon content and reduced volatile matter, enhancing its applicability as a fuel (Kim et al., 2024). Studies consistently emphasize the need to optimize particle size to achieve superior briquette quality, as smaller sizes promote better energy density and combustibility (Setter et al., 2021a; Y. Wang et al., 2018).

The investigation into the effect of hazelnut shell charcoal particle size on briquette quality is crucial for optimizing biomass briquette technology. While existing studies have explored particle size impacts on other biomass materials, the unique characteristics of hazelnut shells necessitate focused research. This study aims to systematically analyze how varying particle sizes influence the physical and combustion properties of briquettes made from hazelnut shell charcoal.

Briquettes made from finer particles generally exhibit higher density and hardness, as seen in studies with pecan pericarp and coffee husks, where smaller particle sizes improved these attributes (Ngangyo Heya et al., 2022; Setter et al., 2021a). Larger particle sizes tend to increase swelling, which can affect briquette stability during storage and transport (Ngangyo Heya et al., 2022). The calorific value of briquettes is influenced by particle size, with finer particles often yielding higher energy density, as demonstrated in coffee husk briquettes (Setter et al., 2021a). The combustion efficiency of briquettes can be optimized by controlling particle size, which affects air supply and heat distribution during burning (Nikiforov et al., 2024).

The findings of this study are expected to have significant implications for both scientific and practical applications. From a scientific perspective, the research enhances our understanding of the relationship between particle size and briquette quality, offering insights that can be applied to other types of biomass. From a practical standpoint, the utilization of hazelnut shells as a briquette raw material supports waste reduction, promotes renewable energy production, and creates economic opportunities for hazelnut-producing regions. By adhering to ASTM standards for testing and evaluation, this study ensures the reliability and comparability of its results, further strengthening its contribution to the field of biomass energy research.

RESEARCH METHODOLOGY

Materials and Equipment

The primary material used in this study was hazelnut shell waste, sourced from Posiwatu Village, Wulandoni District, Lembata Regency, Indonesia. The hazelnut shells were cleaned and dried to remove impurities before undergoing the carbonization process. A starch-based binding agent was prepared by mixing starch powder with water in a 1:5 ratio (w/w) and heating the mixture until it formed a gel.

The equipment used included a carbonization furnace operating at temperatures between 400–500°C, a crushing machine to reduce the shells into smaller particles, and sieves with mesh sizes of 20, 40, and 60 to achieve uniform particle size distribution. A hydraulic press was used to apply a consistent pressure of 10 MPa during the briquetting process. The moisture content of the biomass was

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measured using a JV010S moisture meter, while the compressive strength of the briquettes was determined using a SONDA500N force gauge.

Experimental Design

This study employed a Completely Randomized Design (CRD) with three treatments based on the particle size of hazelnut shell charcoal powder: particles passing through 20 mesh, 40 mesh, and 60 mesh sieves. Each treatment was replicated five times to ensure the reliability of the results. A control group, consisting of briquettes made from raw hazelnut shells without carbonization, was also included for comparison.

Data Collection and Analysis

The quality parameters of the briquettes, including bulk density, compressive strength, moisture content, ash content, volatile matter, and fixed carbon content, were evaluated in accordance with ASTM standards. Data were analyzed using Analysis of Variance (ANOVA) to determine the effect of particle size on briquette quality. Post-hoc analysis was conducted using Duncan's multiple range test at a 5% confidence level to identify specific differences between treatments. Assumptions of normality and homogeneity of variance were checked, and data transformations were applied where necessary.

Ethical and Environmental Considerations

This study adhered to ethical guidelines for material sourcing, ensuring that the hazelnut shells were obtained sustainably and with minimal environmental impact. The carbonization process was conducted in a controlled environment to minimize emissions, and the use of hazelnut shells as a biomass source was evaluated in terms of its contribution to waste reduction and renewable energy production.

RESULT AND DISCUSION

Bulk density

The relationship between particle size, as determined by the mesh size (20, 40, and 60 mesh), and the bulk density of the briquettes is clearly demonstrated in the experimental results (Figure 1.). The bulk density, measured in grams per cubic centimeter (g/cm³), showed a consistent increase with decreasing particle size. Specifically, briquettes produced with particles passing through a 20-mesh sieve had an average bulk density of 0.86 g/cm³, while briquettes with particles passing through a 40-mesh sieve showed a higher bulk density of 0.915 g/cm³. The highest bulk density of 0.975 g/cm³ was achieved with particles passing through a 60-mesh sieve, which was significantly different from the other treatments tested.

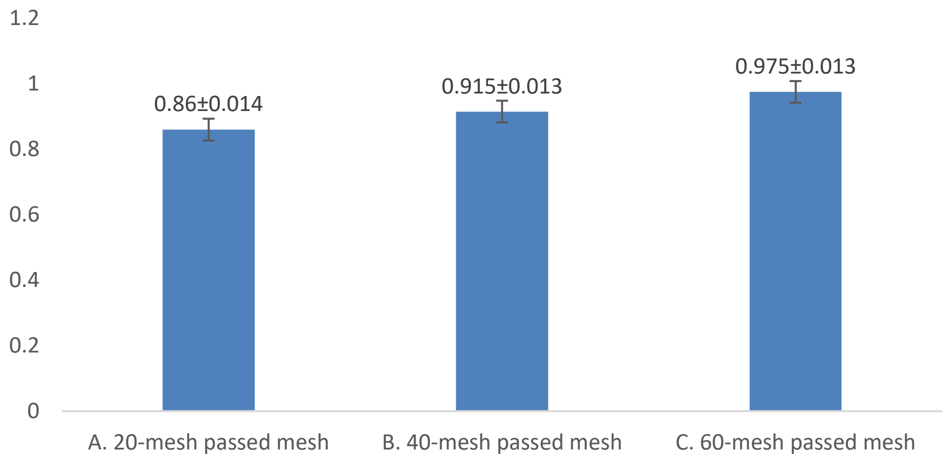

Figure 1. Bulk Density of Hazelnut Shell Briquettes with Different Particle Sizes

The trend indicating that smaller particle sizes contribute to a denser and more compact briquette structure is supported by various studies. Smaller particles enhance packing efficiency and interparticle bonding, leading to improved mechanical properties of briquettes. Research shows that as coal particle size decreases, the uniaxial compression strength and elastic modulus of briquettes

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increase, indicating stronger interparticle cohesion (Pang et al., 2019). For coffee husk briquettes, particles smaller than 1.2 mm exhibited superior compressive strength and energy density compared to larger sizes (Setter et al., 2021b) Fine particles lead to better packing and reduced voids, enhancing the overall density and mechanical performance of briquettes (Okot et al., 2019). Smaller particles create a greater meshing force, which is crucial for the structural integrity of briquettes (Pang et al., 2019). Fine powders in superalloys showed limited plastic deformation, resulting in a more stable microstructure, which can be analogous to the behavior in briquettes (Qu et al., 2022).

The standard deviation values for bulk density were relatively low across all treatments, ranging from 0.013 to 0.014 g/cm³, indicating consistent and reproducible results. This finding suggests that particle size reduction improves the physical quality of the briquettes, resulting in high-density fuel.

Compressive strength

The particle size of the raw material, as determined by the mesh size of the sieve, showed a significant effect on the compressive strength of biomass briquettes. In this study, three particle size categories were evaluated: 20 mesh (coarse particles), 40 mesh (medium particles), and 60 mesh (fine particles) (Figure 2.). The results showed a clear trend where smaller particle sizes were associated with increased compressive strength. Briquettes produced with 20 mesh particles showed the lowest average compressive strength of 45.69 N/cm². When the particle size decreased to 40 mesh, the compressive strength increased to 52.13 N/cm², while the finest particles (60 mesh) produced the highest compressive strength of 58.38 N/cm² which was significantly different ($p < 0.05$) compared to all other treatments tested.

The trend of increased particle packing efficiency and interparticle bonding in smaller particle sizes significantly enhances the mechanical integrity of briquettes. Finer particles effectively fill interstitial voids, leading to a denser structure and improved resistance to external forces. This phenomenon is supported by various studies that highlight the inverse relationship between particle size and compressive strength. Smaller particles provide a larger surface area for binder interaction, resulting in stronger adhesive forces and a more homogeneous matrix (Setter et al., 2021). Research indicates that briquettes made from particles smaller than 1.2 mm exhibit superior compressive strength and energy density compared to larger fractions (Setter et al., 2021b). A study on wheat straw briquettes found that mechanical durability decreases with increasing particle size, with the highest durability observed in the 0–2 mm fraction (Dyjakon et al., 2020). The bonding mechanisms in densified biomass pellets are complex, involving molecular and structural chemistry interactions that enhance particle cohesion (Anukam et al., 2021). Cold sintering techniques have shown that interphase bonding can significantly improve the strength and density of iron compacts, paralleling the benefits seen in biomass briquetting (Paradis et al., 2022). While smaller particle sizes generally enhance mechanical properties, it is essential to consider the potential trade-offs, such as increased energy requirements for processing finer materials. Additionally, the role of additives in improving bonding and durability remains an area for further exploration (Anukam et al., 2021).

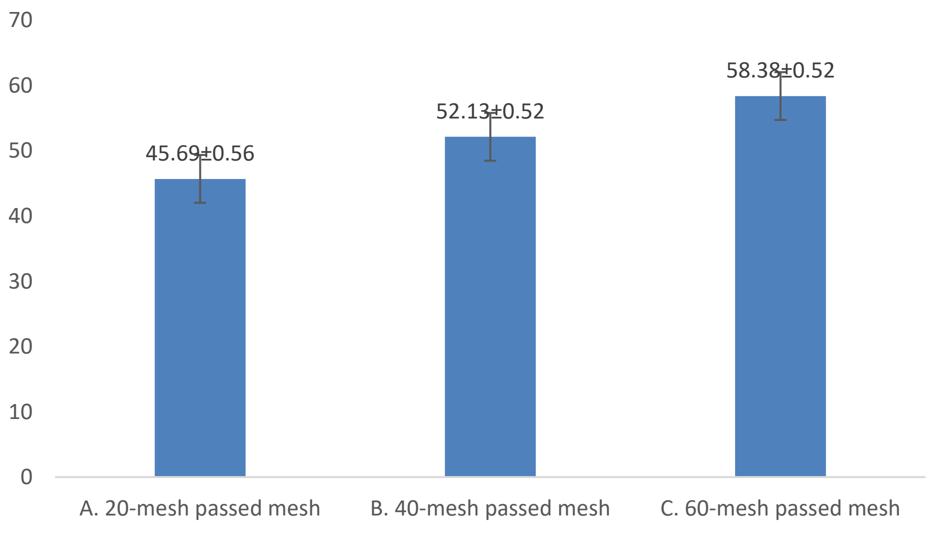

Figure 2. Compressive Strength of Briquettes as Influenced by Particle Size

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Moisture content

The relationship between mesh size (20 to 60) and the moisture content of briquettes exhibits a clear and consistent pattern (Figure 3). According to the data provided, moisture content decreases progressively with smaller mesh sizes (increasing particle fineness). Briquettes composed of 20-mesh particles exhibit the highest moisture content at 8.4%, whereas those with 40-mesh and 60-mesh particles show significantly lower moisture levels of 7.85% and 7.13%, respectively ($P<0.05$).

The reduction in moisture content in briquettes made from finer particles can be explained through two main mechanisms: increased specific surface area and enhanced structural compactness. These factors significantly influence the briquetting process and the resulting physical properties of the briquettes. Finer particles, such as those passing through a 60 mesh screen, exhibit a higher specific surface area, which enhances interparticle interactions during compression (Zheng et al., 2024). This increased interaction reduces void spaces within the briquette, allowing for more effective expulsion of trapped moisture during formation (Marreiro et al., 2024). Smaller particles tend to create denser and more homogeneous structures when compressed, which limits the briquette's ability to retain moisture from environmental exposure or residual moisture from production (Nikiforov et al., 2023).

Studies indicate that briquettes made from fine fractions have improved durability and lower moisture content, contributing to better combustion properties (Abdel Aal et al., 2023).

Furthermore, drying or heating processes during briquette production may be more effective for finer particles due to their larger surface area, which promotes uniform evaporation of moisture. In contrast, coarser particles (20 mesh) retain higher moisture levels due to their porous structure, which traps humidity within larger interstitial spaces. Practically, the use of fine particles (60 mesh) enhances briquetting outcomes by improving moisture stability, though the associated increase in density may necessitate careful consideration of combustion dynamics.

Statistically, the low standard deviations (0.12–0.13%) across all treatments underscore the consistency of the data. These findings highlight that mesh size not only influences physical properties such as bulk density and compressive strength but also plays a critical role in regulating moisture content—a key determinant of storage quality and thermal performance in briquettes.

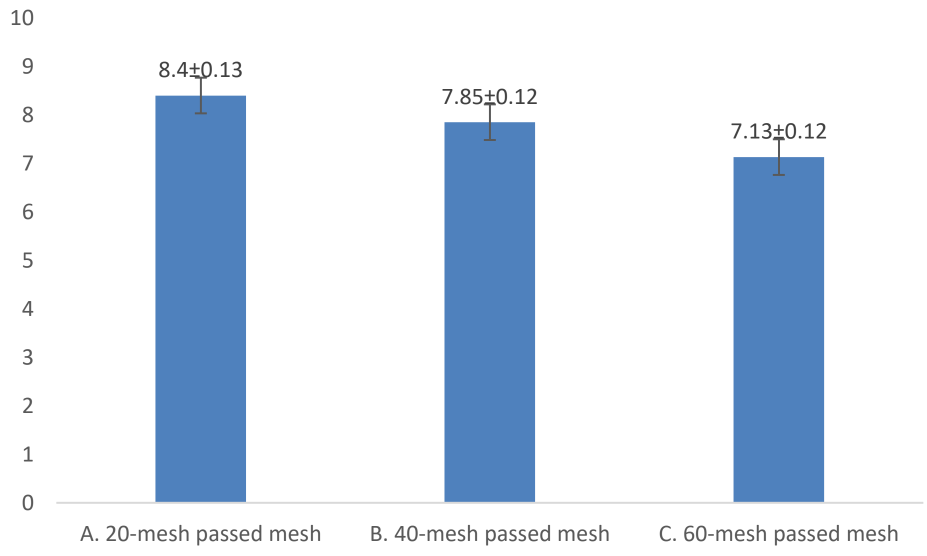

Figure 3. Moisture Content Variation in Briquettes with Different Particle Sizes

Ash content

The particle size of the raw material, classified based on the sieve mesh size, showed a significant inverse correlation with the ash content of the biomass briquettes (Figure 4.). The results revealed a clear trend where smaller particle sizes were associated with reduced ash content. Briquettes produced with 20 mesh particles showed the highest average ash content of 4.10%, 40 mesh particle size the ash content decreased to 3.55% and the briquettes with the finest particles (60 mesh) produced the lowest ash content of 2.85% which was significantly different ($p < 0.05$) from the other treatments tested.

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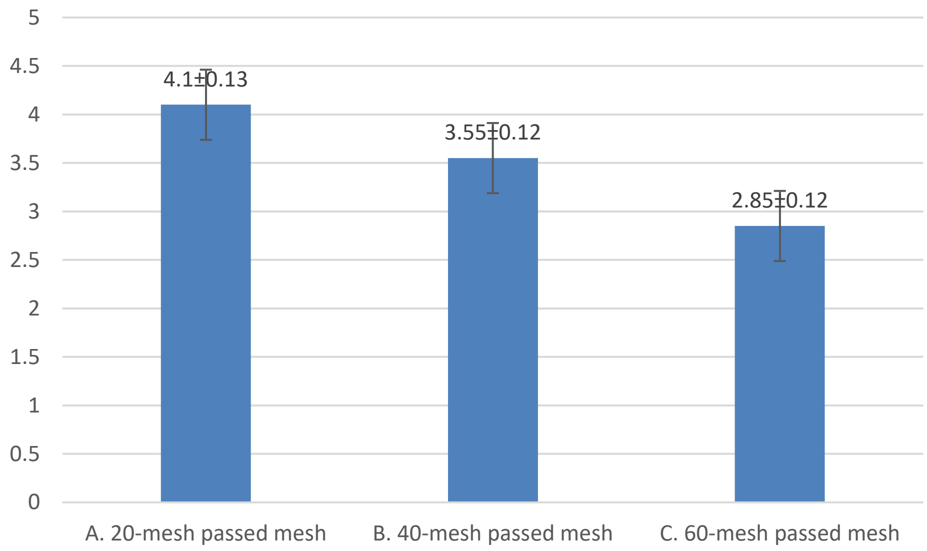

Figure 4. Ash Content of Briquettes Produced from Different Particle Sizes

The inverse relationship between particle size and combustion efficiency can be attributed to several key factors that enhance the combustion process. Smaller particle sizes facilitate improved heat distribution, promote complete oxidation, and minimize inorganic residue retention, leading to more efficient combustion. Finer particles allow for a more uniform heat distribution during combustion, which is crucial for maintaining optimal reaction conditions (Li et al., 2025). Smaller particles enhance the oxidation of organic matter, resulting in higher combustion efficiency. For instance, a study indicated a 5.13% increase in combustion efficiency when reducing particle size from 5 mm to 3 mm (Li et al., 2025). Smaller particles have a higher surface area to volume ratio, which accelerates thermal decomposition and reduces residual ash formation (Xiumin et al., 2001). Research shows that fine fuel particles (less than 1 mm) significantly influence ash deposition behavior, further supporting the reduction of inorganic residues (Plankenbühler et al., 2019).

This finding is in line with the principles of biomass thermochemical conversion, where particle size optimization is critical to minimize ash-related challenges, such as slagging and fouling. Lower ash content in finer particles improves fuel quality, increases combustion efficiency, and reduces maintenance requirements in industrial applications. Consequently, the use of 60-mesh particles is recommended to produce briquettes with superior fuel properties, in line with sustainability and operational efficiency goals in renewable energy systems.

Volatile matter

The relationship between mesh size (20 to 60) and volatile matter content of the briquettes showed a statistically significant inverse correlation, as evidenced by the experimental data (Figure 5.). Briquettes consisting of coarser particles (20 meshes) showed the highest volatile matter content of 25.04%, while briquettes with intermediate (40 meshes) and finer particles (60 meshes) showed decreasing values of 23.65% and 21.65%, respectively ($P<0.05$).

The decrease in volatile matter with smaller particle sizes during briquette formation is primarily due to enhanced thermal dynamics and structural characteristics. Finer particles, such as those at 60 meshes, exhibit a greater specific surface area, which improves heat transfer efficiency, facilitating the evaporation of light organic compounds. Conversely, coarser particles (20-mesh) retain more volatiles due to their lower surface-to-volume ratio, which restricts heat penetration and traps volatiles in voids. This phenomenon is further influenced by the denser microstructure of fine-particle briquettes, which reduces porosity and limits the physical trapping of volatiles.

Finer particles enhance heat transfer, leading to more efficient evaporation of volatiles (Nikiforov et al., 2023). Increased surface area allows for better contact with heat sources, promoting the release of hydrocarbons and water-bound organics (Balraj et al., 2021). Coarser particles have a lower surface-to-volume ratio, limiting heat penetration and trapping volatiles (Setter et al., 2021b).

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The denser microstructure of fine-particle briquettes reduces porosity, further limiting volatile retention (Pang et al., 2019). Briquettes made from finer particles demonstrate improved burning characteristics, such as longer burning time and lower burning rates (Nikiforov et al., 2023). The mechanical properties of briquettes, including strength and energy density, are enhanced with smaller particle sizes (Pang et al., 2019).

The low standard deviations (0.31–0.37%) across all treatments underscore the reproducibility of these results. These findings highlight that particle size optimization is critical to tailoring volatile content a key parameter affecting combustion efficiency, emission profile, and energy density. Lower volatiles in fine-particle briquettes can improve combustion stability and reduce smoke emissions, although potentially requiring adjustments to ignition properties. Thus, mesh size serves as an important variable in balancing material composition and functional performance in briquette design.

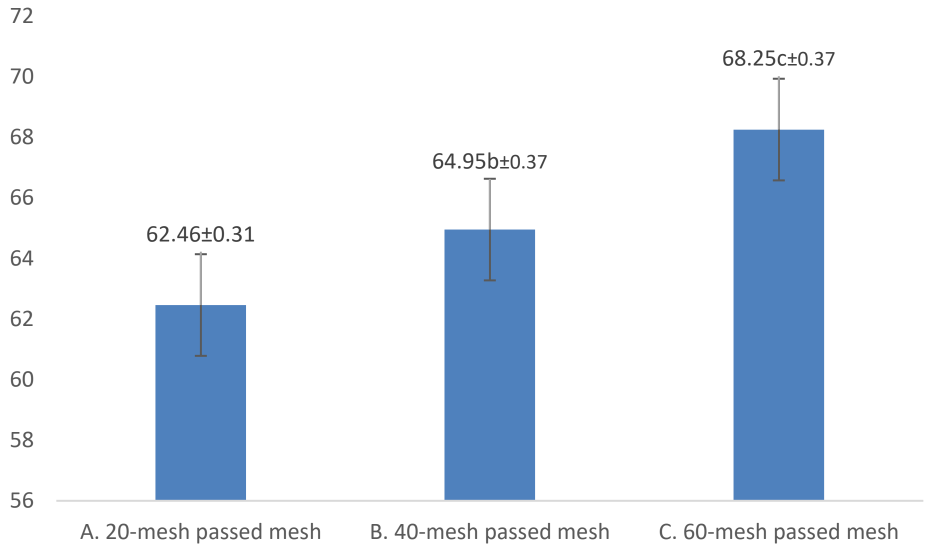

Figure 5. Volatile Matter Content in Briquettes with Different Particle Sizes

Fixed carbon

The relationship between particle size (as indicated by mesh size) and fixed carbon content of biomass briquettes was evident in the experimental results. Briquettes produced with finer particles (60 meshes) showed the highest fixed carbon content of 68.25%, while briquettes with coarser particles (20 meshes) showed the lowest value of 62.46%. The intermediate particle size (40 meshes) resulted in a fixed carbon content of 64.95%, reflecting a consistent increasing trend with decreasing particle size. This pattern suggests that reducing particle size (increasing mesh number) increases fixed carbon retention, likely due to increased structural compactness and reduced porosity.

Smaller particles facilitate tighter packing, minimize voids and optimize the carbonization process, which retains a higher proportion of carbonaceous material during thermal conversion. Finer particles (60 meshes) achieved a fixed carbon content of 68.25%, while coarser particles (20 meshes) had 62.46% (Ngangyo Heya et al., 2022). Intermediate sizes (40 meshes) showed a fixed carbon content of 64.95%, indicating a consistent trend of increasing carbon retention with decreasing particle size (Ngangyo Heya et al., 2022). Smaller particles facilitate tighter packing, minimizing voids and enhancing the carbonization process, which retains more carbonaceous material (Ngangyo Heya et al., 2022; L. Wang et al., 2013). Studies indicate that reduced particle size leads to increased pellet strength and decreased porosity, further supporting higher fixed carbon yields (J. J. S. Dethan, 2024; Xu et al., 2024). While finer particles improve fixed carbon content, they may also lead to challenges in handling and processing, as smaller particles can be more prone to dust formation and may require careful management during briquette production (Hansted et al., 2024). The low standard deviation values (0.56–0.60%) across all treatments indicate high reproducibility and uniformity in the experimental process. These findings imply that finer particle size not only increases the energy density of briquettes but also improves their combustion efficiency, as higher fixed carbon content is correlated with greater thermal stability and longer

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combustion time. This study highlights the importance of optimizing particle size in biomass briquette production to achieve superior fuel quality, in line with the increasing demand for sustainable and high-performance solid biofuels.

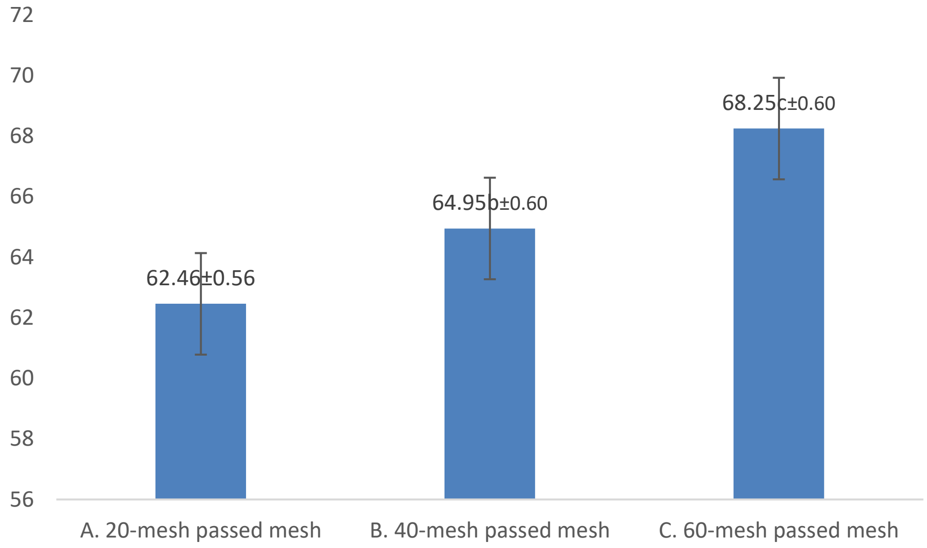

Figure 6. Fixed Carbon Content of Briquettes with Different Particle Sizes

CONCLUSION

This study demonstrates that particle size plays a crucial role in determining the quality of briquettes produced from hazelnut shell charcoal. The results show that finer particle sizes (60 mesh) enhance briquette density, compressive strength, and fixed carbon content while reducing moisture, ash, and volatile matter. These improvements contribute to better combustion efficiency and fuel quality, making hazelnut shell briquettes a viable renewable energy alternative. The findings provide valuable insights for optimizing biomass briquette production and highlight the potential of hazelnut shell waste in sustainable energy applications. Future research should explore the economic feasibility and large-scale implementation of this briquette production method to further support renewable energy development.

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