

STRUCTURAL OPTIMIZATION OF AGRO-INDUSTRIAL HAMMER MILL BLADES BASED ON FINITE ELEMENT SIMULATION AND EXPERIMENTAL VALIDATION

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ABSTRAK

Mesin hammer mill banyak digunakan untuk penggilingan bahan agroindustry. Namun geometri mata pisau dan pemilihan saringan yang tidak optimal sering menyebabkan konsentrasi tegangan berlebih, keausan dan distribusi ukuran partikel yang tidak merata. Penelitian ini bertujuan mengoptimalkan desain mata pisau menggunakan metode elemen hingga (FEM) dan memvalidasi performa desain terbaik melalui pengujian eksperimental dengan saringan 3 mm, 4 mm, dan 5 mm. Tiga desain dianalisis secara numerik pada kecepatan rotor 2700 rpm dengan gaya potong 31,392 N serta dilakukan evaluasi tegangan von Mises, perpindahan, regangan, dan faktor keamanan. Hasil simulasi menunjukkan bahwa Design 1 memiliki tegangan, perpindahan dan regangan terendah serta faktor keamanan tertinggi, menandakan stabilitas struktural dan ketahanan fatigue yang optimum. Hasil pengujian eksperimental menunjukkan bahwa saringan 4 mm memberikan keseimbangan optimal antara throughput, efisiensi energi dan kehilangan material yang minimal. Hammer mill yang dikembangkan beroperasi stabil dengan kapasitas 21 kg/jam dan performa mekanis andal. Integrasi optimasi berbasis FEM dan validasi eksperimental menyediakan kerangka ilmiah yang kokoh untuk sistem penggilingan agroindustry berbiaya rendah dan berperforma tinggi, sekaligus mendukung produksi berkelanjutan melalui pengurangan energi dan limbah, sejalan dengan SDG 2 (Zero Hunger) dan SDG 12 (Responsible Consumption and Production). Penelitian selanjutnya dapat mengeksplorasi optimasi rotor untuk berbagai jenis bahan baku dan implementasi kontrol adaptif kecepatan guna meningkatkan efisiensi energi.

Kata Kunci : agroindustry, metode elemen hingga, efisiensi penggilingan, hammer mill, optimasi desain.

ABSTRACT

Hammer mills are widely used for grinding agroindustrial materials. However, suboptimal blade geometry and sieve selection often lead to excessive stress concentration, premature wear, and uneven particle size distribution. This study aims to optimize hammer mill blade design using the Finite Element Method (FEM) and to validate the best-performing design through experimental tests with sieve diameters of 3 mm, 4 mm, and 5 mm. Three blade designs were numerically analyzed at a rotor speed of 2700 rpm under a cutting force of 31,392 N, evaluating von Mises stress, displacement, strain, and factor of safety. Simulation results indicated that Design 1 exhibited the lowest stress, displacement, and strain, along with the highest factor of safety, demonstrating optimal structural stability and fatigue resistance. Experimental validation revealed that a 4 mm sieve provided the best balance between throughput, energy efficiency, and minimal material loss. The developed hammer mill operated stably with a capacity of 21 kg/h and reliable mechanical performance. The integration of FEM-based optimization and experimental validation offers a robust scientific framework for developing low-cost, high-performance agroindustrial grinding systems, while supporting sustainable production through reduced energy consumption and material waste, in alignment with SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production). Future research may explore rotor geometry optimization for various feedstocks and the implementation of adaptive speed control to further enhance energy efficiency.

Keywords : agroindustry, finite element method, grinding efficiency, hammer mill, design optimization.

1. INTRODUCTION

The global agri-food system is entering a critical phase characterized by accelerating demand growth, climate pressure, and resource constraints. According to the Food and Agriculture Organization (FAO) ((FAO), 2023), global food demand is projected to increase by approximately 50–60% by 2050 to meet the needs of an estimated 9.7 billion people (Hamad and Tayel, 2026). Parallel to this trend, the OECD–FAO Agricultural Outlook (2023–2032) reports that global agricultural production must grow by nearly 1.3% annually to sustain rising consumption, particularly in developing regions. In the livestock sector, feed production has surpassed 1.2 billion metric tons annually, with Asia-Pacific showing the highest growth rate due to intensifying poultry, aquaculture, and ruminant industries (Alltech, 2024). Feed demand is expected to increase by more than 15% over the next decade as protein consumption rises in emerging economies. This surge in food and feed production intensifies reliance on mechanical size reduction processes to improve digestibility, homogenization, nutrient bioavailability, and downstream processing efficiency. However, size reduction is recognized as one of the most energy-intensive unit operations in agro-processing, often accounting for 20–30% of total processing energy consumption (Food and Agriculture Organization (FAO), 2022). Consequently, improving the efficiency and durability of grinding systems is not merely an engineering optimization task but a strategic requirement in achieving sustainable and resilient food production systems.

Hammer mills remain the dominant technology for agroindustrial grinding due to their structural simplicity, adaptability to various biomass materials, and relatively low investment cost. Extensive research has been conducted on hammer mill systems. Lubis *et al.* (2023) investigated the manufacturing process of hammer mill blades designed for a production capacity of 200 kg/h (Lubis, Darianto and Iswandi, 2023). Another study examined the effect of wheat impact on hammer mill blade wear (Iskandar *et al.*, 2016). In that investigation, the blade material was subjected to loading at six different points to identify the locations experiencing the highest wear

intensity. The operational principle relies on repetitive high-speed impact generated by rotating hammers mounted on a shaft, fragmenting material before passing through a calibrated sieve that controls particle size distribution (Guo *et al.*, 2016). Despite this mechanical simplicity, the internal phenomena governing hammer mill performance are highly complex. Rotating blades operate under severe cyclic loading conditions dominated by centrifugal forces, impact stresses, and dynamic vibration effects. These factors contribute to stress concentration, premature wear, fatigue failure, and inefficient energy transfer. Inefficient blade geometry can significantly increase specific energy consumption while reducing throughput and operational stability (Bitra *et al.*, 2009). Recent structural reliability studies on rotating components demonstrate that geometric optimization can reduce peak stress by up to 30% and extend fatigue life substantially (Krishna, Mudgala and Seth, 2021). Furthermore, simulation-driven redesign using Finite Element Method (FEM) has shown potential to mitigate localized stress concentration and reduce metallic contamination risks in agricultural grinding systems (Mohammed *et al.*, 2023).

FEM is a numerical technique widely employed to solve differential equations and complex physical problems by discretizing a complex domain into smaller, manageable elements (Tjong, 2021). FEM enables detailed analysis of mechanical phenomena occurring within structural components under various loading conditions. Previous research has demonstrated the effectiveness of FEM in determining the maximum load capacity of a European-manufactured MC22 hammer mill (Moiceanu *et al.*, 2019). FEM analysis can therefore be utilized to predict maximum stress and loading conditions in hammer mill blades. Following numerical simulation, Moiceanu *et al.* (2019) further conducted experimental investigations on a hammer mill used for agricultural product grinding with various blade tip design configurations to validate the simulation results (Moiceanu *et al.*, 2019). Nevertheless, most existing research isolates structural analysis from rotor dynamic assessment, fatigue life prediction, and energy performance evaluation, limiting the holistic

understanding required for sustainable system optimization.

In the context of global sustainability and energy transition, the optimization of grinding machinery must transcend traditional empirical redesign toward integrated, multi-domain engineering approaches. The food and feed processing sector is increasingly expected to contribute to decarbonization targets and resource efficiency improvements under global climate agreements. Sustainable Development Goal 2 (Zero Hunger) emphasizes the necessity of ensuring food security through productive and resilient agricultural systems, while Sustainable Development Goal 12 (Responsible Consumption and Production) calls for improved resource efficiency, reduced waste, and lower environmental footprint in industrial processes (Nations, 2023). Grinding systems with poor structural reliability and excessive energy consumption undermine these objectives by increasing operational costs, material losses and energy-related emissions. Despite the clear sustainability implications, a significant research gap persists in integrating structural optimization, fatigue life prediction, impact energy modelling and experimental statistical validation within a unified framework, particularly for small- to medium-scale agroindustrial hammer mills that dominate developing economies.

Addressing this gap, the present study proposes a comprehensive structural–dynamic–energetic optimization methodology combining finite element analysis, fatigue assessment (Goodman and Soderberg criteria), impact energy formulation and ANOVA-based experimental validation.

Unlike previous studies that mainly focus on either structural simulation or experimental milling performance separately, this study integrates finite element structural optimization, fatigue life assessment, impact energy modeling, and experimental statistical validation within a single framework. In addition, the study investigates the combined influence of blade geometry and sieve diameter on energy efficiency and throughput, which has rarely been evaluated simultaneously in small-scale agro-industrial hammer mills. Recent studies have highlighted the need for integrated design approaches to improve reliability and

energy efficiency of biomass grinding systems (Bhosle et al., 2025; Gaspar et al., 2025; Zhang et al., 2026). Therefore, this research provides a comprehensive optimization framework that links structural mechanics, process performance and sustainability considerations. By embedding mechanical reliability and energy efficiency within a sustainability-oriented design framework, this research contributes directly to advancing resilient agro-processing technologies aligned with SDG 2 and SDG 12, supporting global efforts toward food security, responsible production, and low-carbon industrial transformation.

2. METHOD

This study employed an integrated numerical–experimental methodology consisting of four main stages: (1) requirement identification and conceptual design of hammer mill blades, (2) structural simulation using the Finite Element Method (FEM), (3) fabrication of the optimal design, and (4) experimental validation and statistical analysis. The workflow was designed to systematically evaluate the influence of blade geometry on structural reliability and grinding performance. Numerical simulation was first conducted to identify the most structurally stable blade configuration, followed by experimental testing to validate milling performance under different sieve diameters.

The blade material was structural carbon steel ST37, with mechanical properties of ultimate tensile strength (S_{ut}) of 370 MPa, yield strength (S_y) of 235 MPa, elastic modulus (E) of 200 GPa, Poisson's ratio (ν) of 0.3, and density of 7850 kg/m³. These properties were used as input parameters in the finite element analysis. The test material consisted of dried corn with a moisture content of 12–14%, representing actual livestock feedstock. The research process began with identifying agro-industrial user requirements, including production capacity, product fineness, and operational efficiency. Based on these requirements, three geometric variations of swing hammer blade designs were developed using SolidWorks software. The prototype hammer mill has overall dimensions of 600 × 900 × 1100 mm and is powered by a 6.5 HP (\approx 4.8 kW) gasoline engine. The rotor is equipped with 18 swing-type blades and

accommodates three sieve variations with hole diameters of 3 mm, 4 mm, and 5 mm.

The overall research workflow is illustrated in Figure 1 to provide a clearer representation of the methodological steps.

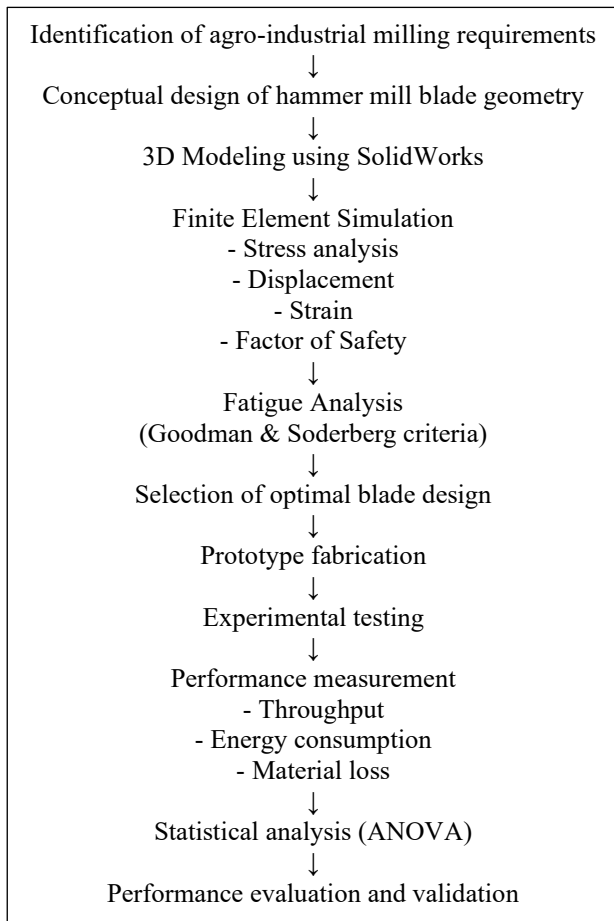


Figure 1. Research workflow for hammer mill blade optimization integrating FEM simulation and experimental validation.

Structural analysis was performed using the SolidWorks Simulation module based on the Finite Element Method (FEM) under a static structural analysis approach. The evaluation parameters included von Mises stress distribution, total displacement, strain, and factor of safety (FOS). Mesh refinement was conducted iteratively until numerical convergence was achieved to ensure simulation accuracy. Three blade design variations were developed by considering mass distribution, impact angle, and fillet radius to minimize stress concentration. Structural analysis was carried out at a rotational speed of 2700 rpm, accounting for centrifugal force and a cutting force of 31.392 N. The angular velocity was calculated using Equation (1).

$$\omega = \frac{2\pi N}{60} \quad (1)$$

where ω is the angular velocity (rad/s) and N is the rotor rotational speed (rpm). The centrifugal force is calculated using Equation (2).

$$F_c = mr\omega^2 \quad (2)$$

where m is the blade mass (kg), r is the radius of rotation (m), and ω is the angular velocity (rad/s).

The theoretical impact energy was calculated using Equation (3), where E_k represents the kinetic energy (J). The simulation outputs included von Mises stress, total deformation, and factor of safety (FOS).

$$E_k = \frac{1}{2}m(\omega r)^2 \quad (3)$$

Dynamic stability was evaluated by comparing the natural frequency and the operating frequency. The natural frequency was determined using an equivalent mass–spring approach, as expressed in Equation (4), where k is the equivalent stiffness (N/m) and m is the rotor mass (kg). The operating frequency was calculated as $f_{op} = \frac{N}{60}$. A safe operating condition is achieved when f_{op} is sufficiently distant from f_n , thereby avoiding resonance.

$$f_n = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \quad (4)$$

Fatigue life analysis was performed using the Goodman and Soderberg criteria (Marghitu, Diaconescu and Ciocirlan, 2001), as presented in Equations (5) and (6).

$$\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_{ut}} < 1 \quad (5)$$

$$\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_y} < 1 \quad (6)$$

where σ_a is the stress amplitude, σ_m is the mean stress, S_e is the endurance limit, S_{ut} is the ultimate tensile strength, and S_y is the yield strength.

The optimal design identified from the simulation results was fabricated and experimentally tested at a rotational speed of 2000 rpm with sieve size variations of 3–5 mm. Each test was conducted in triplicate to ensure data reliability. The measured parameters included output mass, processing time, and power consumption. The specific energy consumption was calculated using Equation (7), where P is the motor power (kW) and \dot{m} is the mass production rate (kg/h).

$$SEC = \frac{P}{\dot{m}} \quad (7)$$

Experimental data were analyzed using one-way ANOVA at a significance level of $\alpha = 0.05$ to evaluate the effect of sieve diameter on overall system performance.

3. RESULTS AND DISCUSSION

3.1 Structural Analysis Based on Finite Element Method

Three swing-type blade designs were developed to optimize grinding performance and structural stability. The designs varied in blade geometry, including mass distribution, impact angle, and fillet radius, to minimize stress concentration and deformation (Figure 2). All designs were modeled using SolidWorks and analyzed via Finite Element Method (FEM) under identical operational conditions: ST37 structural steel, rotor speed of 2700 rpm and a cutting force of 31,392 N. Design 1 was intended to maximize structural strength, Design 2 focused on a balance between weight and coverage, and Design 3 tested a simplified geometry for manufacturing efficiency. These variations allowed a systematic evaluation of stress distribution, total displacement, strain, and factor of safety to identify the optimal blade configuration.

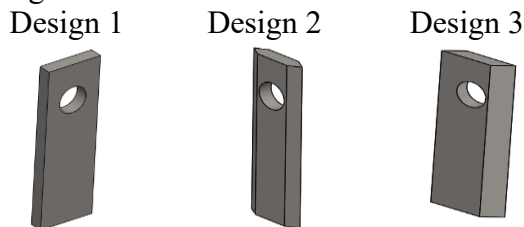


Figure 2. Hammer mill blade design variations

Table 1 presents the simulation results of the three hammer mill blade designs. The simulation results provided numerical values for each evaluated parameter, which are summarized in Table 2.

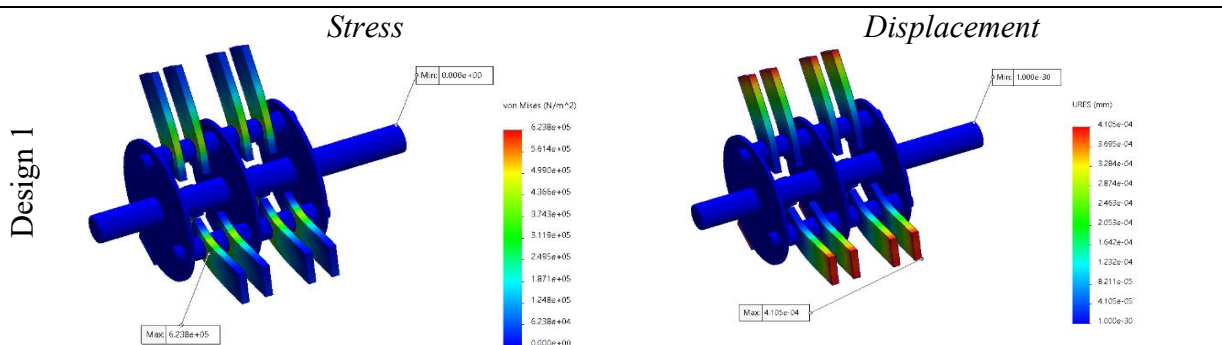
Table 2 summarizes the simulation results obtained from the FEM analysis for the three blade designs. The parameters evaluated include maximum von Mises stress, total displacement, equivalent strain, and factor of safety (FOS). These parameters were selected because they represent the key indicators of structural integrity and operational reliability in rotating impact components. Lower stress and deformation values indicate improved resistance to mechanical failure and reduced risk of fatigue crack initiation during high-speed rotation. Meanwhile, the factor of safety provides a quantitative measure of the structural margin between the operating stress and the material yield strength. Therefore, the comparison of these parameters enables identification of the blade geometry that offers the most stable mechanical performance under operational loading conditions.

Table 1. Simulation results of hammer mill blades

Parameters	Design 1	Design 2	Design 3
Stress (N/m ²)	6.23x 10 ⁵	1.23x 10 ⁶	3.21x 10 ⁶
Displacement (mm)	4.50x 10 ⁻⁴	1.15x 10 ⁻³	4.95x 10 ⁻³
Strain	2.32x 10 ⁻⁶	3.71x 10 ⁻⁶	1.05x 10 ⁻⁵
Factor of Safety	5.6 x 10 ²	2.5 x 10 ²	1.1 x 10 ²

The simulation results indicated that Design 1 exhibited the most uniform stress distribution, with a maximum von Mises stress of 6.238×10^5 N/m², substantially lower than Design 3, which reached 3.219×10^6 N/m². Stress concentrations in Design 3 were identified at geometric transition corners, potentially serving as crack initiation points. Design 1 also showed the lowest displacement and strain values,

Table 2. Simulation Results of Hammer Mill Blades



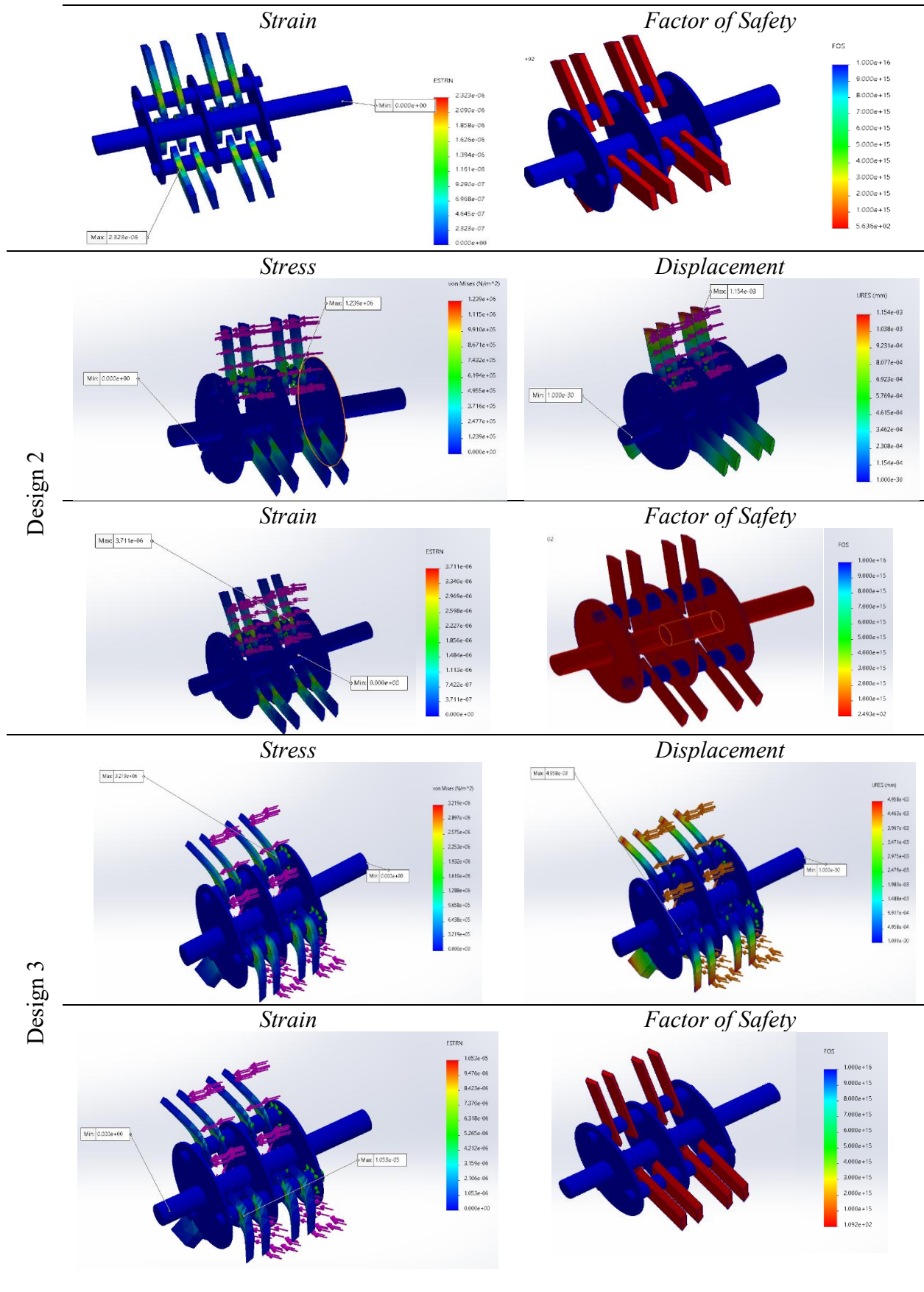


Table 3. Experimental Performance of Material Separation at Different Sieve Diameters

Sieve (mm)	Mean Output (g)	Mean Time (s)	Mean Loss (%)	Throughput (kg/h)	SEC (kWh/kg)
3	767	129.66	4.12	21.3	0.225
4	775.33	89.33	3.49	31.2	0.154
5	773.66	74.66	3.28	37.3	0.129

Table 4. One-way ANOVA results for sieve diameter effects

Parameter	Source	SS	df	MS	F	p-value
Throughput (kg/h)	Between groups	822.08	2	411.04	432.1	<0.001
	Within groups	2.85	6	0.475		
	Total	824.93	8			
SEC (kWh/kg)	Between groups	0.0218	2	0.0109	986.7	<0.001
	Within groups	6.63×10^{-5}	6	1.11×10^{-5}		
	Total	0.0219	8			
Material Loss (%)	Between groups	1.10	2	0.550	38.6	<0.001
	Within groups	0.085	6	0.0142		
	Total	1.185	8			

SS = Sum of Squares; df = Degrees of Freedom; MS = Mean Square; F = F-statistic; $p < 0.05$ indicates a statistically significant difference among groups.

indicating superior structural stiffness. The factor of safety of 5.6×10^2 demonstrates a very high operational safety margin. Mechanically, the geometry of Design 1 provides a more balanced mass distribution and impact angle, resulting in a homogeneous centrifugal force distribution. These findings are consistent with others researcher, who reported that optimizing impact rotor/hammer mill geometry can reduce stress concentrations (Doroszuk and Król, 2022; Bhosle *et al.*, 2025).

Overall, the simulation confirms that the FEM approach is effective in identifying the most structurally stable blade design prior to fabrication (Gaspar, Soares and Martins, 2025). Recent studies reported that structural redesign using FEM combined with experimental validation can significantly reduce stress concentration and improve operational efficiency in grinding machinery (Bhosle *et al.*, 2025; Gaspar, Soares and Martins, 2025; Ji *et al.*, 2025; Saygili and Çakmak, 2025).

3.2 Experimental Performance Analysis of Sieve Diameter Variation

The influence of sieve diameter on material separation efficiency and hammer mill performance was systematically evaluated, demonstrating that discharge configuration is a critical determinant of operational efficiency. As summarized in Table 3, at a 3 mm sieve, the mean output was 767 g over 129.66 s, with 4.12% material loss, yielding a throughput of 21.3 kg/h and a specific energy consumption (SEC) of 0.225 kWh/kg. Increasing the diameter to 4 mm slightly increased mean output to 775.33 g, while reducing processing time to 89.33 s and material loss to 3.49%, corresponding to a 46.5% increase in throughput (31.2 kg/h) and a 31.6% reduction in SEC (0.154 kWh/kg). Further enlargement to 5 mm maintained similar output (773.66 g), decreased processing time to 74.66 s, and reduced material loss to 3.28%, achieving the highest throughput of 37.3 kg/h and lowest SEC of 0.129 kWh/kg, representing an overall 43% energy reduction relative to 3 mm. These results indicate that particle retention and sieve resistance are primary bottlenecks, consistent with comminution theory that finer particle reduction requires exponentially higher energy. The Figure 3 illustrates the effect of sieve diameter

on grinding performance, comparing particle output and distribution for (a) 3 mm, (b) 4 mm, and (c) 5 mm sieve holes.

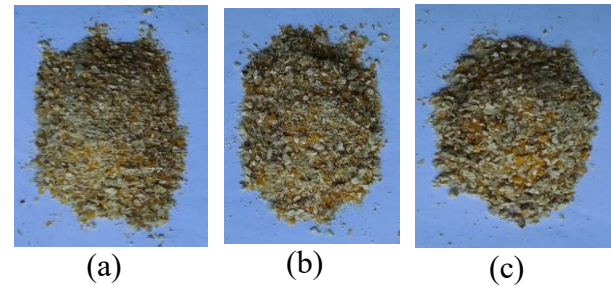


Figure 3. Grinding performance with sieve hole variations: (a) 3 mm, (b) 4 mm and (c) 5 mm

Regression analysis confirmed a strong negative correlation between diameter and SEC ($R^2 > 0.95$), while dynamic stability remained robust (Figure 4). From an engineering perspective, 3 mm favors maximum fineness, 5 mm maximizes energy efficiency, and 4 mm offers an optimal trade-off between throughput, energy consumption, material loss, and particle quality. This phenomenon is consistent with the energy–size reduction relationship model described by Kumar *et al.* (2023), in which particle size reduction is directly proportional to an increase in specific energy consumption (Kumar, Sahu and Tripathy, 2023). The observed SEC reduction and throughput enhancement have significant sustainability implications, lowering energy demand, CO₂ emissions, and production costs, and aligning with SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production). Overall, sieve diameter emerged as a dominant factor, highlighting that optimization must extend beyond blade geometry to include discharge configuration for high-efficiency, energy-conscious, and sustainable milling.

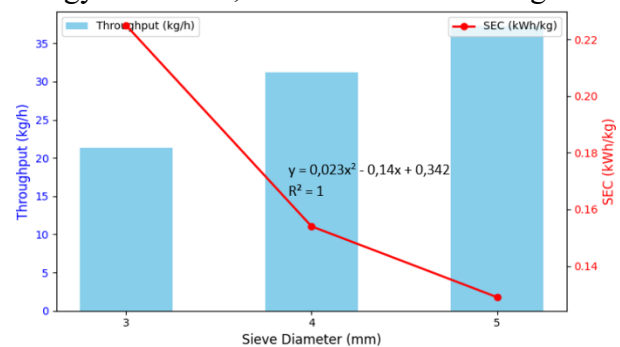


Figure 4. Effect of sieve diameter on throughput and specific energy consumption

3.3 One-Way ANOVA Analysis of Sieve Diameter Effects

A one-way ANOVA was conducted to assess the effect of sieve diameter (3, 4, and 5 mm) on hammer mill performance, including throughput, specific energy consumption (SEC), and material loss, at a significance level of $\alpha = 0.05$. Each treatment was tested in triplicate. The results indicate that sieve diameter had a statistically significant effect on all measured parameters (Table 4). Throughput increased significantly with diameter ($F(2,6) = 432.1$, $p < 0.001$), SEC decreased ($F(2,6) = 986.7$, $p < 0.001$), and material loss showed a slight but significant reduction ($F(2,6) = 38.6$, $p < 0.001$). Post-hoc Tukey's HSD tests confirmed that all pairwise comparisons were statistically significant. These results demonstrate that sieve diameter is a dominant factor in hammer mill performance, with a 4 mm sieve providing an optimal balance between productivity, energy efficiency, and product quality.

Discussion

The optimization of hammer mill blade design using the Finite Element Method (FEM) significantly enhanced structural stability and grinding performance. Among the three designs, Design 1 exhibited the lowest stress, deformation, and strain, along with the highest factor of safety. Fatigue life analysis based on the Goodman and Soderberg criteria confirmed that maximum alternating and mean stresses remained well below allowable limits, ensuring the blade can withstand cyclic centrifugal and cutting forces without failure, with the Goodman criterion providing a slightly more conservative estimate. Integration of simulation and experimental results further indicated that structural stability contributes to consistent particle distribution, with no plastic deformation or excessive vibration observed during testing, confirming FEM predictions of high blade resilience. Experimental validation demonstrated stable operation at a throughput of 21 kg/h, while sieve diameter strongly influenced process efficiency, product fineness, and energy consumption. Increasing the sieve from 3 mm to 5 mm raised throughput from 21.3 to 37.3 kg/h, reduced SEC from 0.225 to 0.129 kWh/kg, and slightly decreased material loss

from 4.12% to 3.28%. One-way ANOVA confirmed that sieve diameter significantly affected all parameters ($p < 0.001$), with post-hoc analysis indicating that all pairwise differences were statistically significant. These findings demonstrate that sieve diameter is a dominant factor in hammer mill performance, and that a 4 mm sieve provides an optimal trade-off between productivity, energy efficiency, and product quality.

The obtained results are consistent with recent findings reported in structural optimization studies of impact-based grinding machinery. For instance, Bhosle et al. (2025) reported that optimized geometric transitions and fillet radii can significantly reduce stress concentration in rotating mechanical components. Similarly, Gaspar et al. (2025) demonstrated that FEM-based redesign of hammer crusher components reduced peak stress and improved operational reliability in industrial grinding systems. The present study supports these findings by showing that Design 1, which incorporates improved mass distribution and smoother geometric transitions, achieved the lowest stress and deformation values. Compared with conventional hammer designs reported in previous studies, the optimized configuration in this work provides improved structural stability while maintaining efficient grinding performance.

In terms of energy efficiency, the observed reduction in specific energy consumption with increasing sieve diameter aligns with the comminution energy relationship described by Kumar et al. (2023) and more recent energy optimization studies in biomass milling systems. These studies highlight that finer particle size reduction requires significantly higher mechanical energy due to increased resistance and longer residence time inside the grinding chamber.

Overall, this integrative FEM–experimental approach establishes a scientifically robust and practically applicable framework for designing low-cost, high-performance agro-industrial grinding systems with structurally reliable blades, energy-efficient operation, and stable, scalable performance suitable for micro- and small-scale applications.

4. CONCLUSION

4.1. Conclusion

This study successfully investigated the structural performance and operational efficiency of agro-industrial hammer mill blades through finite element simulations and experimental validation. The results demonstrated that blade geometry and material composition significantly influence stress distribution, deformation, throughput, and specific energy consumption. Optimizing blade design using FEM not only improved mechanical performance but also enhanced process efficiency by reducing energy consumption and material loss. The findings provide valuable insights for both practical applications in agro-industrial milling and the development of predictive models for future design improvements. Design 1 demonstrated superior structural stability and fatigue resistance, while a 4 mm sieve achieved an optimal balance between throughput, energy efficiency, and minimal material loss. The integration of FEM-based structural optimization and experimental performance validation provides a reliable engineering framework for developing efficient and durable agro-industrial milling systems. These findings not only provide a scientifically robust framework for high-performance, low-cost agro-industrial grinding systems but also support sustainable production by reducing energy consumption and material waste, aligning with SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production).

4.2. Recommendations

Based on the findings of this study, it is recommended to further optimize hammer mill blade geometry and material selection through advanced FEM simulations and experimental validation, while exploring the development of predictive models to enhance energy efficiency and throughput in agro-industrial milling applications.

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