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Research Article

Optimizing Motor Power and Peripheral Speed for Enhanced Energy Efficiency in Barley Hammer Milling

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Abstract | Electricity is a scarce resource in many production regions, leading to energy waste in concentrated feed mills due to the underutilization of motor power. This research aims to reduce electrical energy consumption and improve productivity in barley milling a critical component for both livestock and poultry feed by determining the optimal peripheral speed and selecting the appropriate motor power. An experimental study was conducted using a commercial mill (200 kg/hr capacity) with two motor sizes (1.5 kW and 4.5 kW) and three hammer peripheral speeds (45, 56.4, and 78.9 m/s). The results showed significant electricity waste when using the 4.5 kW motor, as it operated at a partial load of only 24.5% far below the ideal 75% threshold. In contrast, the 1.5 kW motor achieved a more efficient load of 66.5%. Increasing the peripheral speed to 78.9 m/s significantly enhanced specific productivity, reaching 129.5 kg/kWh, and improved the hammer mill's mechanical efficiency. Economically, the combination of a 1.5 kW motor and high peripheral speed reduced grinding costs to 0.0076 $/hr. These findings provide a practical framework for optimizing feed production for the poultry and livestock sectors, ensuring maximum energy efficiency and reduced operational costs in resource-limited environments.

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Keywords | Electric motor, Electrical load, Hammer mill, Productivity, Poultry feed, Grain cost

Introduction

Providing electricity is difficult in remote desert areas where livestock are raised, leading to increased interest in using solar energy as a photovoltaic power source. However, several challenges hinder the adoption of solar energy, including cost (Khatib, 2012). This necessitates exploring solutions to reduce the cost of solar systems by using smaller-scale systems, resulting in lower construction and maintenance costs. One solution is to reduce the size of the devices powered by the solar system, thereby decreasing their electricity consumption and ultimately reducing the overall size of the solar system (Berlan *et al*., 2025).

The hammer mill is widely used in factories and small farms because it produces different grinding grades that meet the needs of rural families and their animals, as well as being easy to operate and maintain (Patterson and Kitto, 2020; Kitto, 2017; Braun *et al*., 2021). However, its high electricity consumption is a drawback, reaching up to 50% of total electricity consumption (Alvarez *et al*., 2020). It may consume 6 to 15 electrical units per ton of flour. In addition, the increasing global demand for animal feed for the agricultural sector in general, whose market value is expected to exceed billions of US dollars by 2030, is leading to intensified production in feed mills, which poses significant challenges regarding energy consumption and environmental sustainability (OECD, 2021; FAO, 2012).

The mill efficiency analyses rely solely on the classical equations mentioned in the scientific literature (Alvarez *et al*., 2020; Haijun *et al*., 2024). Research indicates that the net energy utilized for actual grain fragmentation in hammer mills represents only a small fraction of the total energy input, often less than 1%, with the remainder dissipated as heat and mechanical losses. Energy demand increases significantly with higher feed rates due to the increased mass flow within the grinding chamber. Furthermore, the initial power required overcoming rotational inertia and load resistance is substantially higher than the power needed to maintain stable operation at increased speeds. Consistent with recent findings, power requirements and current draw tend to stabilize or show improved specific efficiency as the mill reaches its optimal operating speed (Zhukovskiy *et al*., 2022). The terminal velocity of the hammers represents the linear speed at the hammer tip and is the point of greatest impact in grain crushing, where the maximum torque required to rotate the hammers is reached. On the other hand, changing the operating speed will increase milling productivity by reducing the raw material grinding time and will not lead to increased energy consumption (Zhukovskiy *et al*., 2022). Increasing the peripheral speed also increases the mill's productivity because the number of times the material is subjected to impact and crushing increases (Alkhoury, 2022; Khudher and Mishaal, 2022). This increase in speed at constant torque does not affect energy consumption. It reduces energy consumption due to the faster grain milling speed, thus lowering energy requirements. Mugabi *et al*. (2019) used hammer peripheral speed of 68.12, 81.81, and 102.17 m/s to determine the average geometric diameter of the grits and energy consumption. The results showed a significant effect of speed on these two parameters. The calculated impact energy per unit mass increased by 2.93, 4.23, and 6.60 MJ\t with increasing peripheral speed of 68.12, 81.81, and 102.17 m\s, respectively. However, the impact energy had no effect on the average geometric diameter. There is always a hammer speed that corresponds to the maximum efficiency of electrical energy use in the milling process (Adenigba and Oluwagbayide, 2021).

Hammer mill motors account for a significant portion of the monthly electricity bill. Often, these motors are incompatible or oversized for the load they are designed to serve. While there are no well-established engineering methods for accurately and reliably estimating motor efficiency (Yunhua *et al*., 2015). Replacing standard motors with energy-efficient alternatives requires optimizing mill efficiency and considering the partial load the ratio of actual load to full power output. Partial loads are typically estimated through power, current, or speed measurements. Although standard control systems manage motor operations in grain mills by maintaining nominal load current, they often fail to guarantee maximum electrical energy efficiency during the process (Kaya *et al*., 2022). Chausov *et al*. (2023), indicated that failure to adhere to the operating modes of the mill, which guarantee maximum efficiency in the use of electrical energy, may lead to excess consumption of up to 15% of electrical energy per unit mass of the final products.

Most electric motors are designed to operate between 50% and 100% of their full load. A motor's peak efficiency is typically around 75% of its full load. Motor efficiency tends to decrease significantly at partial loads below 50% of the design load. However, the optimal efficiency range varies among motors, and this range expands for larger motors. The more efficiently a motor utilizes its power, the greater its ability to rotate at its maximum design load, potentially up to 1.15 times in most electric motors (Van Wyk *et al*., 2009).

Loads in small hammer mills vary significantly based on grain type, specific gravity, and feed rate. Consequently, motors selected through design calculations often exceed actual operational requirements, leading to inefficient energy use. According to the U.S. Department of Energy (2014), it is recommended to avoid operating motors under overload conditions, particularly when voltage is below nominal levels, in high ambient temperatures (typical of arid regions), or when motor surfaces are fouled. This is critical if the mill operates for extended periods at less than 50% of its rated load. Therefore, this research aims to minimize electrical energy waste by optimizing motor size and controlling speed through experimental methods. This approach ensures maximum power utilization and enhances productivity per unit of energy consumed, providing practical recommendations for improving efficiency and identifying unutilized energy in barley flour production.

Materials and Methods

Hammer mill: A factorial experiment was conducted using a small commercial mill with a capacity of 200 kg\hr Table 1 during the summer in Basra city. The climatic temperature during the experiment ranged from 41-44°C.

Grains: Barley grains were used in the experiment. Barley grains were chosen because they are among the most difficult grains to grind compared to wheat, yellow corn, and white corn due to their fibrous, non-brittle nature (Wandels *et al*., 2021) Table 2.

Factors studied

The first factor: The power of the electric motor in the mill: two levels, 4.5 kW and 1.5 kW. Figure 1 shows the data plates of the two electric motors used in the experiment.

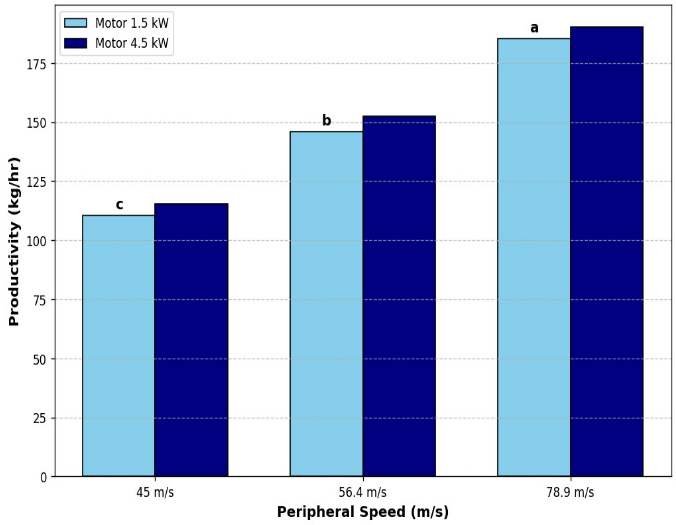

Figure 1: *Effect of hammer peripheral speed and motor power on the milling productivity of barley grains.*
Note: *Bars with different letters (a, b, c) indicate significant differences between peripheral speeds at P < 0.05 according to the Least Significant Difference (L.S.D) test.*

The peripheral speed of the hammer represents the linear speed in m\s (the circular path of the hammer tip away from the axis per unit time) and is calculated from Equation 1:

$$P.s = \omega \times 2\pi L \ldots (1)$$

P.s Peripheral speed (m\s), ω Rotational speed (RPM), L Distance from the center of the axis of rotation to the tip of the hammer (m).

Table 1: *Description of the hammer mill.*

Description	Details
Production capacity of the hammer mill	210 kg\h
Crushing chamber length x crushing chamber diameter	10 cm × 25 cm
Crushing wheel peripheral speed (linear velocity)	65 (m\s)
Number of hammers	10 hammers
Hammer dimensions	8 cm length × 5 cm width ×4 mm thickness, Toothed type
Clearance between hammer tip and screen	4 mm
Screen opening	2.5 mm circular
Feed opening diameter	5 cm
Screen outlet area	10 x 25 = 250 cm2

Table 2: *Physical and mechanical properties of barley grains used in the study.*

Grain type	Grain length mm	Grain width mm	Grain thickness mm	Mean arithmetic diameter mm	Weight of 1000 seeds g	Slip Angle D^O	Density kg/m^3	Surface Area mm^2	Relative humidity %
Barley	7.48	2.77	1.96	4	215.88	37	691.2	37.3	13

Table 3: *Specifications of the electric motors used in the experiment.*

Specification	Motor 1 (4.5 kW)	Motor 2 (1.5 kW)
Brand	—	YACHAN
Type / Model	YL100L-2-2	YL-90S-2
Rated power	4.5 kW	1.5 kW (2 HP)
Rated speed	2800 r/min	2830 RPM
Rated voltage	220 V	220 V
Frequency	50 Hz	50 Hz
Rated current	12.9 A	9.3 A
Insulation class	B	F
Protection degree	IP44	IP 44
Capacitance	250 µF / 250V	—
Production date	2023.11	2020.03

The three terminal speeds were obtained using the Equation 2 (Khurmi and Gupta, 2005).

$$NM \times DM = NC \times DC \ldots (2)$$

NM and DM are the number of motor revolutions and the diameter of the motor pulley. NC and DC are the number of hammer wheel revolutions and the diameter of the airport wheel pulley.

Studied responses

Partial load: This represents the percentage of power output from the motor (actually consumed during grinding) to the power input to the motor and is calculated from Equation 3 (U.S. Department of Energy, 2014).

$$Load = (EE/ (M\ P)) \times 100 \ldots. (3)$$

Where; Partial load (%). EE is the actual power utilized (consumed), calculated from Equation 4 (Evans *et al.*, 2021), and MP is the motor's rated power (4.5 kW, 1.5 kW).

$$EE= (I \times V \times PF \times COS\varnothing)/1000 \ldots (4)$$

Where; I electrical current, Amperes, V electrical voltage, PF Mechanical efficiency assumed to be 0.95; COSØ 1.73

This parameter is defined as Specific Productivity or Energy Use Efficiency (EUE). It represents the ratio of the total output (productivity) to the total electrical energy consumed during the milling process. This indicator is crucial for evaluating the technical performance of grain mills and optimizing energy utilization in agricultural processing (Wandels *et al.*, 2021; Haile *et al.*, 2022). It is calculated using Equation 5 as follows:

$$EUE = PC/EE \ldots\ldots(5)$$

Where; EUE is the Energy Use Efficiency (EUE) (kg\kwh), PC is the actual productivity of the hammer mill (kg\h) and is calculated from Equation 6 (Khudher *et al.*, 2022).

$$PC = W/T \ldots\ldots(6)$$

Where; W is the weight of the crushed grain (kg), T is the operating time (hours).

Hammer mill efficiency: It represents the percentage of actual mill productivity relative to theoretical mill productivity. Calculated from Equation 7 (El-Shal *et al.*, 2010).

$$\eta = (pc/pct) \times 100 \ldots (7)$$

Where; η, efficiency of hammer mill (%); Pct., theoretical productivity of hammer mill = (200 kg\h).

Milling cost: This is one of the variable costs that represent the cost of consuming the electrical energy needed to operate the hammer mill per hour. It is calculated from Equation 8, (Dhahir, 2025).

$$M\ cost = 1/\ PCs \times price\ of\ EU \ldots. (8)$$

Where; M cost, cost of consuming the electrical energy ($\h); EU, Electrical unit (kWh); Price of EU Electrical unit price = 0.0076 $

Preparing the hammer mill

Before conducting the experiments, the hammer mill was prepared as follows: A sieve with a 2.5 mm opening diameter was chosen, which is suitable for fine grinding required for the production of compressed feed (pellet) from the grains used in poultry feed. Furthermore, this diameter is more energy-intensive compared to larger sieve diameters. The feed opening diameter was chosen to be 2.5 cm to ensure the amount of grain entering the grinding chamber matches the maximum load the motor can handle, it was observed that during the mill's adjustment to the appropriate feed opening, the hammers experienced difficulty starting due to overload when the feed opening was too large, resulting in a large grain flow. Therefore, the feed opening was adjusted to half its capacity for both motors used in the experiments.

Experimental testing

Each operation was performed by placing a quantity of grain in the tank until it was completely full. The feed opening was opened to allow the grain to flow in, and during the milling process, the electrical current, voltage, and power factor was recorded. After the milling process was completed, the timer was stopped, and the time taken for milling was recorded. The quantity of grain coming out was also weighed to calculate the actual productivity. The motor, with a rated power of 1.5 watts (2 hp), had a rotational speed of 2830 rpm, which is similar to the rated speed of the motor, which was 2800 rpm.

Statistical analysis

Data were statistically analyzed using a completely randomized design (CRD) with factorial arrangement. Analysis of variance (ANOVA) and LSD test were performed at a significance level of 0.05 using statistical analysis software. The total number of treatments was 18 with replications (3 peripheral speed × 2 motor power × 3r), and a completely randomized design (CRD) was chosen to conduct the experiments on the treatments. The total number of treatments was 18 with replicates (3 Peripheral speed × 2 Motor power × 3r) and the completely randomized design (CRD) was chosen to conduct experiments on the treatments. The results were analyzed using SPSS.25 software.

Results and Discussion

Productivity analysis

The results in Figure 1 demonstrate a significant positive effect of increasing the peripheral speed on the mill's productivity ($P < 0.01$). As the speed was increased from 45 to 56.4 and then to 78.9 m/s, productivity reached its peak. Interestingly, the results did not show a significant effect of motor power on productivity, which suggests that increasing motor power, is unnecessary as long as the mill size and feed rate are constant. This is likely because the net power required for actual grain fragmentation is relatively small compared to the total power input.

Partial load and motor efficiency

The ideal partial load for an electric motor to achieve maximum efficiency is approximately 75%. As illustrated in Figure 2, motor power and peripheral speed significantly affected the partial load ratio ($P < 0.01$). Using the larger 4.5 kW motor resulted in a substantial decrease in the partial load, recording an average of only 24.5%, whereas the 1.5 kW motor operated at a more efficient average of 66.5%. These findings confirm that the 4.5 kW motor was oversized for the mill's capacity. This aligns with Jayamaha (2008), who noted that motors operating at less than 50% of their rated load fail to utilize energy efficiently.

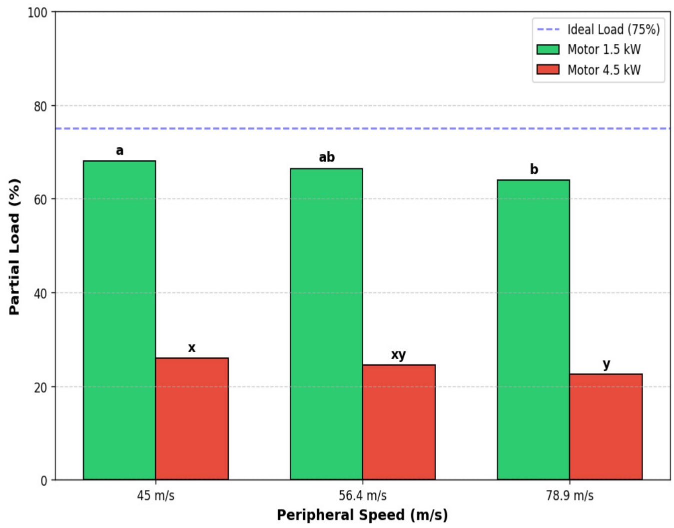

Figure 2: *Effect of hammer peripheral speed and motor power on the partial load percentage of the electric motors.*
Note: *Different letters (a, b, c) and (x, y, z) indicate significant differences in Energy Use Efficiency (EUE) between treatments at a significance level of P < 0.05. The letters (a, b, c) represent the comparisons for the 1.5 kW motor, while (x, y, z) represent the 4.5 kW motor.*

Energy use efficiency (EUE)

Increasing the peripheral speed significantly improved the Specific Productivity (EUE) as shown in Figure 3. The productivity reached 104, 119.6, and 129.5 kg/kWh at speeds of 45, 56.4, and 78.9 m/s, respectively. This improvement is attributed to the increased number of particle impacts, which reduces total grinding time and energy consumption (EE). This is consistent with El-Shal *et al.* (2010), who observed that increasing hammer speed increases the machine's productivity at a rate higher than the increase in power demand. Furthermore, Beshada *et al.* (2006) indicated that at high rotational speeds, energy requirements for crushing decrease as torque decreases.

Hammer mill mechanical efficiency

The analysis of mill efficiency is presented in Figure 4. Motor power and peripheral speed significantly influenced mechanical efficiency ($P < 0.01$). The 4.5 kW motor recorded the highest efficiency at 69%, while the 1.5 kW motor averaged 57.8%. The interaction effect was highly significant ($P < 0.001$); the highest efficiency (71%) was achieved at 78.9 m/s with the 4.5 kW motor, while the lowest (54%) was at 45 m/s with the 1.5 kW motor. These results suggest that while larger motors provide higher mechanical throughput, they must be balanced against the energy waste identified in the partial load analysis

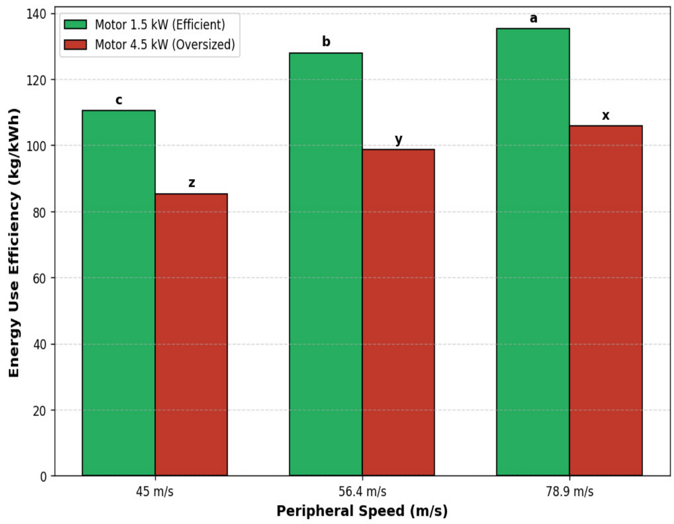

Figure 3: *Effect of hammer peripheral speed and motor power on the Energy Use Efficiency (EUE) during barley grinding.*

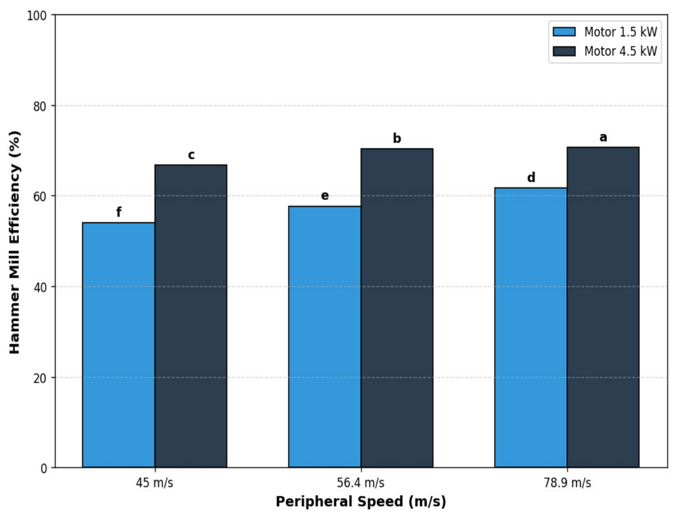

Figure 4: *Effect of hammer peripheral speed and motor power on the hammer mill efficiency (%).*

Note: *Different letters (a, b, c, d, e, f) above the bars indicate significant differences among all interaction treatments (motor power × peripheral speed) at a significance level of ($P < 0.05$) based on the L.S.D test.*

Grinding cost analysis

The economic implications are summarized in Figure 5. Statistical analysis showed that motor power and terminal speed had highly significant effects on the grinding cost, without a significant interaction. The 1.5 kW motor was more economical, recording a lower grinding cost of 0.0076 \$/hr compared to 0.0091 \$/hr for the 4.5 kW motor. Additionally, increasing the peripheral speed from 45 to 78.9 m/s reduced the cost from 0.0083 to 0.0076 \$/hr. These results confirm a direct relationship between motor power and cost, and an inverse relationship between peripheral speed and cost. Optimizing the speed not only enhances productivity but also significantly reduces the variable costs associated with electricity consumption in arid regions.

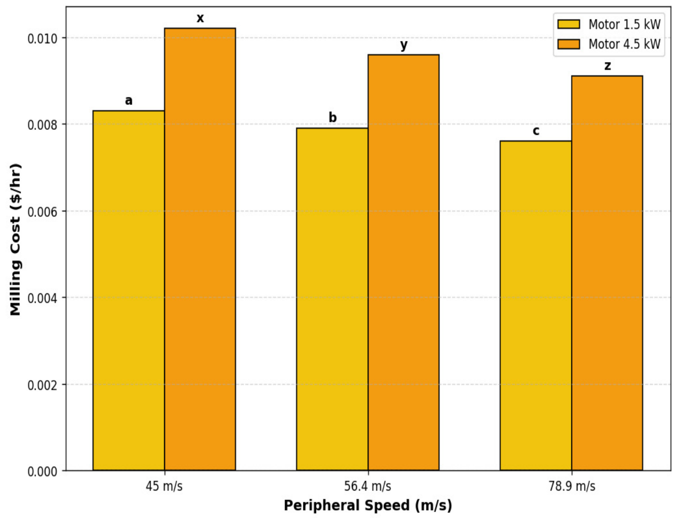

Figure 5: *Effect of hammer peripheral speed and motor power on the milling cost (\$/hr) for barley grains.*

Note: *Different letters (a, b, c for 1.5 kW motor) and (x, y, z for 4.5 kW motor) indicate that the decrease in grinding cost with increased peripheral speed is statistically significant at $P < 0.05$.*

Conclusions

The motors currently used in small hammer mills are significantly overpowered relative to the actual load required for grinding barley. The 1.5 kW motor operated at a partial load of 66.5% (only 8.5% below the ideal 75% threshold), whereas the 4.5 kW motor operated at only 24.5% capacity, indicating substantial energy underutilization.

Increasing the hammer speed provides a significant power surplus and improves grinding efficiency. The results confirm that operating at a high peripheral speed of 78.9 m/s maximizes productivity and energy use efficiency (EUE).

Specific productivity improved significantly as the peripheral speed increased from 45 m/s to 78.9 m/s for the 1.5 kW motor, reaching a peak of 129.5 kg/kWh, highlighting the importance of speed optimization in reducing energy demand per unit of output.

Although the 4.5 kW motor recorded a higher mechanical efficiency of 69%, this does not justify its use for small loads due to the excessive electrical energy waste and partial load mismatch identified.

From an economic perspective, the 1.5 kW motor is the most viable option. Utilizing the smaller motor at optimal speeds reduced grinding costs to approximately 0.0076 $/hr, saving nearly 0.0015 $/hr compared to the larger motor.

Recommendation

It is highly recommended to operate hammer mills at peripheral speeds of 78.9 m/s or higher. This speed maximizes productivity while significantly improving specific energy efficiency.

When selecting a motor for a small-scale mill (200 kg/hr capacity), preference should be given to motors with a rated power of 1.5 kW (2 HP) over larger, oversized motors. This ensures the motor operates within the ideal partial load range (near 75%), as illustrated in Figure 2, thereby avoiding unnecessary electrical losses.

Users in remote desert regions should adopt high peripheral speeds combined with appropriately sized motors to minimize variable grinding costs. This configuration provides the lowest operational cost per hour.

Future studies should investigate the relationship between maximum motor load, feed rates, and efficiency across different grain types (such as corn and wheat) with varying specific weights.

We recommend integrating variable speed drives (VFD) into small-scale mills to allow for precise control over peripheral speeds, ensuring the system maintains its peak efficiency under varying load conditions.

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Novelty Statement

Energy requirements, and consequently the size of the mill's motor, increase when using high terminal hammer speeds. This research determines the optimal terminal speed for barley grinding, thereby reducing electrical energy requirements and allowing for the selection of a smaller mill motor, which in turn lowers the cost of purchasing and maintaining the mill.

Author's Contribution

The first and fourth authors contributed to this manuscript by conducting the experiment, preparing the necessary equipment, and collecting the data. The second author contributed by developing the research idea, preparing the research plan, reviewing sources, and writing the text. The third author contributed by providing statistical analysis, data visualization, and tables.

Statement on generative artificial intelligence and AI-enhanced technologies

An AI analysis of all sections of this manuscript revealed no plagiarism.

Conflict of interest

The authors of this manuscript declare that they have no conflict of interest and no material or moral harm to research institutions.

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