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Maize grains milling efficiency: A performance analysis of a hammer mill

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Abstract

This study evaluated efficient milling of maize grains using a TW-cyclone series hammer mill. The assessment was conducted using two maize varieties—Quality Protein Maize (QPM) and SAMMAZ 11—at two moisture levels (13.5% and 16.5%) and two rotor speeds (950 rpm and 1050 rpm). A factorial experimental design was employed, and statistical analysis was conducted using ANOVA and Duncan's Multiple Range Test. Four output factors were analysed: throughput capacity, milling efficiency, fineness modulus, and estimated energy consumption. The results indicated that moisture content significantly influenced milling efficiency and fineness modulus, while rotor speed had a considerable effect on throughput capacity, fineness modulus, and energy consumption. The maximum throughput capacity of 152.9 kg/hr was achieved with QPM at a moisture content of 16.5% and a rotor speed of 1050 rpm. The SAMMAZ 11 variety produced the finest flour particles, with a fineness modulus of 2.76, under similar conditions. The highest milling efficiency, recorded at 80.79%, was observed with QPM at 13.5% moisture and a rotor speed of 1050 rpm. Conversely, the lowest projected energy consumption of 0.0564 kWh occurred with QPM at 13.5% moisture and a rotor speed of 950 rpm. Percentage contribution analysis revealed that rotor speed was the most influential factor affecting throughput capacity (97.84%), fineness modulus (75.47%), and estimated energy consumption (74.4%). In contrast, moisture content emerged as the most significant factor influencing milling efficiency (62.55%).

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Introduction

Maize (*Zea mays*) plays a crucial role in food security, as well as in economic and agricultural development. In Nigeria, maize is a staple crop that holds immense importance in the country's agricultural and economic systems (Asante *et al.*, 2017). It is highly valued for its nutritional composition, which includes approximately 72% starch, 9% protein, and 4% fat, making it a vital source of carbohydrates, proteins, and fats for both human and animal consumption (Basiouny and El-Yamani, 2016). Beyond its nutritional value, maize serves as a fundamental raw material for starch production and animal feed formulation, highlighting the need for efficient processing methods to meet growing demand (Sidhu *et al.*, 2016). The milling process is essential for converting maize grains into flour, a staple food product. This process enhances the usability of maize and meets industrial and consumer demands for quality flour (Bassey *et al.*, 2022). In rural Nigeria, maize flour production supports food security and the local economy by providing affordable food and employment opportunities for low-income households (Adejugbe, 2023).

Hammer mills are commonly used in Nigeria to grind and sieve grains such as maize, wheat, millet, and sorghum. Their widespread adoption is attributed to their simplicity, portability, and efficiency in processing a diverse range of crops (Jha and Sharma, 2010). These machines are particularly vital in rural areas, where smallholder farmers rely on cost-effective milling solutions to enhance food processing and increase crop productivity. Despite their significant advantages, challenges persist. Performance analysis, component modifications, and the design of affordable hammer mills tailored to local conditions (Adejugbe, 2023) are essential for optimizing milling operations. Ongoing research and development are critical for improving hammer mill efficiency and reinforcing their role in enhancing food security and agricultural development in Nigeria. Milling is energy-intensive, necessitating a comprehensive understanding of the factors that optimize performance and minimize energy consumption (Wang *et al.*, 2018). Critical factors include grain properties—such as variety, size, shape, and moisture content—as well as machine parameters, including rotor speed, screen size, and feed rate (Kaddour and Didamony, 2019). For example, it has been reported that higher moisture content increases energy consumption, while faster milling speeds improve throughput and flour fineness (Bucham *et al.*, 2022). A clear understanding of these variables and their interactions is essential for enhancing performance and improving process efficiency (Tong *et al.*, 2015). Performance metrics, such as throughput capacity, are influenced by feed rate, rotor speed, and maize characteristics (Felix and Francis, 2019). Milling efficiency measures the machine's ability to convert kernels into flour, with higher efficiency indicating less waste and better yield (Salama and Morad, 2019). The fineness modulus, which indicates flour particle size, is critical for determining quality, with lower values preferred for industrial applications (Jiang *et al.*, 2017). Energy consumption is affected by grain moisture, milling speed, and equipment type (Cappelli, 2023). In Nigeria, the challenges of grain processing are exacerbated by the inefficiency of milling equipment. Farmers and processors require cost-effective and efficient machines to meet the growing demands of maize production (Fu *et al.*, 2020). Hammer mills, known for their versatility in grain processing, offer a viable solution. However, their performance depends on factors such as grain variety, moisture content, feed rate, and tempering conditions (Feng *et al.*, 2019). Evaluating these factors is essential for understanding operational efficiency and optimizing their use in flour production (Yancey *et al.*, 2013).

This study evaluated the efficient milling of maize grains by assessing key performance metrics using a cyclone series hammer mill. The investigation focused on the effects of speed, variety, and moisture content on these performance metrics. The research aims to provide insights into the optimal operational conditions for maize milling. The findings are essential for improving milling practices, supporting small-scale milling operations, and enhancing food security in rural communities.

Materials and methods

The study employed a TW-Cyclone series hammer mill at Mika Corn Flours Kumbotso, Kano State, Nigeria, for the milling experiment. The experiment utilized two maize grain varieties: Quality Protein Maize (QPM) with an initial moisture content of 11.5% and SAMMAZ 11 with an initial moisture content of 12.3%. About 30 kg of maize grains were procured from Janguza market, Kano (Latitude: 11°57'39"N and Longitude: 8°22'48"E). The moisture content was measured using an electric balance and the oven-drying technique, following the ASABE standard S352.2. The grains were thoroughly sorted and cleaned to remove debris such as stones and chaff, then stored in airtight Ziplock bags.

Experimental design

The study adopted a full factorial design in a completely randomized layout with three independent variables at 2 levels each: maize variety (QPM and SAMMAZ 11), moisture content (13.5% and 16.5%), and rotor speed (950 rpm and 1050 rpm). Each treatment was replicated three times, resulting in 24 experimental runs.

Experimental procedure

The experimental procedure involved two key steps. Tempering the grains and adjusting the rotor speed of the hammer mill. Tempering was carried out to achieve desired moisture levels of 13.5% and 16.5%. The required quantity of water to adjust the moisture content was obtained from:

Water to add (g)= {(Desired moisture-Initial moisture)/(100-Initial moisture)}×(Weight of wheat) (1)

Grain samples, 1 kg for each experiment were prepared, placed in airtight Ziplock bags, and thoroughly mixed with the required quantity of water. These samples were then left to equilibrate to the target moisture content at room temperature (20°C–25°C). To adjust the rotor speed, the machine was configured by varying the pulley diameters. Using 4-inch and 5-inch pulleys, rotor speeds of 950 rpm and 1050 rpm were achieved, respectively. A digital photo tachometer (T21-147-162) was used in measuring the rotor speed. Milling was conducted under these conditions, with the milling time and output recorded for analysis.

Determination of throughput capacity

Throughput capacity is the mass of maize processed per unit time (kg/hsr). It reflects the efficiency and productivity of the machine in handling materials under specific operating conditions. It was determined using:

$$Q = \frac{M}{T} \qquad (2)$$

Where Q= the throughput capacity (Kg/hr), M= mass of mass of flour produced (kg) and T= milling time (hr).

Determination of milling efficiency

The efficiency in milling was determined as the ratio of the mass of flour produced to the mass of maize grains fed into the mill expressed as a percentage. It represents the percentage of flour yield obtained from the whole grain. It was computed using the relation:

$$\mathrm{E} = \frac{\mathrm{M_f}}{\mathrm{M_g}} \qquad (3)$$

Where *E*= the efficiency (%), M_f= mass of flour (Kg) and M_g= mass of grains (Kg).

This method follows the procedure reported by Nwaigwe *et al.* (2012); Mugabi *et al.* (2019).

Determination of fineness modulus

The fineness modulus is a measure of the uniformity of particle size in a milled product. It is calculated as the sum of the cumulative weight percentages retained on each sieve, divided by 100. A lower fineness modulus indicates finer particles, while a higher value signifies coarser particles. Particle size analysis was conducted using a set of standard sieves (4, 6, 8, 12, 16, 20, 30, 40, 50, 70, 100, 140, 200) along with a mechanical shaker (RX-29). The cumulative weights retained on each sieve were determined from the relation:

$$\%\ \text{retained in sieve} = \frac{\text{Weight of samples}}{\text{total weight}} \times 100 \qquad (4)$$

Determination of estimated energy consumption

The energy consumption of the hammer mill was estimated theoretically. The energy usage (kWh) was calculated by multiplying the milling time by the machine's power rating (4.8 kW). This approach was adopted to provide an approximate indication of the machine's energy usage as it was not feasible to measure the actual energy consumption due to the absence of required equipment.

Data analysis

Statistical analysis was conducted using SAS software. Analysis of Variance (ANOVA) was performed for individual responses and on three-factor combination to evaluate the effects of maize variety, moisture content, and rotor speed on throughput capacity, milling efficiency, fineness modulus and estimated energy consumption. Significance levels were determined based on P-values of 0.05 or lower.

Results and discussion

Analysis of variance

Analysis of variance was conducted at a 5% confidence interval (CI) to evaluate the significance and percentage contribution of control factors on the output. The results, presented in Table 1, reveal that rotor speed significantly affects throughput capacity, fineness modulus, and estimated energy consumption, while moisture content primarily influences milling efficiency, fineness modulus, and estimated energy consumption.

Table 1. Analysis of variance on individual variables

Variables	Source	DF	Adj SS	Adj MS	F-value	P-value	% contribution
Throughput capacity	Variety	1	0.450	0.450	0.320	0.580	0.033
	Speed	1	1318.490	1318.490	935.110	0.000	97.848
	Moisture content	1	0.360	0.360	0.260	0.618	0.027
	Error	20	28.200	1.410			
	Total	23	1347.490				
Milling efficiency	Variety	1	5.571	5.571	3.760	0.067	5.805
	Speed	1	0.721	0.721	0.490	0.493	0.752
	Moisture content	1	60.036	60.036	40.500	0.000	62.554
	Error	20	29.647	1.482			
	Total	23	95.975				
Fineness modulus	Variety	1	0.010	0.010	1.620	0.217	1.443
	Speed	1	0.500	0.500	84.950	0.000	75.469
	Moisture content	1	0.035	0.035	5.990	0.024	5.320
	Error	20	0.118	0.006			
	Total	23	0.662				
Estimated energy consumption	Variety	1	0.000	0.000	8.810	0.008	2.048
	Speed	1	0.000	0.000	304.620	0.000	74.403
	Moisture content	1	0.000	0.000	76.530	0.000	18.771
	Error	20	0.000	0.000			
	Total	23	0.000				

$P \leq 0.05$ indicate significant effects

The variety was significant only for estimated energy consumption. In terms of percentage contribution, rotor speed has the most significant impact on throughput capacity (97.84%), fineness modulus (75.47%), and estimated energy consumption (74.4%), followed by moisture content and variety. For milling efficiency, moisture content contributes the most (62.55%), followed by rotor speed and variety. Overall, rotor speed is identified as the most influential factor across the response variables. Given the observed individual effects, it is essential to conduct an additional ANOVA to assess the combined effects of factor interactions.

Analysis of variance for combines effects of factors

The results presented in Table 2 indicate a statistically significant difference in the treatment effects on the response variables at a 5% significance level, as all P-values are less than 0.05. This finding suggests that each treatment combination, across all interaction levels, significantly influences the response variables. However, to identify which treatment combinations yield the best outcomes for each dependent variable, a post hoc test is necessary. Therefore the Duncan multiple range test, which is recommended for this purpose, was conducted.

Post-hoc analysis for optimal factor combinations

The results of the Duncan Multiple Range Test for all responses are consolidated in Table 3. The table identifies the treatment combinations that maximized throughput capacity, milling efficiency and minimize fineness modulus, and energy usage.

Throughput capacity

The results of the Duncan Multiple Range Test indicated that the treatment combination V1S2Q2 achieved the highest throughput capacity of 152.90 kg/hr. This combination, which utilizes Quality Protein Maize (QPM) with a moisture content of 16.5% and a rotor speed of 1050 rpm, significantly enhances processing efficiency by reducing operational time and minimizing resource wastage, thereby improving productivity. These findings are consistent with previous studies, such as Dabbour *et al.* (2015), which underscored the significance of rotor speed and moisture content in increasing throughput capacity. Similarly, Martínez *et al.* (2017) highlighted the impact of moisture variations on milling performance and flour quality.

Table 2. Analysis of variance for combine effects of variables

Variables	Source	DF	SS	MS	F-value	P-value
Throughput capacity	Between groups	7	1340.73	191.53	452.94	0.00
	Within groups	16	6.77	0.42		
	Total	23	1347.50			
Milling efficiency	Between groups	7	90.47	12.92	37.54	0.00
	Within groups	16	5.51	0.34		
	Total	23	95.98			
Fineness modulus	Between groups	7	0.61	0.09	24.78	0.00
	Within groups	16	0.06	0.00		
	Total	23	0.66			
Estimated Energy consumption	Between groups	7	0.00	0.00	56.96	0.00
	Within groups	16	0.00	0.00		
	Total	23	0.00			

P ≤ 0.05 indicate significant effects

Table 3. Duncan's multiple range test for variables

Response	Recommended treatment (DMRT)	Performance value
Fineness modulus	$V_2S_2Q_2$	2.7640
Throughput capacity	$V_1S_2Q_2$	152.90
Milling efficiency	$V_1S_2Q_1$	80.794
Estimated energy consumption	$V_1S_1Q_1$	0.0564

Means for groups in homogeneous subsets are displayed

Fineness modulus

The findings presented in Table 3 indicate that the treatment combination $V_2S_2Q_2$—milling the Samaz 11 variety at 1050 rpm with a moisture content of 16.5%—yielded the finest flour particles, achieving a performance value of 2.764. This underscores the significance of higher rotor speeds and moderate moisture levels in producing finer grain particles. The fineness modulus reflects essential components of the flour, such as protein, starch, crude fibre, and ash, which are vital for the nutritional quality and functional properties of flour in food products (FAO, 2022). These results offer valuable insights into the optimal milling conditions for Quality Protein Maize (QPM).

Milling efficiency

The highest milling efficiency of 80.794%, achieved with the treatment combination $V_1S_2Q_1$ (QPM milled at 1050 rpm and 13.5% moisture), underscores the importance of optimizing operational parameters in small-scale milling. Milling efficiency is particularly crucial in rural Nigeria, where local millers face economic constraints and prioritize maximizing yield while minimizing costs (Olowonubi *et al.*, 2022). Optimal rotor speed and moisture content enhance milling recovery and support economic viability, addressing challenges commonly encountered in small-scale operations (Akanfe *et al.*, 2019; Komolafe *et al.*, 2017). These findings emphasize the potential benefits of adopting improved practices to increase efficiency, reduce resource wastage, and mitigate environmental impacts.

Estimated energy consumption

The treatment combination $V_1S_1Q_1$, which utilizes the QPM variety at 13.5% moisture content and a rotor speed of 950 rpm, was identified as the most energy-efficient option, with an estimated energy consumption of 0.0564 kWh. This finding is consistent with studies indicating that lower moisture content decreases energy requirements during grinding, while moderate rotor speeds enhance energy efficiency by optimizing the balance between input and output quality (Tumuluru and Heikkila, 2019; Jung *et al.*, 2018). This combination effectively balances energy savings and performance, making it a viable choice for efficient corn flour production.

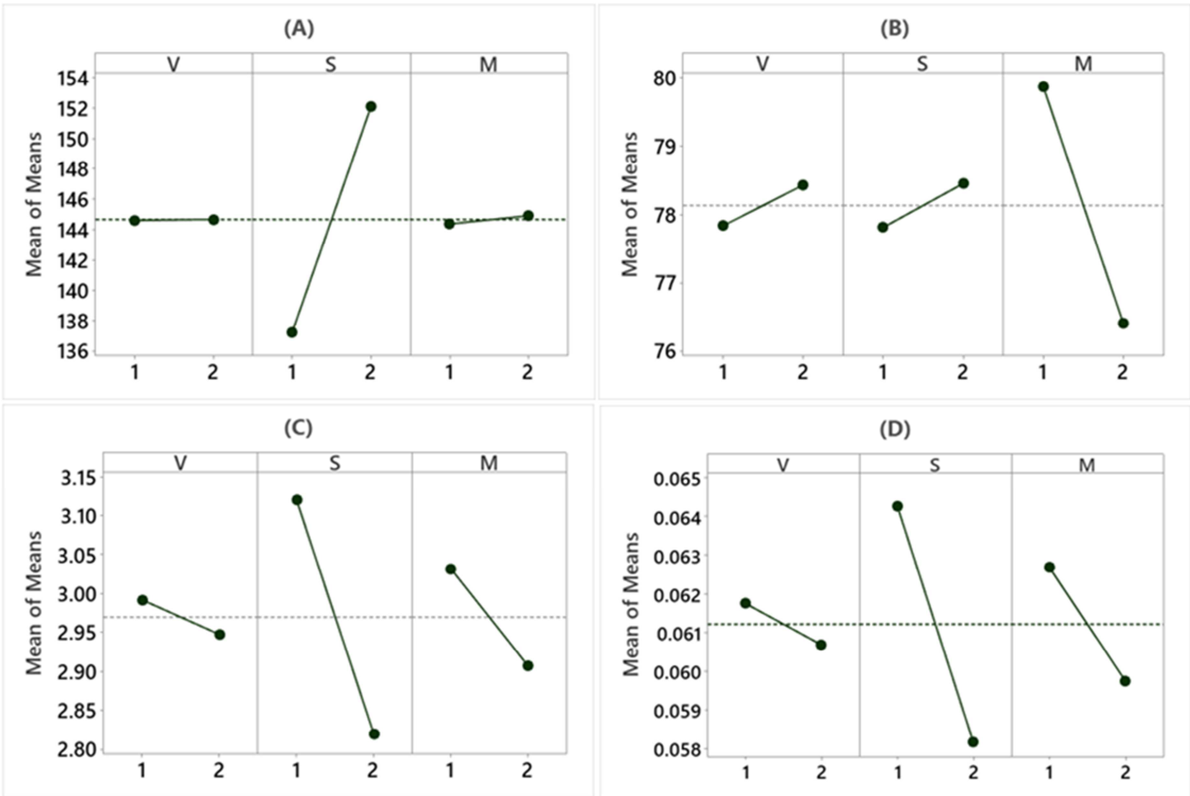

Fig. 1. Main effects plots of factors and levels on (A) throughput capacity, (B) milling efficiency (C) fineness modulus and (D) estimated energy consumption

Main effects of factors

The main effects of factors and levels on the response variables are clearly illustrated in Fig. 1. The throughput capacity of the machine was not significantly affected by changes in milling speed and moisture content; however, it was found to be higher when the variety changed from QPM to Samaz11. Conversely, while increases in milling speed and variety enhance efficiency, moisture content significantly reduces efficiency as it rises from 13.5% to 16.5%. All factors exhibited similar effects on fineness modulus and estimated energy usage. Both fineness modulus and estimated energy usage decrease with increases in milling speed, moisture content, and changes in maize variety. Since energy consumption is an estimated calculation, it is believed that higher milling speeds result in faster grinding, thereby reducing milling time.

Conclusion

The study reveals that rotor speed, moisture content, and maize variety significantly influence milling performance metrics. Rotor speed had the greatest impact on throughput capacity (97.84%), fineness modulus (75.47%), and energy consumption (74.4%), while moisture content was the most influential factor affecting milling efficiency (62.55%). Among all the independent variables, rotor speed emerged as the most critical factor.

The findings of this study may provide practical guidance for small-scale maize milling operations, where inefficiencies in milling often affect outcomes efficiency. Small scale maize millers can utilize these insights to enhance operational efficiency, improve the quality of maize flour, and contribute to strengthening food security within local communities.

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