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Research Article

Evaluating the Effects of Milling Speed and Screen Size on Power Consumed During Milling Operation

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ABSTRACT

This study was conducted to evaluate the effect of rotor speed and screen size on power consumed during milling operation. The milling system was tested using three fish feed ingredients; bone meal, groundnut cake and maize. The moisture contents of the ingredients bought from the market are 13.1%, 14.7% and 17.5% dry basis, respectively. The milling machine was evaluated with the 3 kg of each feed ingredient and was replicated three times for each of the experimental parameters. The machine parameters varied during the experiment includes four screen sizes (1.5 mm, 2.0 mm, 2.5 mm and 3.0 mm) and five rotor speeds (1500 rpm, 1800 rpm, 2100 rpm, 2400 rpm and 2700 rpm). Regression analysis was carried out on the data collated. The analysis was used to develop a model which is capable of predicting the electrical energy (kJ) consumed. There was no significant effect of screen size on the average power consumed during milling since there is no linear relationship between power consumed and screen size. However, there is a significant effect of speed on average power consumed, the power consumed increases as speed decreases therefore making milling operation at higher speed to be cost effective since it doesn't require much power to achieve the required output. The P-Value depicts that screen size has no significant effect on the electrical energy consumed during the milling operation while speed has a significant effect on the electrical energy used at 95% confidence level.

RESEARCH ARTICLE

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INTRODUCTION

In ancient times, cereal grains were crushed between two stones and made into crude cake. The advent of modern automated systems employing steel material such as hammer mills has revolutionized the processing of cereals and their availability as human foods and for other purposes (Donnel, 1983). Most of the existing hammer mill machines are designed for very large-scale production by the multinational companies such as breweries, feed mills and flour mills. But due to the recent sensitization of the public on the need for self-employment, there is an increase in small-scale companies. Thus, there is a very high demand for small-scale hammer mill machines (Adeomaya and Samuel, 2014). Nowadays there are increasing attempts to develop standard practical diets for farmed fish in Nigeria. A wide range of feed stuffs are produced as by-products from animal processing industries. Some of this feed stuffs are currently used in rations for both terrestrial animals and fish (Udo and Umoren, 2011). Since fish feeds are generally the largest single cost item of most fish farm operations, it follows that the selection of meal ingredients for use within diets will play a major role in dictating its ultimate nutritional and economic success (Ovie and Eze, 2013).

This project aims to alleviate the problems of peasant farmers in rural settlements and animal feed production companies, whose wish is to process their grain/cereal into animal feed at the minimum energy cost. Due to the exorbitant fee being levied as energy (power) tariff, some millers don't do adequate milling in order to cut down the energy consumed during the milling process, this recurrent behavior has led to production of feed with inappropriate particle size. The primary aim of this work is to evaluate the effect of milling (rotor) speed and screen size on the energy consumed during milling operation.

MATERIALS AND METHODS

Materials

The fish feed ingredients used for the performance evaluation were sourced from commercial feed milling centers (freedom feed mill and K2 feed mill) within Akure, Ondo State, Nigeria. The ingredients used are bone meal, groundnut cake and maize grain.

The Milling Machine

An existing milling machine was used to carryout the research. The milling system consists of the following components, the electric motor, transmission system, pneumatic system, hammering unit, screen, pressure relief unit, cyclone and the support frame.

Power unit: The system is driven by an electric motor of 10 hp which has a revolution of 2900 rpm.

Transmission system: It consists of shafts, pulleys and belts. The electric motor is the prime mover of the machine, as the pulley which is connected to the shaft of the electric motor is being propelled into action by the rotation of the electric motor; power is being transmitted from this pulley via a belt to another pulley which is connected to the shaft of the hammering unit.

Hammering unit: The hammering unit consists of four sets of hammers; each set is positioned on a role and each role has six hammers thereby making a total of 24 hammers. Individual hammers are of 5.1 by 7.2 cm.

Screen: The screens used for this research work are of varying aperture sizes; 1.5 mm, 2 mm, 2.5 mm and 3 mm.

Pneumatic system: The pneumatic system has a blower which positioned above the screen in the hammering unit. This blower consists of blades which are of 1.5 by 7.8 cm in dimension. The blower sucks the milled products which drops from the screen and subsequently transports the milled product pneumatically via the duct down into the cyclone.

Pressure relief unit: The air pressure in the pneumatically conveyed material is separated with the aid of the pressure relief fabric. The air pressure is able to escape through the fabric material while the milled particle dust gradually settles in the cyclone.

Bone meal Groundnut cake Maize

Figure 1. Fish feed ingredients.

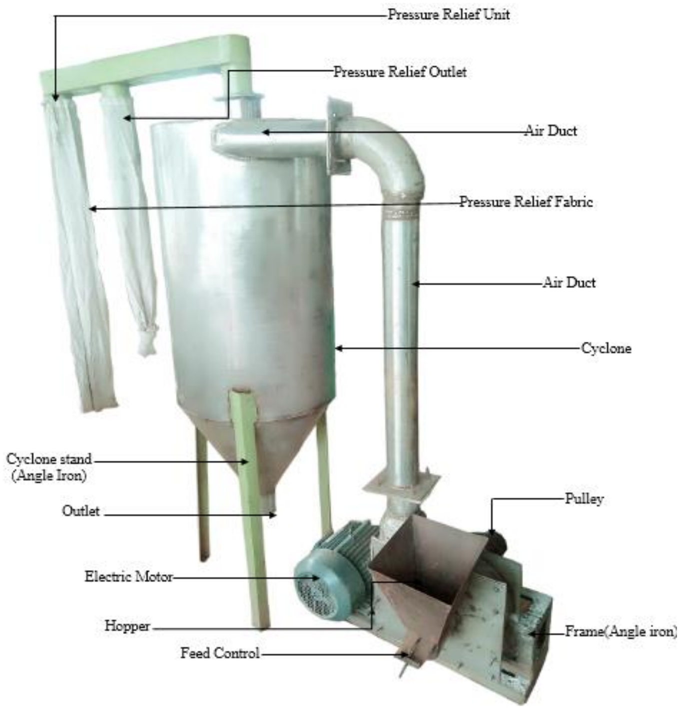

Figure 2. A milling system with pneumatic conveyor and cyclone.

Determination of average power consumed

A digital volt meter was used to measure the voltage consumed by the milling and mixing system during the period of operation of the machines, the voltmeter has accuracy specification of +/- 0.5% rdg and maximum input of 1000 VDC, 750 VAC for direct and alternating current, respectively. The ammeter used during the performance evaluation is a 3 phase, 4 wire, 10 (100) amps (whole current) electronic credit meter (Figure 3).

Figure 3. Measuring instrument (Ammeter & Digital volt meter).

Moisture content determination

An oven (Searchtech instrument DHG-9053A) was used to determine the ingredients moisture content.

Description of the dry oven

The drying chamber: This is the upper part of the mechanical dryer. It has a door, which is keyed to the top of the dryer, where the specimens are being loaded and off loaded. It allows contains four suspended sample baskets which are made of stainless steel. This is where the drying takes place. The base of the drying chamber is made up of perforated steel.

The heating chamber: This contains the heating element which is located at the lower part of the oven.

The centrifugal fan: This is attached to one side of the oven. It is operated by an electric motor. The fan sucks fresh air from the surrounding and blows it across the drying element which is located at the lower part of the dryer. The speed of the fan was regulated by electric voltage regulator.

The heating element: This serves as a source of heat for the dryer located at the lower part of the dryer. Heat is circulated into the drying chamber when the fan is blown across the heating element.

The exhaust: Also called the chimney, a square shaped hole on the top of upper part of the oven to allow moist air to leave, and regulate the airflow and temperature within the oven.

The drying layers: The drying layers are located inside the oven, they are made of stainless steel, and they are suspended inside the oven to ensure uniform drying.

Control panel: This is where the dryer is switched on and off. The heating element of the oven is trigged on from the switch on the control panel to pre-heat the oven to a certain air temperature before the agricultural product is introduced into the oven on the sleeve (Figure 4).

Figure 4. Laboratory oven (search tech instrument DHG-9053A).

Methods

Determination of machine speed

The milling and mixing machine was evaluated at five different speeds, in order to achieve the required speeds, the revolution per minute of the electric motor on the milling and mixing system needs to be reduced with the aid of pulleys. The pulley size required was determined with the equation bellow.

$$N_1 D_1 = N_2 D_2 \qquad (1)$$

Where: N_1 is speed of the driving pulley in rpm (speed of the electric motor)
D_1 is diameter of the driving pulley (mm), N_2 is speed of the driven pulley in rpm (speed of the hammering unit) and D_2 is diameter of the driven pulley (Pyarelal *et al.*, 2017) and (Aderemi *et al.*, 2020). The pulleys' diameters were measured with a venire caliper and the speed (2900 rpm, 10 HP) of the electric motor was specified on the electric motor by the manufacturer.

Pulley diameter

In order to achieve the required speed for the evaluation of the milling machine, it is imperative to vary the pulley diameters on the driven shaft. Below are the calculated pulley diameters and the corresponding speeds.

Table1. Required pulley diameter and the corresponding speed on the milling machine.

Pulley diameter (mm)	Speed (rpm)
145	1500
120	1800
105	2100
90	2400
80	2700

Determination of the ingredient's moisture content

The percentage moisture content of the ingredients was determined on dry basis.

$$MC = \frac{Ww - Wd}{Wd} \times 100 \quad (2)$$

Where:

W_w is weight of wet material

W_d is weight of dry material (Chambliss, 2002).

Table 2. Ingredients moisture content.

Ingredients	Moisture content (db)
Bone meal (BM)	13.1%
Groundnut cake (GNC)	14.7%
Maize (M)	17.5%

Evaluation of the milling machine

Masses of 3 kg of bone mill, ground nut cake and corn grain were measured using a mass balance and each of the samples measured was replicated three times. These measured samples in three replicates were milled respectively at five different speeds (1500 rpm, 1800 rpm, 2100 rpm, 2400 rpm and 2700 rpm) and four different screen sizes (1.5 mm, 2 mm, 2.5 mm, 3 mm). The time taken to mill the ingredients was recorded using a stop watch while the average milling time and machine output for the three replicates of each ingredient at various speeds and its corresponding screen size was calculated. The electrical power consumed during each milling operation was recorded with an electric meter and the corresponding average voltage was measured with a digital volt meter.

Determination of machine power consumption

i) To measure power requirement an ammeter was connected between the electric motor of the grinding mill and the electrical supply.

ii) The current taken up by the machine when there is no input of grain i.e. the idle current before commencement of milling process was measured using an ammeter.

iii) The feed was emptied into the milling machine at a constant feed rate. Meter readings were taken at every 5 seconds intervals until all the grains were milled. This was indicated by the meter reading when it goes back to the idle power.

iv) Voltage readings were taken using a voltmeter across the power supplies.

v) Power was obtained by using

$$p = (A \times V \times PF)/100 \quad (3)$$

Where:

P is the power (kW),

A is the current (ampere),

V is the voltage and

PF is the dimensionless power factor between (-1) and +1 generated respectively with grinding time read from the clamp meter.

The power factor of an electrical power system is defined as the ratio of the real power flowing to the load with the apparent power in the circuit (Norazatul *et al.*, 2015).

Electrical energy consumption during milling

The electrical energy consumption during milling was calculated using Eqaution (3).

$$E = P \times t \quad (4)$$

Where E is the energy (kWs with conversion of 1 kWh = 3600 kJ) and t is grinding time.

The specific energy consumption during milling operation was calculated using Equation (4).

$$Esc = \frac{input\ electrical\ energy; E(kj)}{weight\ of\ milled\ product\ (kg)} \quad (5)$$

Where: E_{sc} is the specific energy input (kJ kg^{-1}) (Norazatul *et al.*, 2015).

Statistical analysis

Milling performances parameters' values (average power consumed and electrical energy used during milling) were subjected to statistical analysis to determine the mean, standard deviation, coefficient of variation, linear and nonlinear regressions. One-way ANOVA was used to test for significance among the treatments and post hoc comparison using Tukey test to separate significantly differing treatment means after main effects were found significant at $p < 0.05$. The significance tests of the milling performances parameters' (average power consumed and electrical energy used during milling) of the main treatment effects (speed and screen size) and their interactions were performed using the Analysis of Variance (ANOVA) within the General Linear Model (GLM) procedure using Minitab 17 statistical software. Multiple Range Test (DMRT) was used to compare the mean at 95% confidence level.

RESULTS AND DISCUSSION

The Tables (3-7) below show the relatioship between varying milling speeds, mass of product (BM, GNCand MAIZE), screen sizes, milling time and pulley size and their corresponding effect on power consummmed during milling.

Table 3. Evaluation of the hammer mill at 1500 rpm.

Speed (rpm)	Mass of feed 3 kg (Mf)	Mass of product (kg) (Mp)			Milling time (minutes)	Power (kW)	Pulley size (mm)	Screen size (mm)
		GNC	BM	Maize				
1500	3	1.6			18	0.3	145	2
1500	3			1	12	0.25	145	2
1500	3		1.8		14.1	0.26	145	2
1500	3			1.8	18.01	0.28	145	1.5
1500	3	1.5			17.13	0.3	145	1.5
1500	3		2		15.2	0.27	145	1.5
1500	3		2.9		9.5	0.2	145	2.5
1500	3			2.3	19	0.4	145	2.5
1500	3	2.1			18.31	0.3	145	3
1500	3			2.1	17.1	0.3	145	3
1500	3		2.6		10	0.1	145	3
1500	3	2.4			17.03	0.3	145	2.5

Table 4. Evaluation of the hammer mill at 1800 rpm.

Speed (rpm)	Mass of feed 3 kg (Mf)	Mass of product (kg) (Mp)			Milling time (minutes)	Power (KW)	Pulley size (mm)	Screen size (mm)
		GNC	BM	Maize				
1800	3	2.9			9.3	0.23	120	2
1800	3			1.6	11.18	0.35	120	2
1800	3		2.9		5.01	0.1	120	2
1800	3	2.1			8.15	0.2	120	1.5
1800	3			2.3	6.01	0.1	120	1.5
1800	3		2.85		4.12	0.07	120	1.5
1800	3			1.7	12.17	0.2	120	3
1800	3	2.5			10.02	0.3	120	3
1800	3			2.2	4.3	0.1	120	2.5
1800	3		2.85		5	0.1	120	3
1800	3	2.5			4.45	0.1	120	2.5
1800	3		2.5		3.25	0.1	120	2.5

Table 5. Evaluation of the hammer mill at 2100 rpm.

Speed (rpm)	Mass of feed 3 kg (Mf)	Mass of product (kg) (Mp)			Milling time (minutes)	Power (kW)	Pulley size (mm)	Screen size (mm)
		GNC	BM	Maize				
2100	3		2.8		1.16	0.1	105	2
2100	3			2.7	2.15	0.1	105	2
2100	3	2.9			2.1	0.07	105	2
2100	3	2.7			4.4	0.1	105	1.5
2100	3			2.85	7.49	0.2	105	1.5
2100	3		3		4.03	0.1	105	1.5
2100	3			2.6	11.1	0.3	105	3
2100	3	2.1			8	0.1	105	3
2100	3		3		3.55	0.1	105	3
2100	3		2.7		2.35	0.1	105	2.5
2100	3			2	4.1	0.1	105	2.5
2100	3	2.6			3.58	0.1	105	2.5

Table 6. Evaluation of the hammer mill at 2400 rpm.

Speed (rpm)	Mass of feed 3 kg (Mf)	Mass of product (kg) (Mp)			Milling time (minutes)	Power (kW)	Pulley size (mm)	Screen size (mm)
		GNC	BM	Maize				
2400	3			3	3.02	0.1	90	2
2400	3		3		4.16	0.05	90	1.5
2400	3			2.6	9.01	0.1	90	1.5
2400	3	2.6			6.15	0.1	90	1.5
2400	3	3			3.3	0.1	90	3
2400	3			2.3	7	0.2	90	3
2400	3		3		3.14	0.1	90	3
2400	3		2.7		2.4	0.1	90	2.5
2400	3			2.7	3	0.1	90	2
2400	3		3		2	0.05	90	2
2400	3	3			1.56	0.1	90	2
2400	3	2.9			1.5	0.1	90	2.5

Table 7. Evaluation of the hammer mill at 2700 rpm.

Speed (rpm)	Mass of feed 3 kg (Mf)	Mass of product (kg) (Mp)			Milling time (minutes)	Power (kW)	Pulley size (mm)	Screen size (mm)
		GNC	BM	Maize				
2700	3		2.9		1.46	0.05	80	2.5
2700	3	2.95			2.45	0.1	80	2
2700	3		2.95		2.25	0.1	80	2
2700	3			2.75	3.18	0.1	80	2.5
2700	3			2.9	3.41	0.1	80	2
2700	3			2.85	6.02	0.1	80	1.5
2700	3		3		4.01	0.2	80	1.5
2700	3	2.9			5	0.1	80	1.5
2700	3		3		1.45	0.05	80	3
2700	3	3			2.07	0.06	80	3
2700	3			2.6	4.15	0.1	80	3
2700	3	2.87			2.03	0.1	80	2.5

Power consumed during milling

The chart (Figure 5 and 6) shows that there is no significant effect of screen size on the average power consumed during milling, this can be seen in the chart as it shows no linear relationship between power consumed and screen size. From the data gathered during the research in the tables above, Table (3-7) shows that screen size does not have a significant effect on the power consumed during milling. In table 3, 0.1 kW of power was recorded at all the screen sizes during some of the milling operations, same thing was obtained in Table 3, where 0.3 kW power was also recorded to be consumed during some of the milling operations carried out with all the screen sizes. It is also shown in Table 3 that the highest power (0.4 kW) consumed occurred at 2.5 mm screen. However, there is a significant effect of speed on average power consumed as it is shown in Figure 6, the power consumed increases as speed decreases therefore making milling operation at higher speed to be cost effective since it doesn't require much power to achieve the required output. It was observed during the process of the research that lower milling speeds takes more time to mill the same quantity of product when compared with higher speeds, this observation shows that power consumption during milling is a factor of speed and the retention time (duration of milling).

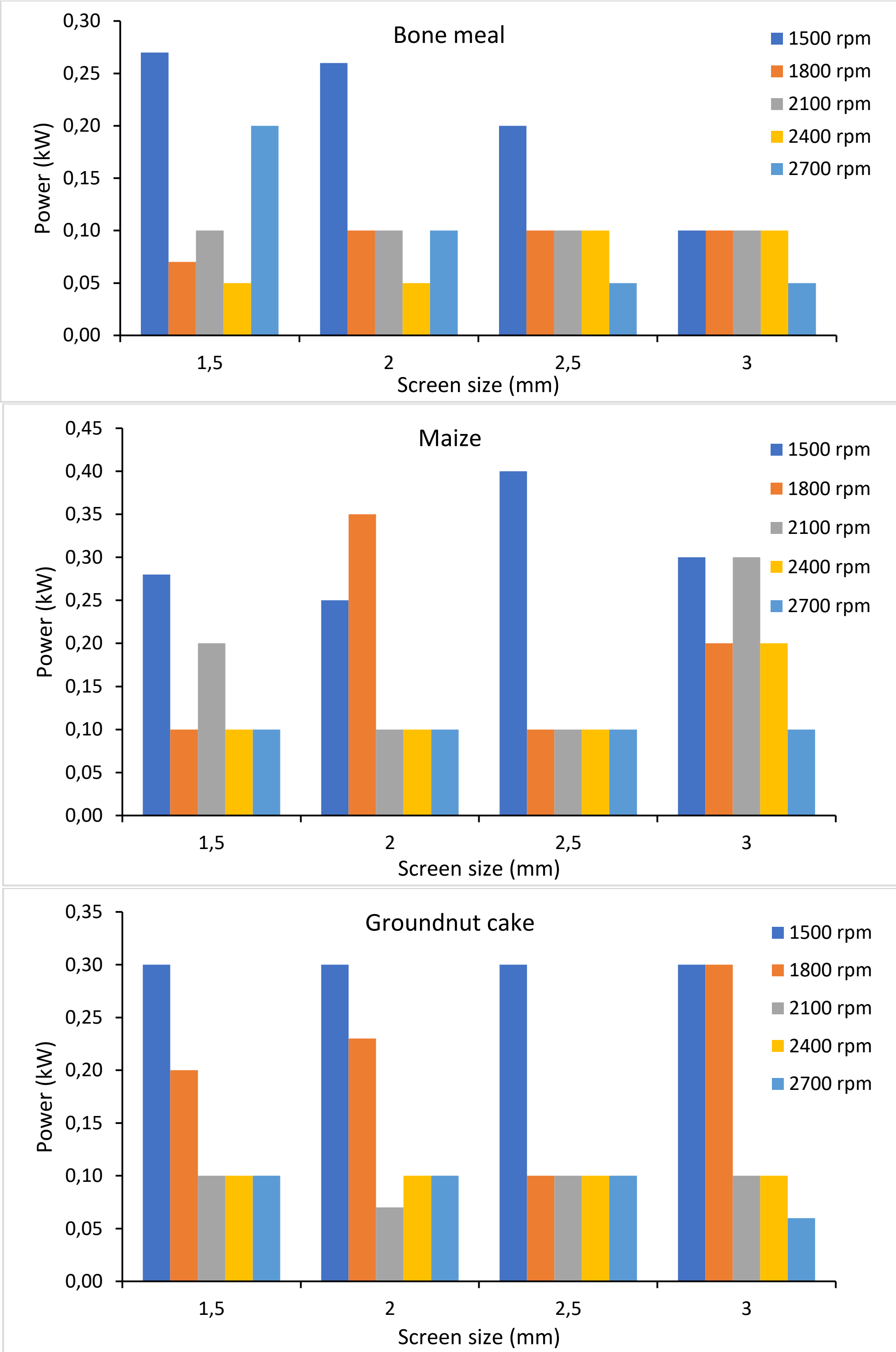

Figure 5. Effect of screen size on power consumed during milling.

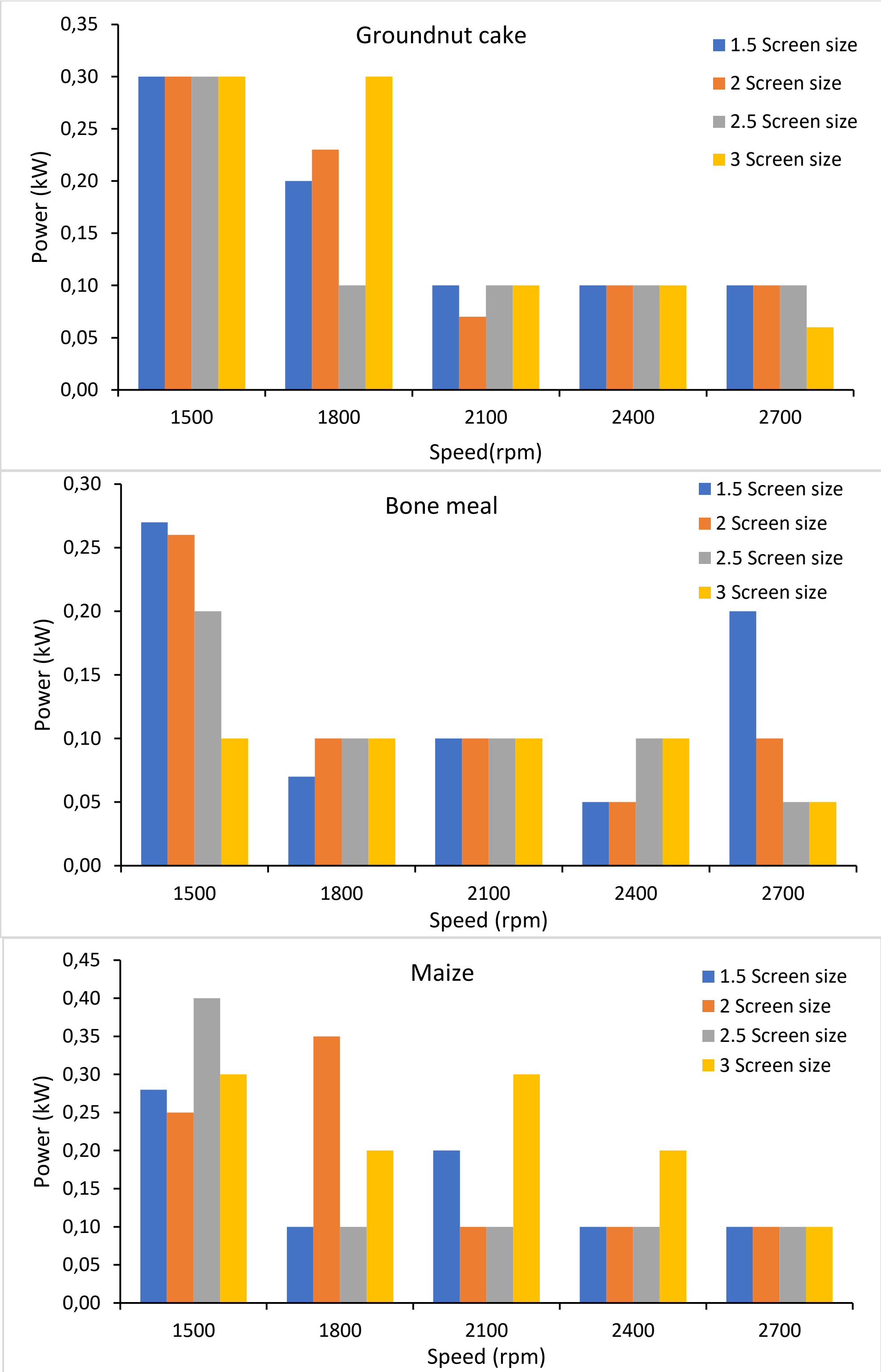

Figure 6. Effect of speed on power consumed during milling.

Effect of speed and screen size on electrical energy consumption

The effect of screen size and rotor (milling) speed was evaluated on the performance of a milling system, the tables below (Table 8) show the factors considered and Table 9 shows the level of significance of the factors. The P-Value depicts that screen size has no significant effect on the electrical energy consumed during the milling operation while speed has significant effect on the electrical energy used at 95% confidence level.

For more precise verification of the level of significance and the interaction differences between the various factors, the factors were subjected to Turkey and Bonferroni simultaneous test at 95% confidence level. Figure 8 shows the difference of means for electrical energy, there is a slight difference in the electrical energy consumed between (2400-1800 rpm) and (2400-1500 rpm) while there is significant difference between (2700-1500 rpm) and (2700-1800 rpm). Nonetheless, there is no significant difference when the effect of screen size was compared in Figure 9.

Table 8. Factor information (electrical energy).

Factor	Type	Levels	Values
Speed (rpm)	Fixed	5	1500, 1800, 2100, 2400, 2700
Screen size (mm)	Fixed	4	1.5, 2.0, 2.5, 3.0

Table 9. Analysis of variance (electrical energy).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Speed (rpm)	4	42549	10637	4.19	0.006
Screen size (mm)	3	5416	1805	0.71	0.551
Speed (rpm)*Screen size (mm)	12	56264	4689	1.85	0.073
Error	40	101573	2539		
Total	59	205803			

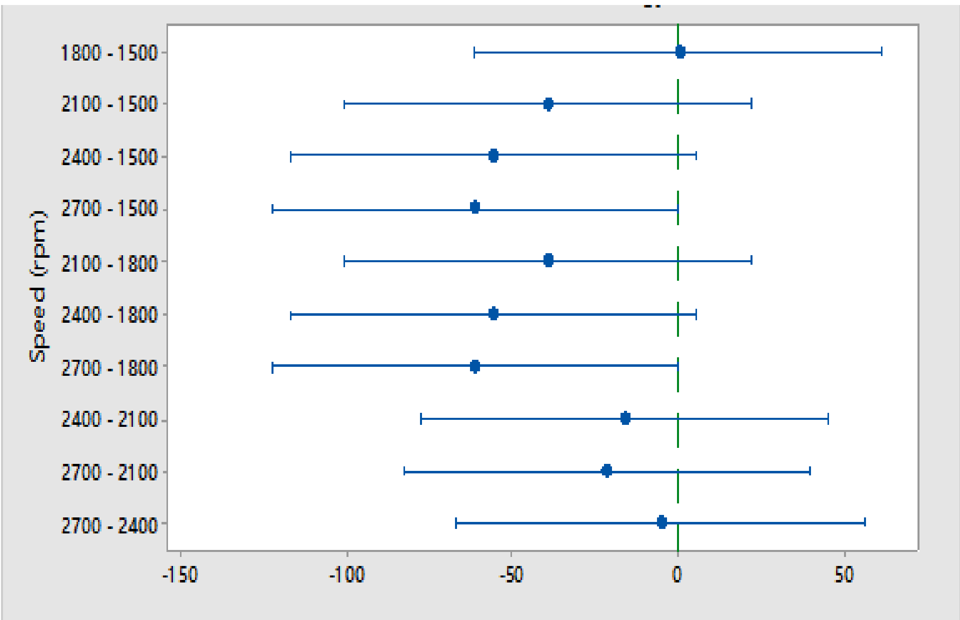

Figure 7. Differences of means for electrical energy (milling speed, rpm).

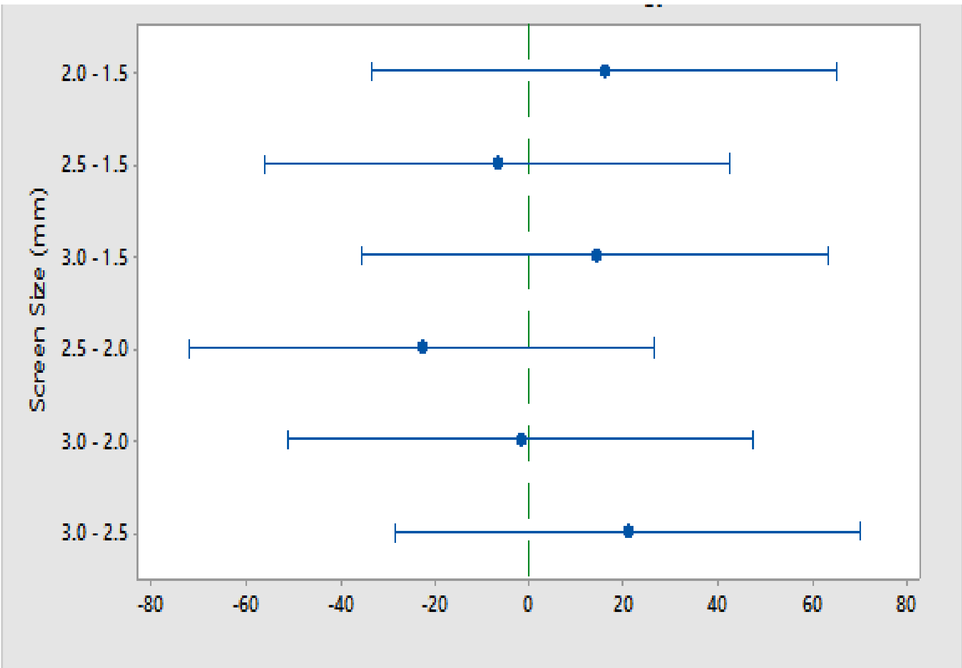

Figure 8. Differences of means for electrical energy (milling screen size, mm).

The electrical energy main effect plot in Figure 7 shows there is no significant difference in the electrical energy consumed between 1500 rpm and 1800 rpm and there is a subsequent decrease in the electrical energy used as the speed increase further. Figure 9 and 10 shows that screen size does not have a significant effect on the energy used.

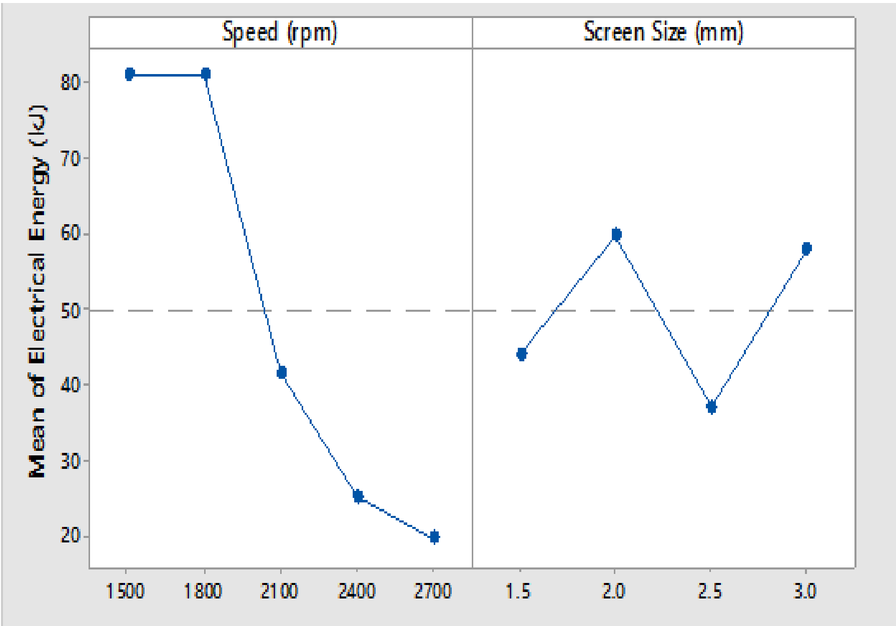

Figure 9. Electrical energy versus speed and screen size.

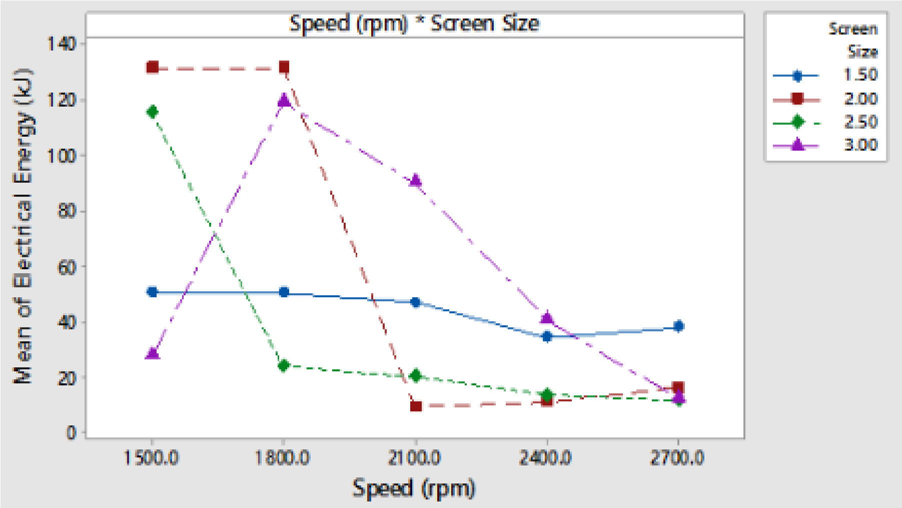

Figure 10. Effect of speed on electrical energy consumption (milling).

In Figure 9 above, it is shown that the electrical energy consumed reduces as speed increases, at lower speed more electrical energy is consumed because the ingredient spends longer time in the milling chamber before adequate milling is achieved.

Statistical model

Regression Analysis: Electrical Energy (milling) (kJ)

Table 10. Regression analysis: Electrical energy (milling, kJ).

Model No	Model Equation	R^2
I	16.9 - 0.0078Sp + 4.9Ss+ 5.61Mt	0.296
II	-510 + 0.467Sp + 5.5Ss+ 8.44Mt - 0.000107Sp²	0.344
III	-96 - 0.0033Sp + 100Ss+ 6.09Mt - 21.1Ss²	0.304
IV	-79.2 + 0.0045Sp + 8.8Ss+ 25.65Mt - 1.015Mt²	0.460
V	546 + 0.18Sp + 248Ss+ 24.9Mt - 0.00006Sp²- 80.7Ss 1.22Mt²+ 0.05Sp*Ss + 0.0018Sp*Mt + 2.44Ss*Mt	0.569
VI	-590 + 0.20Sp + 278Ss+ 42.2Mt - 0.00005Sp²- 77.3Ss²- 1.19Mt²+ 0.03Sp*Ss - 0.009Sp*Mt - 5.7Ss*Mt + 0.005Sp*Ss*Mt	0.573

Evaluation of the statistical models

Energy used during milling (kJ)

The model that best described data characteristic is the one that gives the highest R^2 as shown in Table 11 below with the lowest χ^2 and RMSE values. Based on these criteria, Model 6 is the best fit for the data with R^2, χ^2 and RMSE values of 0.57, 1504.03 and 38.45 respectively.

Table 11. Model of lowest χ^2 and RMSE values.

Models	R^2	MSE	RMSE	X^2
1	0.296	2413.650	49.129	2454.560
2	0.344	2249.820	47.432	2287.950
3	0.304	2388.450	48.872	2428.930
4	0.460	1852.440	43.040	1883.840
5	0.569	1480.910	38.483	1506.010
6	0.573	1478.960	38.457	1504.030

CONCLUSION

There is no significant effect of screen size on the average power consumed during milling since there is no linear relationship between power consumed and screen size. However, there is a significant effect of speed on average power consumed, the power consumed increases as speed decreases thereby making milling operation at higher speed to be cost effective since it doesn't require much power to achieve the required output. It was observed during the process of the research that lower milling (rotor) speeds takes more time to mill the same quantity of product when compared with higher speeds. This observation shows that power consumption during milling is a factor of speed and the retention time. The P-Value depicts that screen size has no significant effect on the electrical energy consumed during the milling operation while speed has a significant effect on the electrical energy used at 95% confidence level.

DECLARATION OF COMPETING INTEREST

The authors declare that there are no conflict of interest

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Ademola Adebukola Adenigba: Conceptualization, methodology, investigation and writing of the original draft.
Samuel Dare Oluwagbayide: Data analysis and edting of drafted copy.

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