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DESIGN, FABRICATION AND TESTING OF AN ENGINE DRIVEN GRAIN SIZE REDUCTION MACHINE

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Abstract: The size reduction of food materials increases the efficiency of the processing operations by reducing processing time and energy requirements. By breaking down ingredients into smaller particles, the overall mixing, blending, and cooking processes become faster and more efficient. Mostly, this operation is carried out using an electrically powered attrition disc, an electric blender, or a hammer mill. The major challenges associated with these electricity-powered machines include a lack of power supply in rural communities and contamination of the product by the machine parts, since the machine parts are made of mild steel materials. An engine-driven grain size reduction machine was designed, constructed, and tested in order to solve these issues. To develop the machine, material selection, critical design analysis, and calculations were all carried out. Response surface methodology (RSM) using a central composite rotatable design (CCRD) was used for performance testing of the machine settings. The independent variables were varied as follows: speed as 1800 rpm, 2000 rpm, 2500 rpm, 3000 rpm, and 3200 rpm, and moisture content as 10.4, 11, 12.5, 14, and 14.5%. Shearing efficiency, throughput capacity, and final product texture are the dependent variables that are measured. Thirteen runs were conducted in the experiments. The findings demonstrated that the machine can produce materials with the finest texture and shearing efficiency at a speed of 3000 rpm and a grain moisture level of 11%, respectively, with a throughput capacity of 99.86% and 348.6 kg/h. Conversely, materials with a coarse texture and shearing efficiency and throughput capacity of 39.17% and 135.17 kg/h, respectively, were produced when a speed of 2500 rpm and a grain moisture level of 14.62% were combined. It is anticipated that the machine's output will enable it to tackle the issues of inadequate electricity and product contamination related to existing attrition disc grinding machines, ultimately leading to increased agricultural productivity and improved living conditions.

Keywords: Design, fabricate, test, reduction, mill.

1.0 Introduction

The process of reducing large solid unit masses of chemical substances into small unit masses of either fine or coarse-textured particles is known as size reduction. The food and pharmaceutical industries frequently use size reduction techniques. Grinding and comminution are other names for size reduction (Rakesh 2008). Milling is the mechanical reduction of a solid's particle size. In order to produce very small particles, size reduction is also crucial for size separation (Sahishna 2022). The size reduction machine finds extensive applications in both household settings for domestic purposes and in the food processing industry. Its primary functions include the mixing, crushing, and cutting of biomaterials, thereby transforming them into smaller particles. There are many types of size reduction equipment, which are often developed empirically to handle specific materials and then are applied in other various situations. According to Sushant (2013), size reduction is primarily done in the materials processing sector to increase the surface area per unit volume of the particle. To reduce a substance to a very small particle size, separate the valuable amongst the two constituents, accomplish intimate mixing, and separate the valuable components of a mixture. Shear, compression, and impact forces are all part of the size reduction mechanism. Impact happens when something moves quickly and strikes a stationary object, or when something is moving quickly and collides with a stationary object. As reported by Sahishna et al. (2022), attrition occurs when two particles with high kinetic energy collide or when a high-velocity particle experiences a standstill period. When a particle is crushed between the tangentially moving edges of two hard surfaces, shear occurs. In compression, the material is crushed by applying pressure in order to reduce its size. Crushing machines, grinders, ultra-fine grinders, and cutting machines are some of the equipment used in size reduction. Crushers are slow-moving devices used for the coarse reduction of substantial amounts of solid material. Crushing is the initial stage of mineral processing. They can shatter big chunks of hard material because they work through compression. The range of particle sizes is 150–250 mm. It's mostly used to split big chunks of solid material into smaller lumps. Primary and secondary crushing are the two stages of crushing that determine how crushers are categorized. The jaw crusher, gyratory crusher, and roll crusher are the different types of crushers. Any power tool or machine tool that is used to grind particles between the sizes of 74 and 350 micrometers is called a grinder (Paul 2020). The mechanical forces of rock, including impaction, compression, shearing, and attrition, are employed in the powdering or pulverization process known as grinding. Hammer mills, rolling compression mills, and ball mills are examples of grinder types. Ultra-fine grinding techniques are a new class of mining equipment that produces fine powder, micro powder, and other materials with a lower energy consumption than traditional milling techniques in the sub 100µm range (Schutyser 2021).

The cutting machine operates on the principle of cutting and can be used with single-point or multi-point tools (Syed 2021). Size reduction in the cutter mill entails repeatedly cutting or shearing the feed materials with the use of sharp blades. These are the types of mills that are frequently used in laboratories to reduce the initial size of tough, fibrous, soft, and medium-hard materials. Cutting mills should be handled carefully since the metal from the blades and screens can contaminate samples that have been finely reduced. These types of mills are useful for pulverizing dried bones, grains, etc. A cutter mill has a horizontal rotor with several knives fixed to it that rotate against a set of stationary knives fixed to the mill case (Denis, 2021).

Despite the significance of these machines in food processing, they have some major drawbacks, which include a lack of power supply in rural communities, a high cost of the imported machines, and contamination of the product by the machine parts, which results in a high mortality rate due to the consumption of trace metals in the food. There has been an increase in the local fabrication of food processing equipment using materials that are not stainless steel, thus reducing cost, making these attractive to the food processing needs of rural small-scale farmers, mainly due to price considerations. But these materials caused food contamination (Stanley et al. 2011). According to Abdolshahi and Shokrollahi (2020), food contamination can be introduced in processing when appropriate materials are not used in the development of machines or tools for food production and are not well maintained. In Nigeria most of these size reduction machines are powered by electricity. But power instability in Nigeria has become a problem among agricultural food processors. According to a report of manufacturers association of Nigeria (MAN) survey in 2006, most of the industrial areas around the country suffered an average of 14.5 hours of power outage per day against 9.5 hours of supply, and the cost of production associated with the use of alternative source of power (generator sets) constitute 36% of total cost (Okafor, 2008). The present presentation is on the design, fabrication and testing of an engine driven grain size reduction machine.

Materials and Methods

Machine Description

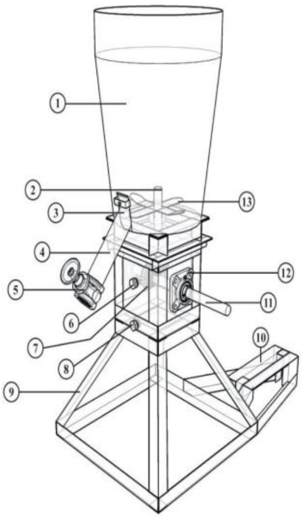
The machine is made up of the following component shown in Figure 1.

i. The frame serves as the structural support for all the machine's components. It is constructed from 2mm-thick mild steel angle iron, providing the necessary stability and durability. It has a height of 300mm and a horizontal base measuring 790mm, ensuring a robust foundation for the machine.

ii. The hopper contains biomaterial before and during the shearing or cutting process. It is used for continuous supply of the biomaterial to the shearing unit. The hopper was selected in order to allow easy flow of the biomaterial introduced. into the shearing unit. iii. The shearing unit consists of mild steel blades that are 90mm long and 4mm thick. The shearing unit is the place where the biomaterial is being sheared or cut by the rotating blades and falls through the collecting unit.

iv. The gearbox is rectangular in shape, with a length of 200mm, a breadth of 200 mm, and a height of 220mm. It is made of 2mm thick angle mild steel iron, 4mm and 2mm thick mild steel plates, oil seals, sets of bevel gears, galvanized 1/2 elbow, bolts and nuts, bearings, and shafts. The bearings help keep the shafts that are attached to the bevel gears in balance and help make the motion steady and smooth. The shafts that are attached to the bevel gears in the gear box are extended in both vertical and horizontal directions. The extended shaft in the vertical direction is connected to a pulley, while the shaft in the horizontal direction is connected to the blades in the shearing unit.

v. The outlet unit is made up of a 2-inch galvanized pipe inclined in one direction to allow the material to flow to the collecting tray. It has been shutter knotted with the aid of a bolt and nut with a 2-inch valve attachment.



LEGEND

ITEM NO.	PART NUMBER
1	Hopper
2	Vertical shaft
3	Shutter
4	Outlet pipe
5	Valve
6	Oil level gauge
7	Bevel gears
8	Oil drainage
9	Frame
10	Prime mover seat
11	Horizontal shaft
12	Pillow bearing
13	Size reduction blade

Figure 1. Isometric view of the Grain size reduction machine

Plate 1. Developed Grain Size Reduction machine

Design of the Major Parts of the Equipment

Determination of Volume of Hopper

The volume of the hopper was determined as reported by Gana (2016), and is given as follows;

$$V = \frac{m}{\rho} \quad (1)$$

$$V = \frac{1}{3} \times \pi \times h \times (R^2 + r^2 + R^2 r^2) \quad (2)$$

Where, V is the volume of hopper (m^3), m is the mass of the biomaterial (kg), b is the breadth of the oven (m), h is the height of the oven (m), ρ is the density of the biomaterial (kg/m^3), R is the radius of outer circle (m), r is the radius of inner circle (m)

Determination of vertical shaft speed

The vertical shaft speed was determined in order to know the actual speed the machine will operate and also to aid the proper calculation and determination of machine pulley diameter

$$T_3 \times N_3 = T_4 \times N_4 \quad (3)$$

$$N_4 = \frac{T_3 \times N_3}{T_4} \quad (4)$$

Where, T_3 is the number of teeth on the horizontal bevel gear, N_3 is the horizontal machine shaft speed (rpm), T_4 is the number of teeth on the vertical bevel gear, N_4vertical machine shaft speed (rpm)

The mass of the horizontal shaft was computed using the established formula stated by Khurmi and Gupta (2005)

$$M_S = \rho_s \times V_s \quad (5)$$

$$V_s = \pi \times \frac{d^2}{4} \times L \quad (6)$$

Where, M_S is the mass of the shaft (kg), V_s is the volume of the shaft (m^3), ρ_s is the density of the shaft (kg/m^3), d is the diameter of the shaft (m), L is the length of the shaft (m), π is constant

Determination of the Shaft Diameter

The diameter of the shaft was computed using the established formula stated by Khurmi and Gupta (2005)

$$d^3 = \frac{16}{\pi S_s}\sqrt{(K_b M_b)^2 + (K_t M_t)^2} \quad (7)$$

where, d *is* expected diameter of shaft(m) , M_t is belt moment (Nm), M_b is bending moment (Nm), K_b is the shock and fatigue applied to bending moment, K_t is the shock and fatigue applied to torsional moment, S_S *is* permissible shear stress of the shaft

Machine power requirement

The power required by the machine for shearing of the grains was determined as reported by Gana et al. (2016)

$$P_S = \left[\frac{2\pi N \tau_t}{60}\right] \quad (8)$$

$$\tau_s = F_S \times r_S \quad (9)$$

$$F_S = (M_{SM} + M_g + M_s + M_p)g \quad (10)$$

Where Ps is the total power required for shearing of the grains (kW), τ_S is the torque in the shearing unit (Nm), F_S the total force or weight on the horizontal shaft in the shearing units (N), r_S radius of the shearing mechanism (m), M_{SM} is the mass of the shearing mechanism (kg), M_g is the mass of the grains (kg), M_S is the mass of the shaft (kg), M_p is the mass of the pulley (kg), g is the the acceleration due to gravity

Design of the pinion and gear shafts

The length of pinion gear shaft was computed using the established formula stated by Khurmi and Gupta (2005)

$$L = \sqrt{\left(\frac{D_G}{2}\right)^2 + \left(\frac{D_P}{2}\right)^2} \quad (11)$$

Where L is the slant height of pitch cone or cone distance (m), D_G is the pitch diameter of the gear (m), D_P is the pitch diameter of the pinion (m)

The diameter of the pinion shaft was obtained using the torsion equation reported by Khurmi and Gupta (2005)

$$T_e = \frac{\pi}{16} \times \tau \times [d_p]^3 \quad (12)$$

Where, T_e is the equivalent twisting moment (Nm), τ is the maximum permissible shear stress for the shaft (Nm^{-2}), d_p is the diameter of pinion shaft (m)

Determination of Torsional Deflection of the Shaft

Torsional deflection of a solid shaft was determined as reported Khurmi and Gupta, (2005), and is given as

$$\sigma = \frac{584\,TL}{G \times D^4} \quad (13)$$

Where, G = torsional modulus of elasticity of steel (N/mm), D is the shaft diameter (mm), L is length of the shaft (mm)

Twisting Moment

The high rotating speed of the horizontal shaft which is attached to the shearing mechanism is influenced by twisting moment. The twisting moment of the shaft was determined as expressed by Gana and Gbabo (2017)

$$M_t = \frac{60W}{2\pi N} \quad (14)$$

Where M_t is twisting moment (Nm), N is speed of rotation of the shaft (rpm), W is power transmitted (watts), π *is* constant (3.14)

Second Polar Moment of Area of the Shaft

The second polar moment of area of the central shaft is essential in determination of the resistance of the shaft to bending and deflection and was computed as reported by Khurmi and Gupta, (2005) as:

$$J = \frac{\pi d s^4}{32} \quad (15)$$

where, J *is the* second polar moment of area , d_S *is the* the diameter of shaft (m)

Working Mode of the Machine

The 6.5-hp petrol engine is switched on and allowed to run empty to ensure that all components of the machine are properly aligned and also help warm up the petrol engine. Power generated from the gasoline engine is transmitted to aid the rotation of the cutting blades via the belt, pulley systems, and gearbox. The machine is turned off, the shutter and valve are closed, and the grains are fed into the hopper. This is done to prevent material loss as a result of spillage. The machine is put on again for the grinding action to take place. The rotation of the cutting blades on the grains causes them to shear or cut into much smaller sizes. This process of shearing and cutting forms the reduced products.

Design of experiments

The experimental was designed as a function of the shearing speed (A) and the grain moisture content (B) using a central composite rotatable design (CCRD) of response surface methodology (RSM). In order to obtain the required data, the range of values for each of the four variables (k) was determined as reported by Gana et al. (2017) and is presented in Table 1. The total number of runs for the two variables (k = 2) and five levels (-α, -1, 0, 1, and +1) experiments was determined by the expression: 2k ($2^2 = 4$ factorial points) + 2k (2 × 2 = 4 axial points) + 5 (center points: fie replications) = 13 (Cukor et al., 2011), and the design is shown in Table 1.

Experiments set up

Based on the design of the experiment, five shearing speeds were varied: 1800 rpm, 2000 rpm, 2500 rpm, 3000 rpm, and 3200 rpm. The grain moisture content was varied as follows: 10.4, 11, 12.5, 14, and 14.5 % moisture content. The experiment was conducted at the Department of Agricultural and Bioresources Engineering, Federal University of Technology Minna, Niger State, Nigeria. Forty kilograms of white sorghum was used during the experiment.

Statistical analysis

An analysis of variance (ANOVA) was carried out to estimate the effects of the main variables and their likely effects on the responses (Gana et al., 2017).

Determination of the Effects of the Independent Variable on the Machine performance

The overall performance of the machine was evaluated on the basis of shearing efficiency and the machine capacity.

1. Shearing Efficiency

This is the ratio of the mass of material before cutting to the mass of the material after cutting expressed in percentage. It was determine as reported by Gana et al. (2016), and is given as

$$S_{EF} = \frac{W_b}{W_a} \times 100 \quad (16)$$

Where, S_{EF} is the shearing efficiency (%), W_a is the weight of materials before cutting (kg), W_b is the weight of the materials after cutting (kg)

Capacity

This is quantity of materials sheared per time. It is expressed in kg/hr and is given as follows:

$$C_m = \frac{W_b \times T}{t} \quad (17)$$

Where, W_b is the weight of the materials after cutting (kg), T is time (hours), t is the time used (minutes)

Results and discussion

Results

The machine was designed using essential fundamental design analysis and calculations. It was fabricated as shown in Plate I, using stainless steel materials by employing specifications and sizes dimensions obtained from the design calculation. After the fabrication, the machine was tested, and the results of the testing of the machine are presented in Table 1. The final product obtained is also shown in Plate II. The shearing efficiency ranged from 36.91% to 99.86%. The highest value of 99.86% was obtained from a combination of a speed of 2000 rpm and a grain moisture content of 14% M.C. The lowest value of 36.91% was obtained from the combination of a speed of 3000 rpm and a grain moisture content of 11% M.C. The machine's capacity ranged from 128.82 kg/h to 348.6 kg/h. The highest value of 348.6 kg/h was obtained from a combination of a speed of 2000 rpm and a grain moisture content of 14% M.C. The lowest value of 128.82 kg/h was obtained from the combination of a speed of 3000 rpm and a grain moisture content of 11% M.C. The combination of higher speed ranges from 2500 to 3207 rpm and low moisture content ranges from 10 to 12.5% M.C.

Plate 2. Grinded sorghum using the fabricated machine

Table 1: Results of performance testing of the machine

Std	Run order	Speed of shearing (rpm)	Moisture content (%)	Shearing Efficiency (%)	Capacity (kg/h)	Texture o f sheared Grain
12	1	2500	12.5	73.39	256.13	Coarse
8	2	2500	14.62	39.17	135.17	Coarse
5	3	1793	12.5	56.87	198.48	Coarse
11	4	2500	12.5	83	289.7	Coarse
1	5	2000	11	77.62	270	Coarse
6	6	3207	12.5	93.83	327.45	Fine
7	7	2500	10.38	90.32	311.6	Fine
9	8	2500	12.5	83.46	289.67	Coarse
4	9	3000	14	66.3	231.4	Coarse
2	10	3000	11	99.86	348.6	Fine
13	11	2500	12.5	83.46	290.4	Coarse
3	12	2000	14	36.91	128.82	Coarse
10	13	2500	12.5	83.39	291	Coarse

Discussion of Results

1. Effects of the machine parameters on texture of the sheared grains

From Table 1, three combinations of the trial produced particles with a finer texture, while the other combination gave a coarser particle. The former combinations have a higher speed of shearing and lower grain moisture content. This indicated that higher shearing speed and lower grain moisture content produced grain particles with a finer texture. This agreed with the finding of Luo et al. (2014), where the product size distribution became much finer with increasing rotor speed, which can be explained as follows: A higher rotor speed improved the hit probability between the blades and materials, enhancing the impacting and grinding effects. Fitzgerald and Themelis (2009) indicated that with a hammer mill, higher rotor speeds generated finer particles with higher energy consumption. This conforms to the findings of Opadotun et al. (2017) and Yancey et al. (2014), which affirmed that the optimal grinder configuration for maximal process throughput and efficiency of a hammer mill is strongly dependent on the tip speed of the rotor, screen diameter, feedstock type, and properties such as moisture content. Hence, in selecting the proper grinder process parameters, speed and screen size are important factors.

2. *Effects of speed shearing and grains moisture content on shearing efficiency*

From Figure 2, the shearing efficiency decreased from 84% to 38% as the seed moisture content increased from 11% to 14%. This could be the result of an increase in friction and resistance to segregation of the seed as the moisture content increased. This agreed with the result of Jung et al. (2018), where food materials with low moisture content have high grinding efficiency since such materials are more brittle. The speed of milling was also observed to increase from 84% to 99% as the speed of shearing increased from 2000 rpm to 3000 rpm. This could be the result of more segregation of the materials with an increase in the speed of shearing. Luo et al. (2014), where higher rotor speed improves the hit probability between blades and materials and enhances impacting and grinding efficiency. Also from Table 2, the speed of shearing and the grain moisture content have positive and negative significant effects, respectively, on the shearing efficiency of the machine. This indicates that an increase in speed results in a corresponding increase in shearing efficiency, while an increase in moisture content results in a decrease in shearing efficiency.

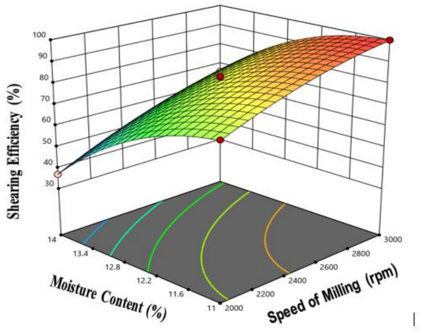


Figure 2: Effects of Speed of Shearing and Grain Moisture Content on Shearing Efficiency of the Machine

Table 2: Results of analysis of variance of shearing efficiency of the machine

Source	Coefficient Estimate	Df	F-value	p-value	
Model	81.34	1	79.91	< 0.0001	Significant
A-Speed of operation	12.99	1	118.52	< 0.0001	
B-Grains Moisture content	-18.33	1	235.97	< 0.0001	
AB	1.79	1	1.12	0.3246	
A^2	-2.96	1	5.37	0.0537	
B^2	-8.27	1	41.75	0.0003	
Lack of Fit	0.5494	3	0.0093	0.9986	not significant

3. Effects of speed shearing and grains moisture content on machine capacity

From Figure 3, the machine throughput capacity decreased from 255 kg/h to 125 kg/h as the seed moisture content increased from 11% to 14%. This could be the result of an increase in friction and resistance to segregation of the seed as the moisture content increased. This is in line with the report of Jung et al. (2018), where the efficiency and capacity of the food grinding process increase as the moisture content of the material decreases because material with less moisture is more brittle (Walde et al., 2002; Lee et al., 2013). Also, the machine capacity was observed to increase from 125 kg/h to 248 kg/h as the speed of shearing increased from 2000 rpm to 3000 rpm. This could be the result of more segregation of the materials with an increase in the speed of shearing, which does not retain the materials longer in the machine.

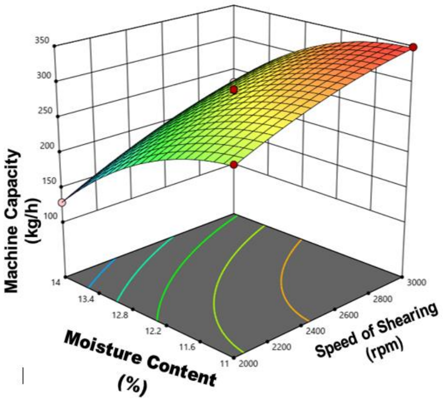


Figure 3: Effects of Speed of Shearing and Grain Moisture Content on machine throughput capacity

This is in line with the report by Opadotun et al. (2017), where the machine throughput increased with increases in the speed of the rotor. This implies that the higher the operating speed and screen size, the higher the output capacity because of the lower residency time in the machine (Yancey et al., 2014). Also from Table 3, the speed of shearing and the grain moisture content have positive and negative significant effects, respectively, on the machine throughput capacity. This indicates that an increase in speed results in a corresponding increase in machine throughput capacity, while an increase in moisture content results in a decrease in machine throughput capacity.

Table 3: Results of analysis of variance of shearing efficiency of the machine

Source	Coefficient Estimate	df	F-value	p-value	
Model	283.38	1	81.95	< 0.0001	Significant
A-Speed of operation	45.45	1	122.51	< 0.0001	
B-Grains Moisture content	-63.49	1	239.07	< 0.0001	
AB	6	1	1.07	0.3362	
A²	-9.82	1	4.98	0.0609	
B²	-29.62	1	45.24	0.0003	
Lack of Fit	14.7	3	0.0211	0.9952	not significant

Conclusion

The equipment was designed, fabricated, and its performance tested. Higher shearing speed and lower grain moisture content produced grain particles with a finer texture, which gave higher shearing efficiency and machine throughput. This affirmed that the optimal grinder configuration for maximal process throughput and efficiency of shearing is strongly dependent on the speed of the rotor and moisture content, among others. Hence, in selecting the proper grinder process parameters, speed and grain moisture content are important factors. Speed shearing has positive and significant effects on the product's quality, efficiency, and throughput. While increases in grain moisture content have negative and significant effects on the product's quality, efficiency, and throughput, The combination of a speed of 3000 rpm and a grain moisture content of 11% produced materials with the finest texture and shearing efficiency of 99.86% and 348.6 kg/h, respectively. On the other hand, the combination of speed of 2500 rpm and grain moisture content of 14.62% produced materials with coarse texture with shearing efficiency and capacity of 39.17% and 135.17 kg/h, respectively. The developed machine can be improved by making dual power operated by making provision to be powered by both petrol and electricity.

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