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Development and Performance Evaluation of a Bone-Milling cum Pulverising Machine

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Abstract: *A process machine for milling and pulverising animal bone into bonemeal was developed. The machine consists of a hopper, a milling chamber with hammers assembly, a pulverising chamber with two abrasive surfaces, a screw feeder, belts and pulleys, hammer mill-shaft, pulveriser shaft as well as an electric motor for power transmission. The design concept integrated the milling and pulverising of animal bones into one machine. Animal bones are milled to a maximum size of about 12mm in the milling unit and then delivered through an auger to the pulverising unit. As one of the two abrasive surfaces of the pulverising unit rotates against the stationary surface, the milled bones are fed between them by the screw feeder through the center of the stationary abrasive disc which is mounted concentrically with an identical high speed rotating abrasive disc. The design calculations were done using existing machine design theories to obtain relevant design parameters of the components for the machine. Based on the calculated design parameters the machine was fabricated. Materials were selected primarily based on strength, availability and economy. Initial performance evaluation of the machine showed good results, although there is room for improvement. The machine pulverises raw and cooked bone at an average rate of 4.68 g/s.*

Keywords: *Development, Evaluation, Bone, Milling, Pulverising, Machine*

1. Introduction

Bone is any of the hard parts that form the skeleton of an animal's body. Bones are rigid organs that constitute part of the endoskeleton of vertebrates. They support and protect the various organs of the body, produce red and white blood cells and store minerals. Bones come in a variety of shapes and have a complex internal and external structure, are lightweight yet strong and hard and they serve multiple functions. These bones can be converted into bonemeal using different methods. Bones like other animal by-products should be adequately heated in order to assure that disease organisms are not spread.

Bone-meal can be used to provide a source of calcium, phosphorus and other minerals in man and livestock feeding programs (FAO, 2012). Bone-meal is a widely available supplemental source of calcium and phosphorus for both ruminant and mono-gastric animals. It is an excellent source of potassium in feeding dairy cattle. Bonemeal is the most affordable source of calcium for farm animals, such as poultry. Its processing into powdered form makes its calcium content readily available when mixed with other animal feed constituents, which include maize, guinea corn, millet, sorghum, palm-kernel cake, ground-nut cake, fish meal, meat, and milk. A machine for reducing the size of animal bones to powder is important for maximising the nutritional value of bonemeal.

In prehistoric times, grain was crushed between two flat stones. Later, a stone with a rounded end was used to grind grain in a cup-shaped stone. This led to the development of the mortar and pestle. More advanced peoples began to use the quern, a primitive mill in which the grain is placed on a flat, circular lower millstone and ground by revolving a similar upper millstone to which a handle is attached (MIWA**,** 2012). Such a device, operated at first by hand, was adapted to use of animal, water, or wind power. The Industrial Revolution initiated the use of steam power and of transportation facilities that resulted in the rise of large-scale milling centers (Donnel, 1983).

The term 'milling' applies to the processing of several materials (e.g., soap, textiles, and metals). Hence, processing establishments are often called mills, for example lumber mills; sawmills; cotton mills; and sugar mills. In a similar manner, the processing of bonemeal could be done by bone mills. The processing of bonemeal from animal bones could be described in two stages because of the peculiarity and attributes of animal bones. The first stage involves the milling of the whole bone (i.e. lump of bone) into small sizes determined by the size of holes in the sieve used. The second stage is the pulverising of the small sized bone pieces into powdery form (FAO, 2012). A bone mill is a piece of equipment that can be used to break bone into small pieces. Typical bone milling machines could be developed by employing hammers for crushing bones. Thus, this machine can be regarded as hammer milling machine. To convert the bone into powder in the second stage, a bone pulverising machine in the form of a burr mill is used. The burr mill consists essentially of two roughened/abrasive plates - one is stationary while the other is rotating. With faster feed and filled flutes, both shearing and crushing can take place. Overfeeding reduces the effectiveness of the pulveriser and excessive heating results. The plates could be designed for a variety of pulverising operations and are usually made of cast iron (Handerson and Perry, 1980).

Modern size reduction equipment (i.e. Hammer mill and Pulveriser) was designed and manufactured to serve a singular function (Kakahy et al., 2001; Nasir 2005; Nwaigwe et al., 2012; Sanni et. al., 2008; Aderemi et al., 2009). They either crush bulk material to grain (Hammer mills) or pulverise grain to powder (Pulverisers). Table 1 provides features of some of these two separate machines. No single one machine can be utilised to completely process bone to powder form. With these two separate machines, achieving the powdery form of bone takes more time and involves more cost. This study details the design and development of a machine, herein named bone milling cum pulverising machine, which could mill and pulverise animal bones in one setup. The machine integrates the functionalities of the hammer mill and pulveriser towards achieving animal bone pulverisation.

2. Materials and Methods

The study involved the identification of the essential design considerations. This was followed by the conceptual and detailed design of the machine using existing design theories. The machine was then fabricated and evaluated.

2.1 Design Consideration

The following design considerations were taken into account during the design stage to ensure an efficient and effective bone milling cum pulverising machine;

i) The machine should consist of two basic operational units: milling unit and pulverising unit powered by the same electric motor to optimise the cost of production.

ii) The machine is to mill bone as the hardest materials. Bone has a milling/ shearing force of 6.45 N at 2-4% moisture content (Adesola et al., 2002).

iii) The hammers are to be attached to hanger rods permanently, but separately fixed and freely swinging with a rotating speed of between 1,400 and 4,000 rpm (Handerson and Perry, 1980)

iv) The maximum size of bone pieces supplied by the hammer mill to the Pulverising unit is 12mm.

v) All static and dynamic stresses resulting from direct loading, bending and torsion were considered in the shaft's design.

vi) To facilitate the construction of the machine, a prototype that is suitable for small-scale enterprise would be adequate. Hence, the targeted capacity of the machine was 18 kg/hr.

Table 1. Existing hammer mills and pulverisers

Machine Type	Feature	Reference
Hammer mill	A hammer mill was designed and constructed from locally available materials for grinding grain particles into smaller size using hammer assembly and sieve. The hammer beats the grain materials into smaller particles whose size depends on the apertures on the detachable sieve.	Nasir (2005)
	A hammer mill which combined both impact and shearing action of hammers with a pneumatic conveying and clarifying action was designed and fabricated for efficient milling of cassava into fine powder	Nwaigwe et al. (2012)
	A hammer mill having a grinding component and a sieving component was developed for milling grains. In the grinding component, there are curved teeth plates mounted around the grinding chamber which enhances the grinding capacity of the machine; two blades mounted on rotor shaft are used as a fan, while rectangular shape hammers are used. The sieving component was attached to the outlet of the grinding component and it is comprised of a screen and a material returning tube which leads to center of the grinding chamber. The material returning tube ensures that milled material which cannot pass through the sieve, under the action of its gravity and negative air pressure in the center of grinding chamber, is returned back to the grinding chamber and ground again.	Xuan et al. (2012)
Pulveriser	A rotary brush and screen mechanism was developed to replace raffia sieve and used for pulverising and sifting in a machine developed for the pulverisation of cassava cake during gari processing.	Sanni et al. (2008)
	A ginger pulverising machine having the following components; a frame assembly, a feed hopper, an electric motor (power drive), rasping unit and the pulping unit a rotor stator consisting of cutting knives attached to a fast rotating shaft), was designed and fabricated with 80% of the materials sourced locally.	Aderemi et al. (2009)

2.2 Design Analysis

The conceptual design of the bone milling cum pulverising machine developed is as shown in Figure 1. Other essential details of the machine are shown in the exploded view in Figure 2. The detailed design analysis, using existing and appropriate design equations, gave the design parameters for the various components of the machine as presented in following sub-sections.

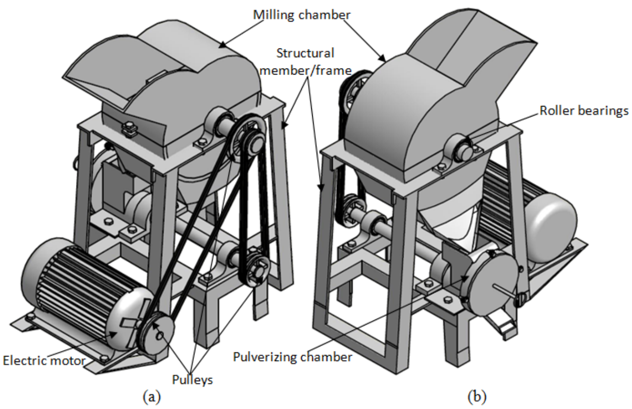


Figure 1. The bone milling cum pulverising machine (a) back side (b) Front side

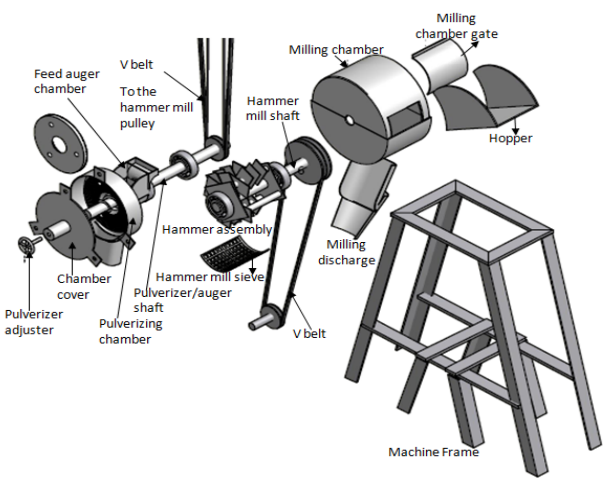


Figure 2. Exploded details of the bone milling cum pulverising machine

2.2.1 Design of the Milling Chamber Unit

The milling chamber is cylindrical in shape and after a detailed analysis in respect of the targeted intake of 1.2 kg of bone its design parameters were calculated from Equation (1).

Volume of a cylinder, $v = \pi\left(\frac{d^2}{4}\right)h$ (1)

Where d is the diameter of each circular ends of the milling chamber, and h is the length of the horizontal axis.

To allow enough space for the hammer, d was set as equal to twice of h, so that d = 360 mm and h = 180 mm were used for the milling chamber.

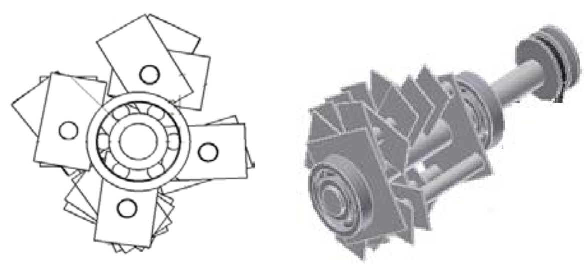
2.2.2 Hammer Design

The hammers were designed to be attached to a hanger rod separately fixed and freely swinging (see Figure 3) with a rotating speed of between 1,400 and 4,000 rpm (Handerson and Perry, 1980). The design analysis considered the force, F, to be delivered by each hammer to be equal to 9.7 N. This value was obtained from the applied design factor of 1.5 and the shearing force of 6.45 N required to mill bone at 2-4% moisture content. The volume of each hammer was then calculated from equation (2).

Volume of a hammer, $V = \frac{F}{\rho g}$ (2)

ρ is the density of the material for the hammer and g is the acceleration due to gravity.

After due consideration of the volume of the hammer required, the shape and size of the milling chamber and the hanger on which the hammers are fixed, hammers of sizes 63.5cm wide, 100 mm long and 6.4 mm thick was used. Twenty pieces of these hammers, four pieces of hangers, three pieces of stator discs, and twenty pieces of collars were then combined and assembled on the crushing shaft to make the crushing hammer assembly.



(a) Schematic drawing (b) 3D drawing

Figure 3. The hammer assembly

2.2.3 Milling Power Requirement

For a breaking force of 6.45 N, which was to be delivered by each of the twenty hammers assembled on the crushing shaft and using a design factor of 1.5, the series of formulae available in Khumi and Gupta (2009) were used to estimate the power requirement of the electric motor that drives the crushing hammer assembly:A 6.8 Hp electric motor was selected to drive the crushing hammer assembly.

2.2.4 Determination of the Milling Shaft Diameter

The crushing shaft carries the hammer assembly and is acted upon by weights of the hammer assembly, the bone being processed and that of the pulley. In operation, the crushing shaft conveys the hammer assembly which crushes the bones. Therefore, the shaft is subjected to both bending and torsional stresses, hence the diameter was determined as 40 mm using Equation (3) as in Ogedengbe and Aderoba (2002) and Khurmi and Gupta (2009):

$$d = \sqrt[3]{\frac{16}{\pi S_s}\left[(K_b M_b)^2 + (K_t M_t)^2\right]^{\frac{1}{2}}} \qquad (3)$$

Where, d is the diameter of the shaft, m; S_S is the allowable shear stress, N/m^2; K_b is the combined shock and fatigue factor applied to bending moment; M_b is the bending moment, Nm; K_t is the combined shock and fatigue factor applied to torsional moment; and M_t is the torsional moment, Nm.

2.2.5 Hammer Mill Sieve

Since the milling unit is expected to deliver crushed bones with maximum size of 12 mm to the pulverising unit, the sieve was made with mild steel plate with perforations of 12 mm drilled holes.

2.2.6 Pulverising Unit Power Requirement

The power required to drive the pulverising unit was estimated in a similar manner with that of the milling unit and this was found to be 3 Hp. Hence the same electric motor of 6.8 Hp that was selected to drive the functional elements of the milling unit was utilised to drive the pulverising unit.

2.2.7 Feed Auger

The feed auger was designed to have a semi-cylindrically shape. After due consideration of the weight and size of the crushed bone from the milling chamber that is expected to flow into the feed auger which conveys it to the pulverising unit, the diameter and length of the auger were estimated at 100 mm and 115 mm, respectively. Also, the diameter and length of the auger shaft were estimated at 40 mm and 115 mm, respectively.

2.2.8 Determination of Shaft Diameter

The diameter of the shaft used in the pulverising unit was also calculated as 40 mm using equation 3.

2.2.9 Pulverising Discs

The normal force required for each disc to pulverise the crushed bones was set at 6.45 N (the breaking force for bone). Two pulverising discs having internal diameter, external diameter and thickness of 100 mm, 240 mm and 15 mm respectively were selected using Equation 4 which was given in Khumi and Gupta (2009) as follows:

$$T_r = \mu N \left[\frac{(r_1)^3 - (r_2)^3}{(r_1)^2 - (r_2)^2}\right] \qquad (4)$$

Where T_r is the frictional torque; μ is the coefficient of friction of the friction surface; N is the axial force with which the pulverising discs are held together: r_1 and r_2 are the external and internal radi, respectively, of the friction surface.

2.2.10 Pulverising chamber

The pulverising chamber design depended largely on the pulverising discs. The chamber was sized to accommodate the pulverising disc arrangement and the crushed bone to be pulverised. The diameter and length of the pulverising chamber was therefore estimated at 274 mm and 67 mm, respectively.

3. General Description of the Bone-Milling cum Pulverising Machine

The machine consists of a milling unit and a pulverising unit integrated together to mill and pulverise animal bone in a single operation. The electric motor is connected to a power supply via a switch and it drives both the milling and the pulverising units by transmitting motion through a V-belts and pulley arrangement. The cylindrical shaped milling chamber was designed to close completely when loaded, so as to prevent crushed bone from being thrown out, thus causing accidents or loss of raw material. By the rotation of the hammer assembly within the milling unit, the hammers strike the loaded bones repeatedly, thereby breaking them.

The milled bone goes directly to the pulverising unit through the outlet under the milling chamber after passing through a 12 mm sieve. An auger built as part of the pulverising unit receives the milled bones from the milling chamber and moves them to the pulverising chamber. The pulverising chamber is also cylindrical in shape. It houses the pulverising discs, with discharge at the lower end. The two pulverising discs pulverise bone between their two roughened surfaces to produce powdery bone particles. The pulverising chamber lets out pulverised bone by gravity, via a box shaped discharge channel attached to its lower end.

4. Performance Evaluation

In order to evaluate the performance of the developed bone milling cum pulverising machine, it was test run to pulverise six (6) samples each of cooked and uncooked bone material. A total of twelve samples was milled and pulverised using the machine. Six of the samples weighed 100 g each while the other six weighed 200 g each. The test was made randomly with cooked bone and uncooked bone material samples. In each case, the weight of the input and output, along with the time taken for the machine to complete its operations were recorded.

The machine efficiency in respect of each sample processed was calculated using Equation 5.The average for sample type with similar weight was determined. Similarly, the mass flow rate for each processed samples was calculated using Equation 6 and the average for sample types with similar weight was determined.

$$\eta_\mu = \frac{\text{weight of output}}{\text{weight of input}} \times 100 \qquad (5)$$

$$m = \frac{\text{weight of output}}{\text{processing time}} \qquad (6)$$

Where η_μ is the efficiency and m is the mass flow rate

The product (i.e. pulverised bone) obtained from the machine during test was sieved to examine their particle size. Sieves of 1,700 µm, 600 µm, 500 µm, 425 µm, 212 µm and 150 µm were used to separate 1,500 g and 750 g samples of pulverised bone, processed from both cooked and uncooked bones, into the appropriate and respective particle sizes. The 1,500g sample was taken from pulverised bones processed from 2,000g cooked or uncooked bones while the 750 g sample was taken from pulverised bones processed from 1,000g cooked or uncooked bones. Table 2 shows the evaluation of performance of the machine.

Table 2. Evaluation result of the developed machine

Sample Type	Weight of input (g)	Weight of output (g)	Processing Time (s)	Machine Efficiency (%)	Average	Mass Flow Rate g/s	Average
Uncooked	1,000	881	188	88.1		4.69	
Uncooked	1,000	887	182	88.7		4.87	
Uncooked	1,000	871	185	87.1	87.97	4.71	4.76
Uncooked	2,000	1,558	291	77.9		5.35	
Uncooked	2,000	1,548	284	77.4		5.45	
Uncooked	2,000	1,539	288	76.95	77.42	5.34	5.38
Cooked	1,000	875	229	87.5		3.82	
Cooked	1,000	892	236	89.2		3.78	
Cooked	1,000	883	240	88.3	88.33	3.68	3.76
Cooked	2,000	1,419	300	70.95		4.73	
Cooked	2,000	1,424	292	71.2		4.88	

5. Results and Discussion

Generally, the machine ran smoothly during the test and there was no bone flying around. Table 2 shows that less material input gives high efficiency in respect of machine output but gave low mass flow rate and vice-versa. For each of the processed samples, the efficiency of the machine in respect of the output is in most cases above 75 % and above 70 % in all the cases. On average, the output efficiency of the machine was 81.14 %, which could be regarded as generally very good. The average mass flow rate of the processed sample is 4.68 g/s which gives an hourly flow rate of 16.85 kg/h.

Tables 3-6 show that the pulverised bone had the highest percentage by mass of 1,700 µm particle size except for when it was processed from 2,000 g uncooked bone samples in which case the oversized particles have higher percentage by mass. The oversized particles consist of pulverised bone with various particle sizes greater than 1,700 µm. Irrespective of the samples (cooked or uncooked) from which the pulverised bone were processed, the 1,700 µm particle size occurred in a higher percentage than all other particle sizes smaller than it. The percentage by mass of the oversized particles is relatively high in pulverised bone processed from 2,000 g cooked bone and uncooked bone samples. The implication of this is that more of the bones supplied to the machine were processed to 1,700 µm particle size and below when the weight of the input is 1,000 g compared to when it was 2,000 g.

Results show that the machine efficiency is higher when the weight of input is 1,000 g compared to when the weight of input was 2,000 g (see Table 2). However the mass flow rate is higher when the weight of input is 2,000g.

Table 3. Mass and percentage by mass of particle sizes of 1,500 g of pulverised bone taken from the ones processed from 2,000 g cooked bone samples

Particle size µm	Mass Retained (g)	% Mass retained
Oversize	240.7	16.05
1,700	762.4	50.85
600	93.9	6.26
500	168.8	11.26
425	213.8	14.26
212	15.9	1.06
150	3.9	0.26

Table 4. Mass and percentage by mass of particle sizes of 750 g of pulverised bone taken from the ones processed from 1,000 g cooked bone samples

Particle size µm	Mass Retained (g)	% Mass retained
Oversize	63.23	8.43
1,700	249.98	33.34
600	89.03	11.87
500	111.26	14.84
425	119.01	15.87
212	60.95	8.13
150	56.42	7.52

Table 5. Mass and percentage by mass of particle sizes of 1,500 g of pulverised bone taken from the ones processed from 2,000 g uncooked bone samples

Particle size µm	Mass Retained (g)	% Mass retained
Oversize	607.51	40.59
1,700	471.46	31.5
600	136.2	9.1
500	92.8	6.2
425	94.29	6.3
212	61.66	4.12
150	32.78	2.19

Table 6 Mass and percentage by mass of particle sizes of 750 g of pulverised bone taken from the ones processed from 1,000 g uncooked bone samples

Particle size µm	Mass Retained (g)	% Mass retained
Oversize	24.18	3.23
1,700	348.25	46.52
600	60.94	8.14
500	118.28	15.8
425	161.02	21.51
212	26.2	3.5
150	9.73	1.3

The reason for these results may be because as more bones were supplied to the machine for processing in one pass, the space necessary to allow improved hammering and subsequent grinding of the bone got reduced thereby the output efficiency as well as the probability of obtaining pulverised bone with smaller particle sizes is reduced. However, the high input increases the movement of materials through processes under gravity to increase the mass flow rate.

6. Conclusions

A bone-milling unit was designed and fabricated alongside a bone pulverising unit to achieve a bone milling cum pulverising machine. Following design calculations and analysis along with adequate machining operations and fabrication method, the machine was constructed. Evaluation of the developed machine showed that it is able to perform the desired function of milling and pulverising cooked and uncooked bone to powder. This will save the cost of production through combining two machines in one, thereby enhancing productivity through the reduction of the time for material handling.

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