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Machine Design Approach to Bone Waste Utilization in Slaughterhouses of Developing Countries with Focus on Nigeria

Ayodele James Oyejide[1,2], Sunday Olufemi Adetola[3], Augustine Lawal[2]

[1]Department of Biomedical Engineering, University of Ibadan, Ibadan, Nigeria
[2]Department of Biomedical and Mechatronics Engineering, Achievers University, Owo, Nigeria
[3]Department of Mechanical Engineering, Ladoke Akintola University of Technology, Oyo, Nigeria
Email: ayoyja@outlook.com, soadetola@lautech.edu.ng, austinlawal@achievers.edu.ng

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Abstract

The conversion of bone waste obtained from meat processing in slaughterhouses is of great significance across the world, with rising concerns about its utilization in developing countries. In Nigeria, for instance, there are fewer successful strategies to transform bone waste into high-value products. While most research papers have concentrated on revealing the environmental, aesthetic, and catastrophic health problems associated with the current slaughterhouse waste disposal in developing countries, this paper presents an engineering approach to managing slaughterhouse solid wastes that majorly consist of bones and horns. A medium-size bone milling machine was designed and fabricated with well-detailed design principles to make it reproducible in any industrial capacity. 3D modeling and simulation were employed to evaluate the machine design and performance. Static simulations performed show that the machine can withstand values of 219.313 kPa, 12.7 exp 7 MPa and 2182.5 Nm for the shaft bending moment, hammer pressure, and output torque, respectively. The machine is 98% efficient on performance evaluation, milling 250 kg of treated sun-dried cow bones in an average time of 10 min 2 sec. This paper also recommends workable means for the installation and utilization of the bone milling machine in slaughterhouses across Nigeria.

Keywords

Bone-Waste, Nigeria, Milling-Machine, Slaughterhouse, 3D-Modeling

1. Introduction

According to FAO [1], Nigeria's population will grow swiftly and transform extensively in the next three decades. Some studies have also revealed that the population size will double to almost 400 million, with the number of people living in urban areas tripling from the current 94 million to 280 million between 2015 and 2050. The envisaged statistics imply that there will be an increase in fresh meat consumption, not only in Nigeria but globally, every year. Consequently, slaughterhouses produce an enormous amount of beef, pork, and poultry meats. Every year in Nigeria, about 42 million sheep, 18 million cattle, 7.5 million pigs, and 1.4 million equines are slaughtered across the country, while about 13 million households own livestock in the country [2].

This meat processing activity generates wastes such as blood, fat, organic and inorganic solids, salts, and chemicals used during processing operations, which are not often well managed in most developing countries, especially in Nigeria. Extensive studies show that the collected wastes after meat removal from animals have not been suitably utilized [3] [4]. In most cases, the wastes are disposed of without regard to sound environmental management practices, making them harmful to humans and other terrestrial and aquatic life. Studies from urban and rural areas in Nigeria show that many abattoirs dispose of waste in water bodies and drainages, while some have resulted in burning the waste or dumping them at a site where they decay and are fed upon by animals [5] [6] [7]. The most predominant causes of poor slaughterhouse waste management in Nigeria are inadequate enlightenment on the economic importance of slaughterhouse wastes and recovery strategies. Of the about 130 billion kg of animal bone residue produced by slaughterhouses globally every year, more than 8% of these wastes are from Nigeria [8] [9]. Hannah Ritchie [10] also reported that bones constitute 40% of the total by-products gotten from processing livestock in Nigerian slaughterhouses, implying that bone waste management in the country requires rapt attention.

The organic material in livestock bones accounts for approximately 20% of the wet weight of the bone and about 75% of the dry weight; with 98% calcium, 85% phosphorus, and somewhat 50% sodium and magnesium, making it a valuable material for recycling [11]. The properties in animal bones give an excellent substrate for generating biogas, biomedical applications, livestock meal, and plant fertilizers [12]. For instance, bone meal, which is a mixture of ground animal bones and slaughterhouse waste products, was once used as a human dietary calcium supplement, as well as livestock and mono-gastric animal feed due to its mineral supplements [11] [13]. Farmers have also found milled bones relevant for making organic fertilizers. The milled bone contains a reasonable proportion of essential amino acids, minerals, and vitamin B12. When slowly administered, it can serve as a primary source of phosphorus and protein [14]. According to a Colorado State University research, phosphorus from a bone meal is beneficial to plants in the soil of pH below 7.0 (acidic soil) [15]. The only exception is that milled bones have less benefit to plants in cases where enough nitrogen is of interest [16].

As biomaterials, bones contain hydroxyapatite, a component of the inorganic portion in bones used in dental therapy [17], making milled bone of interest in the pharmaceutical and cosmetics industries. The collagen in bones is also a biomaterial in developing biologically active hydrolysates and peptides for food ingredients [18] [19]. Ling & Teo [20] also studied if bone powder could be a suitable replacement for plastics in many ways; they reported that composites made with the powder enhance products such as bone china. A study by Arvanitoyannis & Kassaveti [21] shows that there is currently interest in thermal recycling of slaughterhouse wastes in power plant industries across the globe as secondary fuel. Yusuf and Oyewumi [22] have also investigated the great potentials in converting livestock by-products from Nigerian slaughterhouses into wet biomass and other types of renewable energies. Another economic benefit of animal bone is livelihood and employment, especially in developing countries. A dynamic animal processing industry that utilizes the entire animal in some ways can provide huge revenue and many jobs for the economy [23] [24] [25]. Despite the vast potential of slaughterhouse wastes in Nigeria, they are underutilized and have contributed to environmental and health challenges.

Overcoming the growing challenges of bone waste management in developing countries of Africa requires that the African livestock industry explore new technologies for utilizing the wastes. One of such technologies to manage slaughterhouse solid wastes is to convert them into powder through the aid of milling and pulverizing machines. Consequently, Adetola & Oyejide [26] developed a small-scale bone milling machine proposed for livestock farmers in rural areas of Nigeria, and other authors [27] [28] [29] [30] have also developed similar machines in previous publications. This paper presents, in particular, a detailed design principle and stress analyses considered in the design and fabrication of a typical medium-size bone milling machine for use in slaughterhouses across Nigeria. The work is an engineering approach to the scientific, agricultural, and environmental research reports and recommendations on slaughterhouse waste management in developing countries.

The purpose of this work is to reveal that Nigeria and other developing countries can harness the benefits in utilizing the enormous bone wastes produced in slaughterhouses, through the installation of medium-to-industrial size milling or pulverizing machines developed using available raw materials.

2. Materials and Methods

2.1. Materials

The material used for most parts of the machine is mild steel. Mild steel has strength and low carbon content, which makes it easy to weld and convey. Other materials are shaft, bearing, metal-sheets, angle bar, bolt and nut, belt, pulleys, electric motor, socket, cutting stone, and filling-stone. In this design, the machine is based on the principle of impact and consists of twelve hammers radially and axially spaced on a steel shaft that rotates at high speed on the driving shaft. **Figure 4** shows the fabricated machine assembly. All materials were locally sourced.

2.2. Design Equations, 3D Modeling and Simulation

This section shows the basic equations used in the design of the bone milling machine, the principles adopted, and an idealistic 3D model and simulation used to investigate the possible failures in the hammer assembly, the shaft, and the pulleys before fabrication. The 3D model of the bone milling machine was developed on Autodesk Inventor Professional 2020 and the model was exported to Ansys software (static structural) to evaluate the performance through simulations. Friction and body displacements were prevented by fixing constraints at joints and points where the body parts mate, excluding only the site of interest to fully understand how the part or assembly behaves under certain conditions. The main parts modeled are the stand frame (1 unit), chamber (1 unit), sieve (1 unit), hopper (1 unit), main shaft (1 unit), connecting rods (8 units), metal discs (3 units), pulleys (2 units), belt (1 unit), bolts and nuts (11 units each), electric motor (1 unit), bearing (2 units) and hammer (12 units). The 3D assembly (meshed; left, and solid; right, models) and the skeletal view of the machine are shown in **Figure 1** and **Figure 2**, respectively.

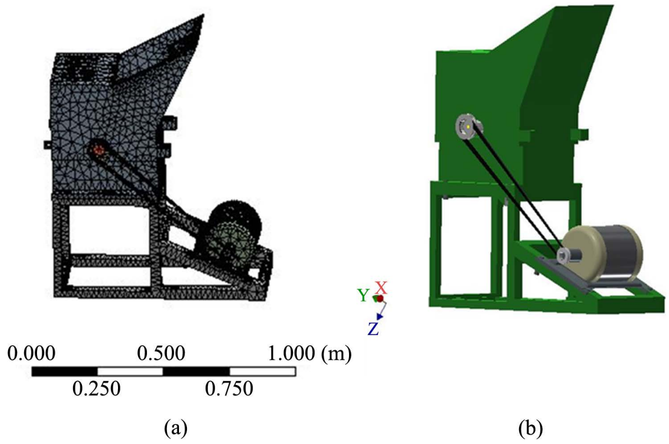

Figure 1. 3D Minimized view of the machine (a) tetrahedral mesh model with 1091525 nodes and 735258 elements and (b) external components consisting of the electric motor, driving shaft, belt, the base and the hopper.

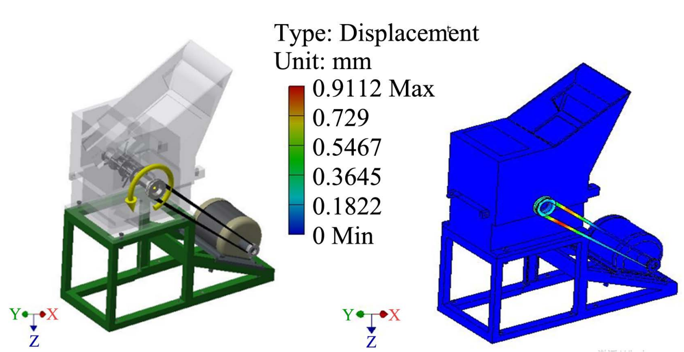

Figure 2. Bending moment on the shaft at maximum revolution.

Shaft Design

The shaft is the prime mover of the hammers, designed with fundamental principles to make sure it is rigid. Based on strength, the cases considered in the design are twisting moment or torque, bending only and combined twisting and bending moments on the shaft.

1) Twisting Moment or Torque only

A shaft length of 0.45 m was selected based on the suggestion in Khurmi & Gupta [31] that a shaft length should be short to limit whirling and torsional vibration during operation [32].

Twisting moment is given as:

$$\tau = qJ/r \tag{1}$$

It is estimated that the average breaking force for dried cattle bones of about 9.9 kg is 97 N [33]. Therefore, 12 hammers will transmit about 4850 N of force on the 50 kg bone feed.

Force applied = 4850 N;

Length of the shaft = 0.45 m.

Torque,

$$T = \text{Force} \times \text{shaft length} = 4850 \times 0.45 \tag{2}$$

The output torque of the machine is 2182.5 Nm.

To find the standard diameter for the shaft:

$$q_{\text{max}} = \frac{16T}{\pi d^3} \le q_{\text{allow}} \tag{3}$$

$$56 \times 10^6 = (16 \times 2183)/\pi d^3$$

$$d^3 = (16 \times 2183)/(\pi \times 56 \times 10^6) = 1.985 \times 10^{-4}$$

However, to keep torsional stress at minimum, a standard value of 50 mm was selected.

2) Shafts Subjected to Bending only

The maximum tensile or compressive stress when the shaft is subjected to bending moment only was determined from the bending equation:

$$M/I = \sigma_b/y \tag{4}$$

where, $I = \frac{\pi}{64} \times d^4$ for a solid shaft and $y = \frac{d}{2}$.

Substituting for I and Y in Equation (4), we have:

$$M = \frac{\pi}{32} \times \sigma_b \times d^3$$

But

$$M = \text{weight} \times \text{length of shaft}/8 \tag{5}$$

Length of shaft = 0.45 m;

Weight of shaft = 4 kg;

Therefore,

$$M = (0.45 \times 4 \times 9.81)/8 = 2.207\ \text{N} \cdot \text{m}$$

$$\sigma_b = (32M)/(\pi d^3);\quad \sigma_b = (32 \times 2.207)/\pi(0.048)^3$$

$$\sigma_b = 219.313\ \text{kPa}$$

3) Shafts Subjected to Combined Twisting and Bending Moment

According to Khurmi [34] two theories that are important in this case are maximum shear stress or Guest's theory, used for ductile material such as mild steel and maximum normal stress, or Rankine's theory, used for brittle materials such as cast iron. Guest's theory was considered in the design because the shaft is a ductile material. The maximum shear stress in the shaft is given by:

$$\lambda_{\max} = \frac{1}{2}\sqrt{(\sigma_b)^2 + 4\tau^2} \tag{6}$$

Substituting the formulas of τ and σ_b from equations 1 and 5, respectively:

$$\lambda_{\max} = \frac{1}{2}\sqrt{\left(\frac{32M}{\pi d^3}\right)^2 + 4\left(\frac{16T}{\pi d^3}\right)^2}$$

Therefore,

$$\lambda_{\max} = \frac{16}{\pi d^3}\sqrt{M^2 + T^2} \quad [34]$$

where the expression $\sqrt{M^2 + T^2}$ is the equivalent twisting moment and is denoted by T_θ

$$\lambda_{\max} = \frac{16}{\pi(0.048)^3}\sqrt{2.207^2 + 1125^2} = 51801632.67$$

$$\lambda_{\max} = 51.8\ \text{MPa}$$

Therefore, the maximum shear stress on the shaft is 51.8 MPa.

The design results obtained in subsections 2.2.1.1, 2.2.1.2 and 2.2.1.3 were validated through simulations presented in **Figure 2** and **Figure 3**, by evaluating the machine performance when subjected to gotten values of shear stress, force, and applied load. The areas of interest are the shaft, hammer assembly and pulley.

The simulation in **Figure 2** evaluates the necessary factor of safety needed to allow minimum fluctuating load without bending or twisting the shaft. The bending moment on the shaft was examined at a speed range of 1440 - 4000 rev/min and shaft stiffness of 2.6˚/m, by applying a bending moment of 219.313 kPa on the driving pulley. To investigate the effect of the load on the rotating assembly alone, the machine was allowed to vibrate minimally except at the foundation and the electric motor base. The static analysis shows that the pulley and belt responded to the stress which acts more towards the shaft pulley. At the maximum applied bending moment (219.313 kPa), the shaft will operate with relatively no failure except that the belt will need to be adjusted to lessen the displacement (0.9112 mm) from the pulley and in essence prevent operational hazard. To cater for the displacement and to prevent such failure in real-life scenario,

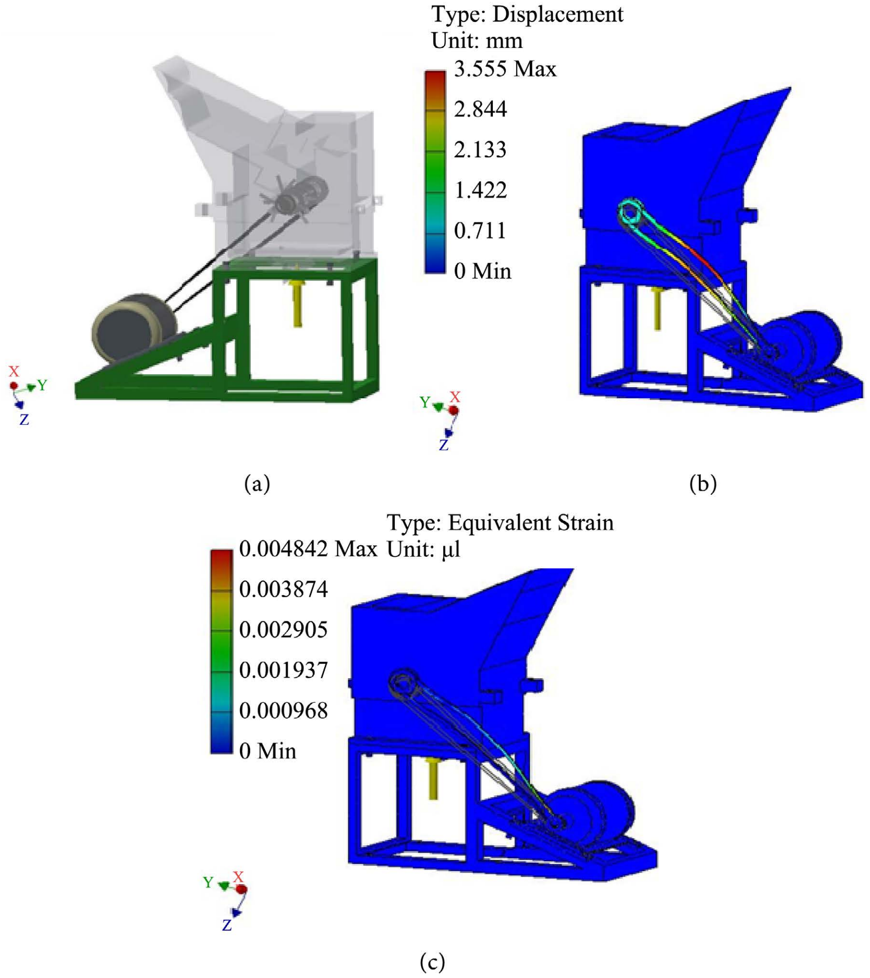

Figure 3. Response to gravity, resulting from vibration during maximum shaft rotation. (a) Visible description of applied gravitational force; (b) Machine displacement due to gravity during operation; (c) Equivalent strain in response to the imposed displacement.

a factor of safety in the range of 9 - 15 uL was considered from the simulation. During fabrication of the machine, a single row, deep groove ball bearing, was selected and the whirling was kept at 0.55836 to withstand the transmitted load.

4) Power Selection, Belt Speed Analysis and Gravity

The power requirement was determined by inserting the value of the total required breaking force of the hammers (see 2.2.1.1) into formulas available in Firouzi [32]. From the result, a 5.5 horse power electric motor was selected at maximum speed of the range 1440 - 4000 rpm. The minimum belt speed at 1440 rpm and power of 4000 W (5.5 hp) is given as:

Belt speed,

$$V = \pi N d_1 / 60 \tag{7}$$

where, N = 1440 rpm and d_1 = 80 mm

$$V = (\pi \times 1440 \times 0.08)/60 = 6.03 \text{ m/s}$$

Excess vibration can undermine the machine's performance; therefore, the forced vibrations and/or self-generated vibrations on the machine at maximum operating rate were examined by subjecting the machine to gravity. We subjected the machine to acceleration due to gravity (9.8 m/s^2), and sensitivity of about 8 - 16 Hz, and discovered that the possible failure occurred at the driving pulley and the driven bearings and belt. The belt was seen pulling off at high speed due to alignment, and the effect tends to break the belt at a maximum strain displacement of 3.555 mm. We considered this potential design failure in the fabrication by making the pulleys of groove angles 320 & 300, groove width 15.85 & 16.00 mm, groove thickness 14.73 mm & 14.73 m and diameters 100 & 80 mm for the large and small pulleys, respectively. A wrap angle and belt tension of 181.79 and 749.99 N were also used by applying available formulas in Khumi and Gupta [34]. For the Roller bearing, five constraints were fixed to prevent all motions and rotation about the x-y axes, while the vibrating surface was also mechanically isolated to limit exposure by installing vibration damping seats.

5) Effect of Pressure on the Hammers

Indisputably, pressure will act on the hammers during rotation when the bones are fed into the chamber through the hopper. Therefore, the effect of pressure on the rotating hammer assembly during operation was also investigated. The machine base is constructed with length of 360 mm and depth of 180 mm, and it can take a minimum of 50 kg of treated dry cow bones in a single feed. Each hammer is 63.5 mm wide, 150 mm long and 6.4 mm thick. Hence, the area of the entire hammer assembly is:

$$A_t = A_s + A_h \tag{8}$$

where, A_t = total area of hammer assembly; A_s = area of shaft and A_h = area of a single hammer.

$$A_s = 2(\pi D) + (2\pi r)h = 2\pi(0.05) + 2\pi(0.025) \times 0.45 = 0.3142 \text{ m}^2$$

$$A_h = lb = 0.15 \text{ m} \times 0.05 \text{ m} = 0.0075 \text{ m}^2$$

$$A_t = 0.3142 + 0.0075 = 0.3217 \text{ m}^2$$

For 12 hammers, A_t = 0.3217 × 12 = 3.8604 m^2.

The maximum possible pressure on the twelve hammers during the milling operation is given thus: pressure = F/A.

$$\text{Force} = m \times a = 50 \text{ kg} \times 9.81 \text{ m/s}^2 = 490.5 \text{ N}$$

Therefore, the hammer assembly can withstand a maximum pressure of 490.5/3.8604 = 12.7 exp 7 MPa.

3. Fabrication of the Milling Machine

The mild steel plate was cut to specification to fabricate the hopper, and some other parts were considered to specification to fit the design as shown in Table 1. Flat metal plate was welded to the tip ends of the hopper front to create holes for joining the base to the hopper using bolts and nuts. Solid shaft of adequate size was selected based on design considerations in Equations (1), (2), and (3). The hammer-chamber plates, of dimensions stated in 2.2.1.5, were also cut to specification and welded together. Six auxiliary shafts were welded to the gaps between the discs and two hammers were inserted on the shafts, making twelve hammers all together. Angle iron bars were welded on both edges to create the support that the hammer chamber stands on, and the bearing support was also welded to the sides of the hammer chamber to aid smooth rotation of the shaft. Finally, the entire component was welded to a stand on a vibrator damper as shown in Figure 4.

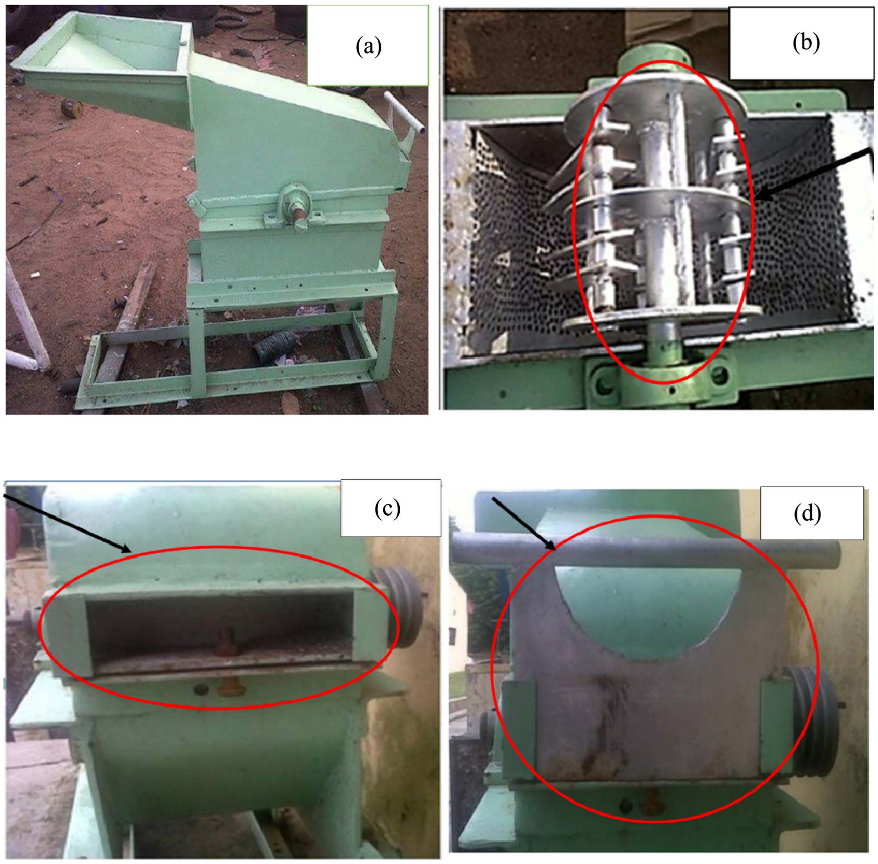

Figure 4. (a) Developed milling machine at the site of fabrication (figure excludes electric motor stand); (b) Complete assembly of hammers and sieve plate; (c) Safety hollow opened after milling operation and (d) Figure of safety hollow closed with mild steel.

Table 1. Materials used in fabrication and description of the dimensions.

No.	Materials	Specification
1	Mild steel angle iron	76 mm × 69 mm
2	Mild steel plate	1220 mm × 2440 mm
3	Mild steel shaft	50 mm × 450 mm
4	Mild steel flat bar	30 mm × 300 mm

Performance Evaluation

Operating the machine requires little technical skill. The milling operation simply involves plugging the electric motor to a stable source of electric power and feeding the bones into the machine through the hopper. The interior of the hopper is chamfered to facilitate unidirectional flow of the raw material by gravity into the milling chamber where the rotating hammers strike and break them into particles of sieve size ≤ 500 μm. The milling performance was evaluated using treated and sun-dried cow bones collected from a large-scale meat processing slaughterhouse in Oja-tuntun, Ogbomoso, Oyo State, Nigeria. The bones were boiled, washed and sun-dried for 18 days. 50 kg of the dry bones were fed gradually into the machine by the operator in a single milling operation and the process was repeated for five consecutive samples, making a total of 250 kg of dry bones. A sample of the dried treated and milled cow bones is shown in **Figure 5**. The milling efficiency of the machine was evaluated through the expected milling rate against the actual milling rate using values obtained during the five milling operations as shown in **Table 2**.

The efficiency was mathematically determined thus:

$$\mu = 50 \text{ kg}$$

$$\lambda e = E_m / n = (10+10+10+10+10)/5 = 50/5 = 10 \text{ min}$$

$$\lambda t = (10.11+10.30+10.32+10.01+10.33)/5 = 51.07/5 = 10.2 \text{ min}$$

$$We = m/At = 50/10 = 5 \text{ kg/min}$$

$$Wr = m/Aat = 50/10.2 = 4.90 \text{ kg/m}$$

$$\eta_m = Wr/We \times 100 = 4.90/5 \times 100 = 0.98 \times 100\% = 98\%$$

where μ = avarage sample weight; λe = average expected milling time; λt = average actual milling time; We = expected working rate and Wr = actual working rate. The difference in milling time resulted from operator's delay in the different feeding process.

A key innovation in this design is the addition of a safety hollow to the back of the machine. The hollow prevents objects or particles from flying out during the milling process, which could hit the eye or other sensitive parts of the body. The safety hollow also serves as housing to receive materials harder than bones, like metals, on impact with the hammers, which flings them in almost a linear direction into the chamfered space at the back on successive or single hit; this is achieved by the interior design of the machine-base shown in **Figure 4(b)**.

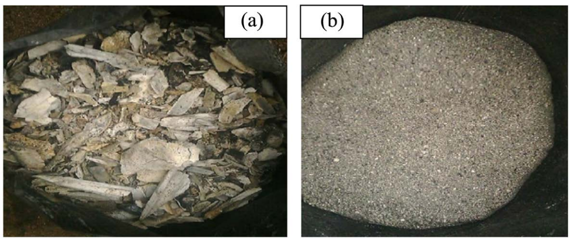

Figure 5. (a) Treated sun-dried cow bone waste fed into the machine and (b) bone powder collected after the milling operation.

Table 2. Output efficiency of the bone milling machine.

S/N	N	M_i (kg)	W_o (kg)	E_m (min)	A_t (min)	n_p (≤μm)	η_m (%)
1	A	50	44.3	10	10.11	500	98.0
2	B	50	43.2	10	10.30	500	98.0
3	C	50	44.4	10	10.32	500	98.0
4	D	50	43.6	10	10.01	500	98.0
5	E	50	44.1	10	10.33	500	98.0

Note: n = sample; M_i = input mass; W_o = output weight; E_m = expected milling time; A_t = actual milling time; n_p = particle size; η_m = machine efficiency.

4. Conclusion

Nigeria is obviously one of the largest meat-producing countries in Africa. Nevertheless, there is no substantial evidence that the tons of bones recovered daily from processing meats in Nigerian slaughterhouses are well managed or utilized. Awareness has been raised about slaughterhouse waste management, especially by Nigeria-based researchers, who suggest that the country needs an attractive national policy to get appropriate sectors interested in investing in recycling the reported wastes for economic value. In this work, we looked into an engineering approach to bone waste utilization on the discussed subject, by developing a reproducible medium-size bone milling machine that operates on the principle of impact and crushing. Sun-dried and treated cow bones were used in the testing because they are the toughest solid waste disposed of in Nigerian slaughterhouses. The machine was able to mill the dry cow bones to the desired particle size, justifying the objective of the design. From the performance evaluation, we can deduce that the high efficiency resulted from the number of hammers in the chamber and power of the electric motor. The numerical modeling and simulation analyses validate the accuracy of the machine design and offered failure predictions and factors of safety that were employed in the fabrication of the machine. To the best of our knowledge, these detailed computational design analyses have not been considered in previous works that suggest milling machines for solid waste management in Nigerian slaughterhouses. The overall cost of producing the machine was relatively low; therefore, the machine is economically feasible for large-scale capacity. The bone milling machine is a potential recovery strategy across abattoirs/slaughterhouses in Nigeria and other African countries facing similar waste management challenges. Adopting the machine in slaughterhouses can create job opportunities for fabricators, the operators of the machine, maintenance personnel, environmental health inspectors and people involved in packaging and selling of the processed bones in rural and urban communities of the country.

Recommendations

To take advantage of the bone milling machine at a national level, we recommend the following:

1) A relatively large-capacity of the machine should be stationed in a clean site in all slaughterhouses, far from the slaughtering and waste deposit site where the treated bones can be dried and crushed/pulverized.

2) Large-scale producing slaughterhouses in Nigeria should be provided with sufficient water supply from a reservoir and industrial-size boilers to treat bones after separation from the meat. The machine can work on diesel engines, so slaughterhouses can be provided with generators in cases where electric power supply is not reliable.

3) The Nigerian government should encourage and invest in packaging of the treated bone powder and make it cheaply available for sale across the country. This will benefit livestock and crop farmers in regions where there is deficiency of potassium in the soil.

4) The proposed means of recycling and recovering bone waste will improve the environment and pave way for other relevant areas where the material can be used. Home-based researchers in Agricultural Sciences and Engineering, Renewable Energy, Chemistry, etc. should take advantage of the available milled product to investigate if the material can be of indigenous use.

5) Small-scale meat producing abattoirs and livestock farmers in rural areas can adopt the portable size of the milling machine to process their bones for personal or commercial use.

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Conflicts of Interest

The authors declare that there is no conflict of interest about the publication of this paper.

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