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DESIGN AND STRUCTURAL ANALYSIS OF A PARTICULATING MACHINE FOR PLANTAIN FLOUR PROCESS PLANT

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ABSTRACT

Plantain is used for the management of type II diabetes. Plantain is usually processed into value-added and storable products, such as flour, in order to extend its shelf-life and make it available for consumption all the year round. Processing plantain into flour requires that its size be reduced before drying in order to increase its drying rate, reduce its processing time, and prevent microbial growth and decay. This paper presents conceptual design and finite element analysis (FEA) of a machine for particulating plantain in a plant that processes unripe plantain into flour. The machine consists of a hopper with cover, a particulating drum, a shaft, a belt drive, an electric motor, a pulley, a delivery chute and a support frame. Model for the machine was developed using Solid Works Computer Aided Design (CAD) application software. Appropriate materials were selected for its component parts and their design analysis was done. Its functionality and structural stability were evaluated by simulating the developed model using Solid Works CAD application software. The FEA conducted on its frame showed maximum stress of 213 MPa, resultant displacement of 0.37 mm, elastic strain of 1.0×10^{-16} and a minimum factor of safety (FOS) of 2.3 when a force of 595 N was applied on the frame. Also, the FEA conducted on the particulating drum showed a maximum stress of 19.3 MPa, resultant displacement of 6.98×10^{-3} mm, strain of 2.62×10^{-5} and a minimum FOS of 8.9 when a torque of 50 Nm was applied. The implication of the FEA results is that the particulating machine will be able to satisfactorily serve its intended purpose under normal working conditions, when fabricated, since the maximum stress values obtained from the FEA of its component parts are far below the corresponding yield strength values of the materials selected for their fabrication. The estimated cost of production for the machine is ₦398,700 ($1,092).

Keywords: diabetes COVID-19, plantain, particulating machine design, finite element analysis, flour process plant.

1. INTRODUCTION

Diabetes has been reported as a risk factor for corona virus (COVID-19) (Seewoodhary and Oozageer 2020). Diabetes' presence has been associated with worse outcomes as well as increased mortality in COVID-19 patients (Hussain *et al*., 2020; Wang *et al*., 2020). Diabetes is one of the major problems in the world today, and it is very interesting to know that plantain can be used for the management of diabetes (Oluwajuyitan and Ijarotimi, 2019). There is an increasing market demand for plantain and its products due to their nutritional and medicinal values (Olutomilola and Omoaka, 2018; Olutomilola *et al*., 2019). After wheat, rice and corn, plantain is known to be the fourth most important crop in the whole world, with annual production of 32.01 million tons (Alonso-Gomez *et al*., 2020). It is a staple food and an important diet in Nigeria and in the humid tropical zones of Africa, Asia, Central and South America. It has been reported that Nigeria is the largest producer of plantain in West Africa and that she also ranked fifth in the world with annual production of 2.7 million metric tons (Adeoye *et al*., 2013; Ayodeji, 2016). Due its perishable nature as a fruit, its postharvest losses are very high and it is usually processed into value-added and storable products, such as flour, in order to extend its shelf-life, make it available for consumption all the year round and make its transportation from one location to another very easy (Olutomilola *et al.*, 2016; Oyejide *et al.*, 2018; Olutomilola *et al*., 2019; Alonso-Gomez *et al*., 2020).

Processing plantain into flour requires that its size be reduced by slicing or particulating it before drying in order to increase its drying rate, reduce its drying time, prevent microbial growth and decay. This has a way of influencing the quality of the flour obtained after processing. In plantain flour production, peeling and washing operations are usually followed by slicing plantain pulps into thin slices for drying. To achieve this, a lot of researchers have designed and developed machines for slicing plantain pulps. Obeng (2004) developed a manually operated plantain slicer which took 5 to 7 seconds to slice a finger of an average-sized plantain pulp into chips of thickness 2 to 3 mm. The study observed that the thickness of the chips produced by the machine compared favourably with commercial standards. Despite the success recorded by the study, the slicer developed by it is not suitable for use in a plantain processing plant because it is manually loaded and offloaded. Hence, it can only be used for domestic purposes.

A lot of researchers have also developed motorized machines for slicing plantain pulps into chips for subsequent processing. Sonawane *et al.* (2011) developed an electrically powered rotary banana slicer for small scale food processing industries, based on engineering properties of banana. The slicer consists of feeders for round slicing, a three-blade cutter with 360 rpm rotational speed, power transmission mechanism, base support and frame. The slicer has an average slicing efficiency of 93.5% and a capacity of 100 kg/h. Kalaivani *et al.* (2012) developed an electrically powered plantain

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slicer with a maximum capacity of 90 kg/h, a cleaning efficiency of 61% and 95.8% of standard slices. Ismail *et al.* (2013) developed an improved plantain slicing machine, with an average efficiency of 93%, using a slider-crank mechanism that is driven by an electric motor through a belt drive.

Okafor and Okafor (2013) developed a motorized machine, with a production efficiency of 74%, for slicing plantain pulps into chips using a cam and spring return mechanism for feeding and slicing the pulps. Obayopo *et al.* (2014) developed a machine for slicing plantain pulps into 5 mm thick chips, with 90% and 91% efficiencies that were based on the rate of production of slices per time for ripe and unripe plantain pulps respectively. It was also recorded that 90.7% and 92.6% of the ripe and unripe plantain pulps' slices were respectively within acceptable range. Ugwuoke *et al.* (2014) developed a motorized rotary slicer for plantain chips production with no recorded efficiency. Adesina *et al.* (2015) developed a plantain slicing machine with a capacity of 52 kg/h and an efficiency of 80%. Akande and Onifade (2015) modified a plantain slicing machine from which an operating capacity of 181.76 kg/h and an efficiency of 95.79% were obtained. Other researchers include Onifade (2016), Osueke *et al.* (2016), Usman and Bello (2017), Bello *et al.* (2017) and Oyedele *et al.* (2018). It has been observed that the machines developed by these researchers are manually loaded with plantain pulps; their capacities are too low for a process plant; and they cannot directly fit into a plantain processing plant. It has also been observed that none of the machines developed by the said researchers for slicing plantain pulps is suitable for use in a processing plant where continuous production of plantain flour is a major factor, and where plantain pulps are needed for drying in particulate form. Hence, there is a need to eliminate the manual feeding of plantain pulps into size reducing machines by developing a particulating machine for plantain pulps which will be suitable for use in a plant that processes plantain into flour.

The development and performance evaluation of cassava grating machines were also reported by Ndaliman (2006), Adetunji and Quadri (2011), Ajao *et al.* (2013) and Oriaku *et al.* (2015). The major grating components of the machines developed by these researchers are perforated metallic drums. It is crystal clear that if the same principle applied in their works for grating cassava is used for plantain pulps, they will form slurry or stick together. This will drastically slow down their drying rate and prolong the processing time. Moreover, based on the properties and geometry of yam, Ayodeji *et al.* (2014) developed a yam peeling and slicing machine for a yam processing plant. Its capacity and efficiency were reported to be 4320 kg/h and 87.86% respectively. It can be inferred from the discovery made from the study that the machine is not suitable for use in plantain processing plant because the properties and geometry of plantain and yam are not the same. Hence, there is a need to still develop a machine for particulating plantain pulps, before drying, in a plant that processes unripe plantain into flour.

2. MATERIALS AND METHODS

2.1 Design Concept of the Particulating Machine

Based on the observations made by Ogazi (1996), there is a need to particulate plantain pulp in order to increase its drying rate so as to reduce its drying or processing time. Hence, the machine was designed to particulate incoming plantain pulps before entering the drying unit of the plantain processing plant. The machine consists of a hopper with cover, a particulating drum, a shaft, a belt drive, an electric motor, a pulley, a delivery chute and a support frame. The major component of the machine is the particulating drum. Its periphery is equipped with cutters in form of stainless steel wires, spikes or rectangular serrated plates, whose height above the drum surface is 5 mm or 10 mm as presented in Figures 1 and 2. Thus the cutters, which are arranged perpendicularly to the surface of the particulating drum, enable the machine to work on shear cutting principle. As the particulating drum rotates, the cutters impact on the surfaces of plantain pulps, which cause them to cut by shearing along a plane, while the delivery chute helps to channel the particulated plantain pulps into the drying section. The delivery chute is provided with a cover in order to prevent the pulps from gathering foreign materials such as dust and the likes. Power is transmitted from an electric motor to the input shaft through belt drive. The frame helps to suspend and provide a firm support for the machine.

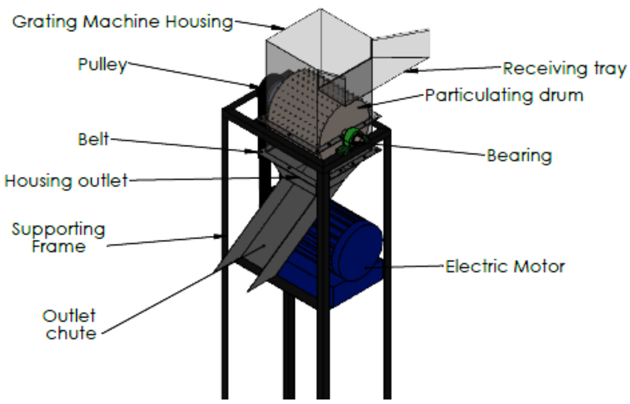

Figure-1. Isometric view of the particulating machine.

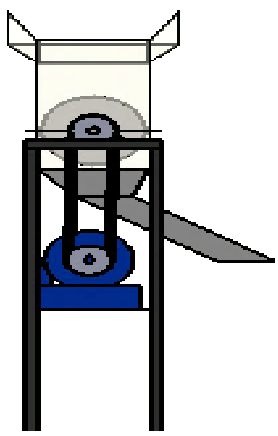

Figure-2. Side view of the machine.

2.2 Design of the Particulating Machine Hopper

The particulating machine hopper is a stainless steel structure in the form of a hollow rectangular box as shown in Figure-3. The stainless steel used for the hopper is 3 mm thick. According to Macrae *et al*. (2014), the volume of the machine's hopper was obtained as 39380800 mm^3 using Equation (1). The hopper was so designed to give room for easy assembling and dissembling by minimizing permanent joints and introducing temporary joints through incorporation of flanges on its four sides.

$$V_{ph} = L_{ph} \times B_{ph} \times H_{ph} \tag{1}$$

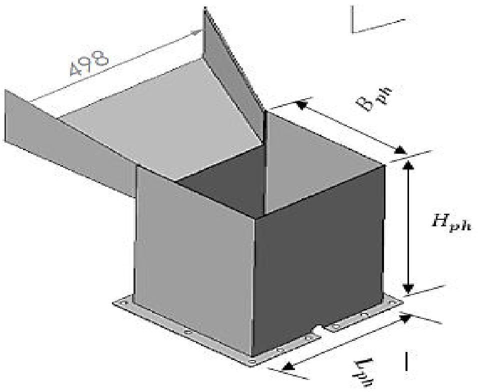

Figure-3. Particulating machine hopper and housing.

2.3 Determination of Shear Stress for Raw Plantain Pulp

According to Obeng (2004), Ugwuoke *et al.* (2014), Ayodeji (2016), Onifade (2016) and Joseph *et al.* (2019), the diameters of raw plantain pulps range from 30 mm to 70 mm; the average diameter of raw plantain pulps is 50 mm; the impact force required to shear raw plantain pulp is 33.15 N; the length of a plantain pulp ranges from 200 mm to 300 mm; and the shear stress for raw plantain pulp was obtained to be 0.017 MPa from Equations (2a) and (2b). Hence, 33.15 N was assumed to be the force required to particulate raw plantain pulp.

$$\tau_p = F_p / A_p \tag{2a}$$

$$A_p = \frac{\pi D_p^2}{4} \tag{2b}$$

2.4 Power Required by the Particulator to Shred Raw Plantain Pulp

According to Onifade (2016), a peripheral velocity of 4.83 m/s is needed by the cutting wires on the particulating drum to particulate raw plantain pulp. Hence, the power required by the particulating drum to make the spikes on it particulate raw plantain pulp was obtained as 160.11 W from Equation (3).

$$P_c = F_p \times \upsilon_{pd} \tag{3}$$

2.5 Power Required by the Electric Motor

According to Khurmi and Gupta (2008), the speed of the particulating drum on shaft was obtained to be 307 rpm from Equation (4) and its diameter was chosen to be 290 mm. The height of particulating wires above the surface of particulating drum is 5 mm. Hence, the introduction of particulating wires on the periphery of the particulating drum gave a total diameter of 300mm.

$$N_{pd} = (\upsilon_{pd} \times 60)/\pi D \approx 307\, rpm \tag{4}$$

The power of the electric motor was estimated to be 320.22 W or 0.43hp by using Equation (5).

$$P_M = P_c \times P_F \tag{5}$$

Hence, an electric motor of 1.12 kW (or 1.5 HP) rated power, with a speed of 1460 revolutions per minute, was chosen for the particulating machine based on safety and its availability in market (Daniyan *et al*., 2014; Onifade, 2016; Ayodeji, 2016).

2.6 Design of Belt Drive for the Particulating Machine

The Speed ratio of the belt drive for the particulating machine and the total power transmitted were determined using Equations (6a) and (6b) respectively. A Service Factor (SF) of 1.3 was also selected for the machine.

$$SR_{pd} = N_{sm}/N_{pd} \approx 4.76 \tag{6a}$$

$$P_D = P_{sm} \times SF \approx 1.456\, kW \tag{6b}$$

Therefore, a wedge-belt of SPZ or QXPZ cross section was selected. From Centre distance tables for SPZ and QXPZ cross section wedge-belts, pulleys of 63 mm and 315 mm pitch diameters were selected for the electric motor and particulating drum shafts respectively, after establishing a minimum pitch diameter of 63 mm for the pulleys.

2.7 Determination of Belt Centre Distance, Length and Correction Factor

According to Childs (2004), Fenner (2009) and Udo *et al.* (2015), the minimum and maximum Centre distances of the two pulleys were respectively estimated by using Equations (7) and (8), but the Centre distance selected must be greater than the diameter of the larger pulley as indicated in Equations (10).

$$C_{d,min} = 0.55\left(D_{\mathrm{Pdp}} + D_{mp}\right) + t_{belt} \approx 216\, mm \tag{7}$$

$$C_{d,max} = 2\left(D_{\mathrm{Pdp}} + D_{mp}\right) = 756\, mm \tag{8}$$

$$C_{d,ave} = \frac{C_{d,min} + C_{d,max}}{2} = 486\, mm \tag{9}$$

$$\begin{cases} C_{d,min} \leq C_d \leq C_{d,max} \\ C_d \text{must be } > D_{\mathrm{Pdp}} \end{cases} \tag{10}$$

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Hence, a center distance of 487 mm, which satisfies Equation (10), was selected for the two pulleys and the corresponding correction factor of 0.90 was selected for it from the same table of value. According to Khurmi and Gupta (2008), the belt length L_B was obtained as 1600 mm using Equation (11).

$$L_B = 2C_d + \frac{(D_{Pdp} - D_{mp})^2}{4C_d} + \frac{\pi(D_{Pdp} + D_{mp})}{2} \quad (11)$$

2.8 Number of Belts Required by the Particulating Machine

By interpolation, rated power per belt (for 63 mm pitch diameter pulley at 1460 rpm) was estimated to be 1.08 kW; while additional power (for speed ratio 4.76 and 1460 rpm speed) was estimated to be 0.24 kW from Power Ratings and Additional Power Ratings tables for SPZ belt Section (Fenner, 2009).

$$P_{rpb} = \text{Rated power} + \text{Additional power} = 1.31\text{kW} \quad (12)$$

$$P_{tpb} = P_{rpb} \times \text{CF} \approx 1.179 \text{ kW} \quad (13)$$

$$n_{br} = \frac{\text{Design Power}}{\textit{Power transmitted per belt}} \approx 2 \quad (14)$$

2.9 Shaft Design for the Particulating Machine

The torque transmitted by the shaft is given by Equation (15). The loading of the particulating machine's shaft was treated as a simply supported beam with uniformly distributed load (which was converted to a point load) in-between supports and an overhang load as shown in Figures-4, 5, 6 and 7. Shaft length of 550 mm was chosen based on the length of grater's hopper and particulating drum. The total weight of the particulating drum is the weight of the material rolled to form the drum plus the weight of the two discs covering the drum at both ends plus the weight of plantain in the machine plus the weight of particulating wires or spikes on the drum surface. Hence, the total weight of the particulating drum was estimated using Equation (22). The tensions in the belt drive were determined using Equations (15), (16), (17), (18), (19) and (20).

$$\mathcal{T}_{tms} = (T_{ts} - T_{ss})R_{pdp} = \frac{P_{sm} \times 60}{2\pi N} = 34.83\ Nm \quad (15)$$

$$T_{ts}/T_{ss} = 10^{\mu\theta/2.3 \sin\beta} \quad (16)$$

Substituting Equation (16) into Equation (15) gives Equation (17).

$$T_{ss} = \mathcal{T}_{tms}/\{R_{pdp}(10^{\mu\theta/2.3 \sin\beta} - 1)\} \quad (17)$$

$$\alpha = (D_{Pdp} - D_{mp})/2C_d = 0.2567\ rad \quad (18)$$

$$\theta = (\pi - 2\alpha) \approx 2.63\ radians \quad (19)$$

$$\mu = 0.54 - [42.6/(152.6 + V_{pd})] \approx 0.27 \quad (20)$$

$\therefore T_{ss} \approx 23\ N$

From Equation (16),
$T_{ts} = T_{ss} \times 10^{\mu\theta/2.3 \sin\beta} \approx 246.45\ N$

$$F_{pdp} = T_{ts} + T_{ss} + W_{pdp} = 279.45\ N \quad (21)$$

$$W_{pd} = W_{RM} + W_{SD} + W_{PIM} + W_{pwd} = g(m_{RM} + m_{SD} + m_{PIM} + m_{pwd}) = 250\ N \quad (22)$$

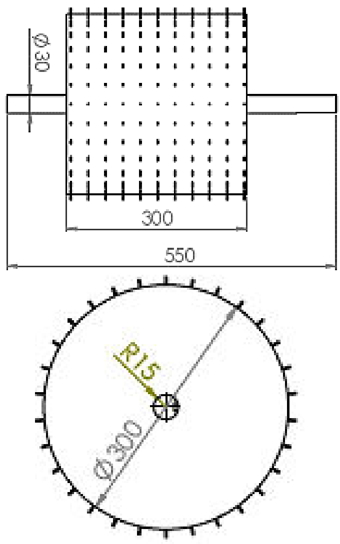

Figure-4. 2D-view of the particulating drum.

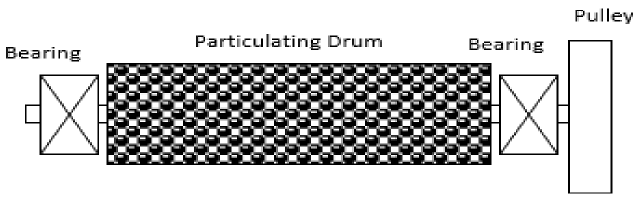

Figure-5. Space diagram of the particulating drum assembly.

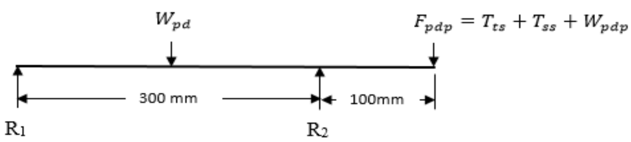

Figure-6. Line diagram of the particulating drum assembly.

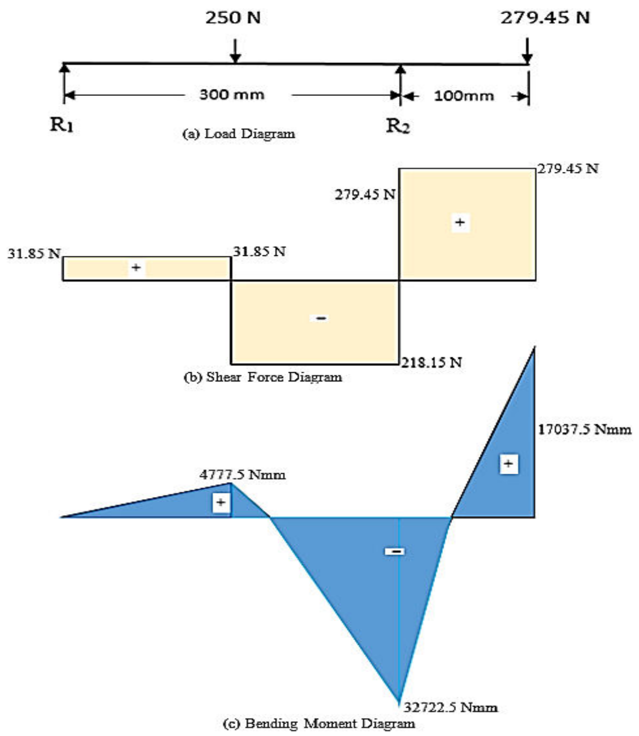

Figure-7. Load, shear force and bending moment diagrams of the drum.

Summing the vertical forces in Figure-7 gives

$$R_1 + R_2 = 250 + F_{pdp} = 529.45\ \mathrm{N} \tag{23}$$

Taking moments about R_1 gives

$$300R_2 = (250 \times 150) + (279.45 \times 400)$$
$$\therefore R_2 = 497.6\ \mathrm{N};\ R_1 = 31.85\ \mathrm{N}$$

Thus, the maximum bending moment is 28000 Nmm. Equation (24) was then used to determine shaft diameter for the machine to be 22.1 mm.

$$d_{pds} = \sqrt[3]{\frac{16\left(\sqrt{(K_m \times M_{bms})^2 + (K_t \times \mathcal{T}_{tms})^2}\right)}{\pi \times \tau_{ms}}} \tag{24}$$

Hence, a shaft of 30 mm diameter was selected for the particulating machine by using 1.36 factor of safety (Khurmi and Gupta, 2008).

3. RESULTS AND DISCUSSIONS

3.1 FEA Evaluation of the Particulating Machine

The workability, functionality and structural stability of the particulating section design were evaluated by FEA of the model developed for it using Solid Works CAD application software. The machine frame model was discretized into 500 elements and 508 nodes in order to generate its solid mesh for FEA as shown in Figure-8. The FEA conducted on the frame showed a maximum stress of 0.11 GPa, a maximum resultant displacement of 0.366 mm, a maximum strain of 1.0×10^{-16} and a minimum factor of safety (FOS) of 2.3 when a force of 595 N was applied on it as shown in Figures-9 to 12 respectively. However, the maximum stress value obtained from the FEA is lower than the yield strength of the mild steel selected as material for the frame as shown in Figure-9. Also, model for the particulating drum was discretized into 40260 elements and 84676 nodes in order to generate its solid mesh for FEA as shown in Figure-13. The FEA conducted on the particulating drum showed a maximum stress of 19.3 MPa, a maximum resultant displacement of 0.00698 mm and a maximum strain of 2.622×10^{-5} when a torque of 50 Nm was applied on it as shown in Figure-14, 15 and 16 respectively. Thus a minimum factor of safety (FOS) value of 8.9 was obtained, which is as presented in Figure-17. However, the maximum stress value obtained from the FEA of the particulating drum is lower than the yield strength of the stainless steel selected as material for it as shown in Figure-14.

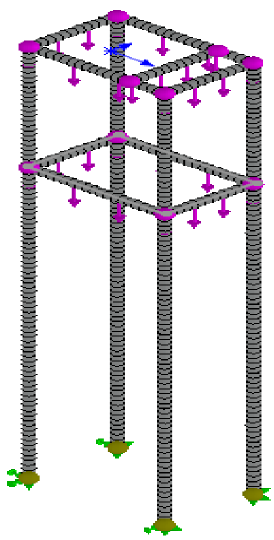

Figure-8. Solid mesh model of the machine's frame.

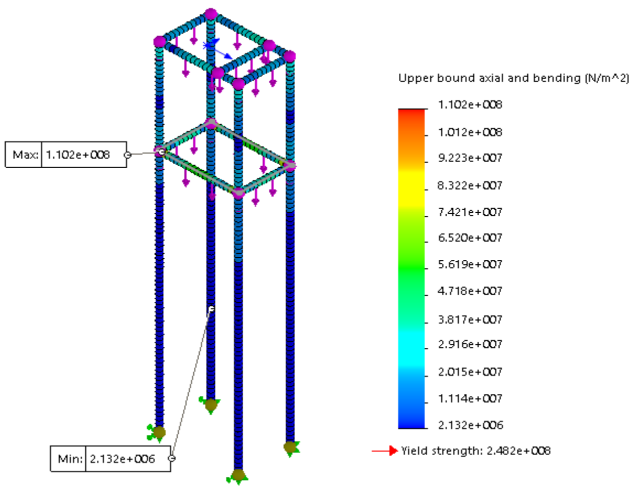

Figure-9. FEM of stress distribution within the frame.

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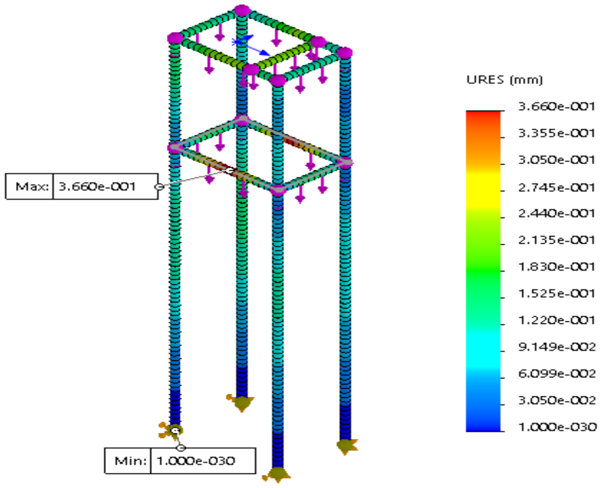

Figure-10. FEM of resultant displacement of frame.

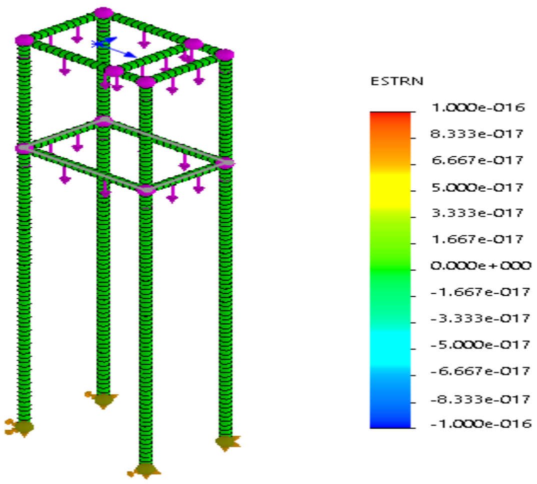

Figure-11. FEM of strain distribution within the frame.

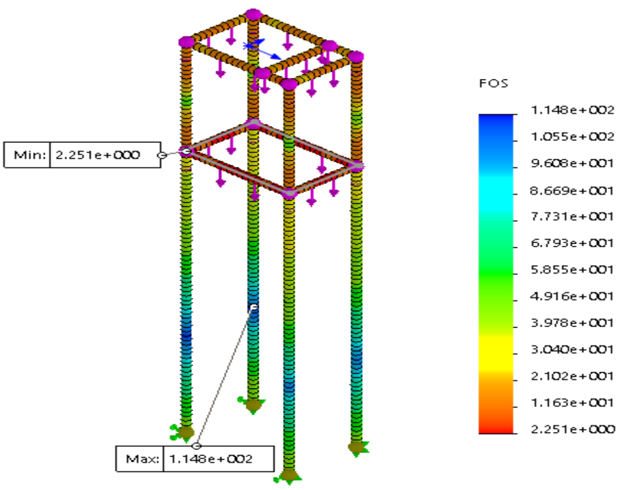

Figure-12. FEM of factor of safety distribution on frame.

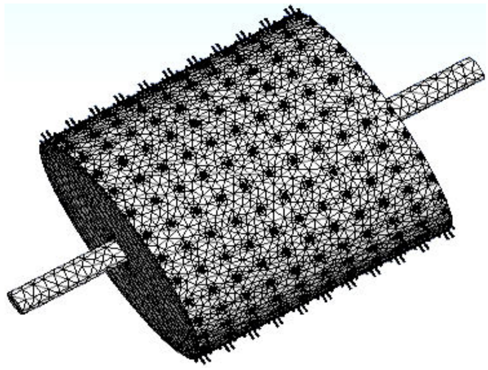

Figure-13. Solid mesh model of the particulating drum.

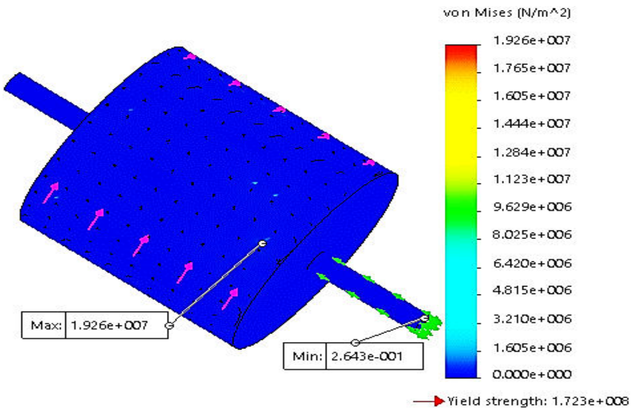

Figure-14. FEM of stress distribution within the drum.

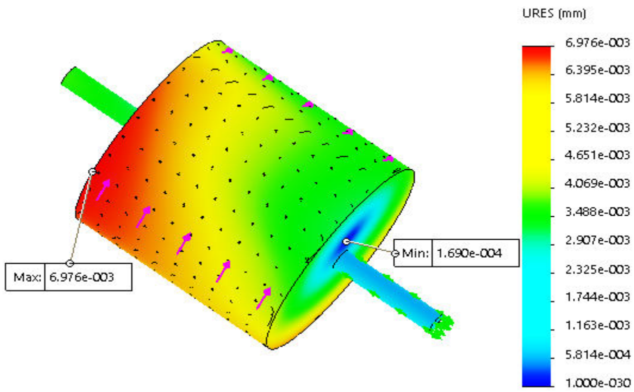

Figure-15. FEM of resultant displacement of the drum.

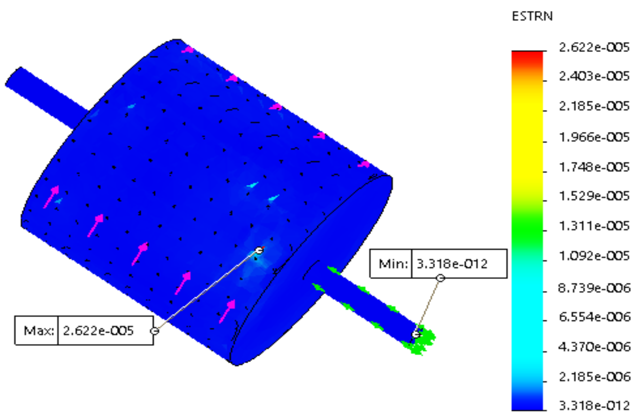

Figure-16. FEM of strain distribution within the drum.

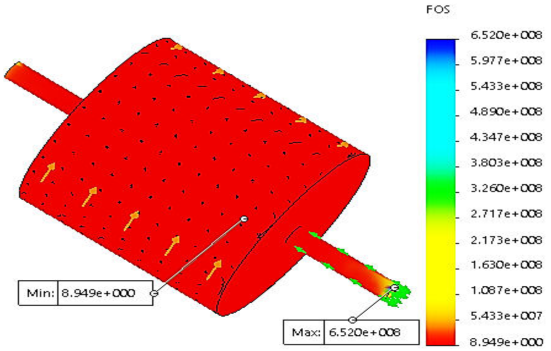

Figure-17. FEM of FOS distribution on the drum.

3.2 Implication of FEA Results for the Particulating Machine

The implication of the aforementioned FEA results is that the particulating machine will be able to satisfactorily serve its intended purpose under normal working conditions, when fabricated, since the maximum stress values obtained from the FEA of its components are far lower than the corresponding yield strength values of the materials selected for their fabrication. However, the locations that are subjected to these stress values are potential areas where failure may likely begin after a long period of time in service; but failure will not likely occur since the FOS values obtained are high enough to prevent the component parts of the machine from experiencing structural failures under normal working conditions. It can therefore be inferred that the design of the particulating machine is adequate and safe for fabrication. However, the materials selected for the machine can be reviewed to further reduce the FOS values obtained. The bill of engineering measurement and evaluation (BEME) for the machine is as presented in Table-1. The estimated cost of production for the machine is ₦398,700 ($1,092).

Table-1. Bill of engineering measurement and evaluation for the machine.

S. No	Component	Total Cost (₦)
1	Particulating chamber, Delivery chute &others	45,000
2	Drum, Drill bits, Machining & Wire Frame	120,000
3	Drive shaft	10,000
4	Pulley	10,000
5	Electric motor & Pillow bearing	75,000
6	Grinding & Cutting disc	2,000
7	Transportation	10,000
8	Welding electrode	12,700
9	Finishing	10,000
10	Conversion cost	50,000
	GRAND TOTAL	398,700

4. CONCLUSIONS

In this study, a unit for particulating plantain pulps before entering the drying unit of a plant that processes unripe plantain into flour was designed. The model developed for it was simulated in order to evaluate its functionality and structural integrity. The results obtained showed that the maximum stresses induced within the component parts of the particulating machine were far below the yield strengths of mild steel and stainless steel selected for the fabrication of its component parts. As a result of this, the minimum factor of safety obtained was 2.3, which is high enough to prevent structural failure of the machine during service (Olutomilola and Omoaka, 2018). It can therefore be inferred that the design is safe for fabrication and that the machine will be able to effectively serve its intended purpose of particulating plantain pulps for drying under normal service conditions without failure.

Moreover, the particulating unit (which is an ongoing research work) will help reduce casehardening effect that is usually experienced by plantain pulps during drying. It will also increase the drying rate of plantain pulps, thereby reducing their residence time in the drying unit. Being an ongoing research, it is to be noted that the machine's design would be improved upon. A prototype of the improved design would be fabricated; its performance would be evaluated, after which it would be automated and incorporated into the process plant.

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List of Symbols

V_{ph} = Volume of the particulator's hopper
L_{ph} = Length of the hopper (326 mm)
B_{ph} = Breadth of the hopper (302 mm)
H_{ph} = Height of the hopper (400 mm)
F_p = Force required to shear raw plantain pulp (33.2 N)
A_p = Area of plantain pulp under shear in m^2
τ_p = Shear stress of raw plantain pulp
D_p = Average diameter of raw plantain pulp (0.05 m)
P_c = Power required by the particulating drum in watts
υ_{pd} = Peripheral velocity of particulating drum
N_{pd} = Speed of the particulating drum in rpm
D = Total diameter of particulating drum (300mm)
P_M = Needed electric motor power (in watts)
P_F = Power factor (2)
SR_{pd} = Speed ratio of the belt drive
N_{sm} = Speed of the selected motor
P_D = Design power or total power transmitted
P_{sm} = Selected motor power
D_{Pdp} = Diameter of particulating drum pulley
D_{mp} = Diameter of electric motor pulley
C_d = Selected center distance
t_{belt} = Belt thickness (8 mm)
$C_{d,min}$ = Minimum center distance between the two pulleys
$C_{d,max}$ = Maximum center distance between the two pulleys
$C_{d,ave}$ = Average center distance between the two pulleys
L_B = Belt length
P_{rpb} = Power rating per belt
P_{tpb} = Corrected power or power transmitted per belt
CF = Correction factor
n_{br} = Number of belts required
$\mathcal{T}_{tms}$ = Torque transmitted by the shaft
T_{ts} = Tight side tension
T_{ss} = Slack side tension
R_{pdp} = Radius of particulating drum pulley
P_{sm} = Selected motor power or power transmitted by shaft (1120 watts)
μ = Coefficient of friction between belt and pulley
θ = Angle of lap or contact between belt and pulley
b = Half the groove angle of the pulley (17.5°)
g = Acceleration due to gravity
m_{RM} = Mass of the material rolled to form the drum (9.05 kg)
m_{SD} = Mass of the two discs covering the drum at both ends, (4.3 kg)
m_{PIM} = Mass of plantain in the machine (10 kg)
m_{pwd} = Mass of particulating spikes or wires on drum surface (2 kg)
K_m = Shock factor for bending (2)
K_t = Fatigue factor for torsion (2)
d_{pds} = Particulating drum shaft diameter
M_{bms} = Bending moment of the machine shaft
τ_{ms} = Allowable shear stress of the machine's shaft (42 MPa) (Khurmi and Gupta, 2008)