Development and testing of a vertical-spikes shelling machine for bambara groundnuts

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This paper aim to develop a low-cost Bambara groundnuts sheller that uses vertical spikes as the shelling mechanism. A vertical spike shelling machine was designed, constructed and evaluated. The Bambara groundnut shelling machine consisted of a hopper, shelling system, frame, motor and power transmission system. The Bambara groundnut sheller used a low-cost shelling mechanism of spikes and shaft system, as it has ability to break different sizes of the Bambara groundnut pods. The prototype was tested for shelling efficiency, percentage mechanical damage of nuts during shelling and machine capacity. The machine was evaluated for shelling efficiency, mechanical damage capacity and cleaning efficiency. The samples used for evaluation were set at different moisture content levels of 6, 15 and 20%. The shelling efficiency of the machine declined from 71.7 to 21.9% as moisture content increased from 6 to 20%. The mechanical damage decreased from 3.66 to 1.46% as the moisture content increase while the machine capacity also declines from 145.6 to 80.1 kg hour⁻¹. The prototype can therefore be viewed as feasible for implementation by small scale farmers.

Key words: Shelling, vertical spikes, efficiency.

INTRODUCTION

Bambara groundnuts are an African crop, mostly grown by local farmers for subsistence and sale to the local communities (Alonge et al., 2016; Tan et al., 2020). This crop is recognized as the third most important legume grain after groundnuts and cowpea (DAFF, 2016). Bambara nuts production is manually and labour intensive from land preparation, crop establishment, crop protection through to harvesting due to lack of processing equipment (Elfediyi et al., 2020; Tan et al., 2020). To ensure that the crop does not rot after harvesting, the nuts should be sun dried and stored at moisture content of between 12 and 14% (Gerrano et al., 2021). Therefore, the Bambara groundnuts require drying and shelling after harvesting to extend shelf life and maintain quality. In South Africa, once the Bambara groundnuts are processed, they are used for various applications that include human consumption as peanut butter or for industrial processes as cosmetics and animal feed (DAFF, 2016).

Traditional manually shelling methods have been seen as a laborious, time consuming and result in high groundnut damage (Atiku et al., 2004). In South Africa,
the manually shelling process involves use of sticks and stones to break the Bambara groundnuts kernels (DAFF, 2016). Processing groundnuts using traditional methods has a lower, throughput and capital returns, and results in higher postharvest losses compared to mechanized systems. Therefore, traditional methods cannot be a panacea to the Bambara groundnut shelling challenges faced by small and medium scale farmers. However, literature shows that there are other available shelling techniques or methods that are mechanized that have been used by farmers and evaluated by researchers. A Bambara groundnut shelling machine that uses a roller shelling mechanism was designed and tested (Atiku et al., 2004). The machine resulted in shelling and winnowing efficiencies of 60 and 79.5%, respectively, at a moisture content of 5% (Atiku et al., 2004). Aviara et al. (2012) mention that shells/kernels are easily cracked by centrifugal mechanism compared to roller mechanism due variations in the size of groundnuts. Based on this discovery, Olowole et al (2007) and Alonge et al. (2016) focused on the design of a Bambara groundnut sheller machine that used the centrifugal method and they achieved higher shelling efficiencies compared to the machine designed by Atiku et al. (2004). Mechanized shelling systems, despite having higher shelling efficiencies and throughput are expensive and require technical expertise to operate, making them unaffordable and inaccessible to small and medium scale farmers who do not have the financial means and lack operation skills (Alonge et al., 2016; Srilak et al., 2021). The current traditional and mechanized systems of shelling Bambara groundnuts do not meet the needs of small and medium scale farmers as they are either low throughput or capital intensive. Therefore, there is need for a simple and affordable design for farmers with budgetary constraints. Hence the main objective of this study was to design a Bambara groundnut shelling machine that uses a vertical spikes mechanism. This mechanism should be simple, inexpensive, and constructed from locally available materials. The shelling mechanism should have both a lower mechanical damage and adequate throughput.

MATERIALS AND METHODS
This study was carried out at Ukulinga research farm at the University of KwaZulu-Natal, Pietermaritzburg campus in South Africa (30°24’S, 29°24’E).

This study was conducted to investigate the following questions:

1. Is the vertical spikes mechanism affordable and efficient during shelling of Bambara groundnuts?
2. Does the shelling method of using spikes contribute to significant groundnut damage?

Description of the vertical spikes shelling machine
A shelling machine with vertical spikes as the shelling mechanism was used in this research. The prototype consisted of hopper, spikes, shaft, electrical motor and frame. The hopper had a triangular prism shape to allow the groundnuts to slide down to the shelling mechanism. During operation, Bambara groundnuts were temporarily stored in an inclined hopper before moving into the drum where they fell by gravity onto the rotating shelling shaft with spikes. This process created an impact force that broke the pods. To drive the shaft, a motor, pulleys and belts were used. Figure 1 shows the completed vertical spikes shelling machine prototype.

Design analysis
This section summarizes the design analysis for the hopper, shelling shaft, frame and power transmission systems. The machine was designed specifically for use by small scale farmers in South Africa as they are the main growers of Bambara groundnuts (DAFF, 2016). The study specifications were to design a:

1. Bambara groundnut shelling machine with a capacity of at least 100 kg hour⁻¹
2. Prototype with a shelling efficiency of at least 80 %, and
3. Shelling machine with mechanical damage of less than 5 %.

Hopper
The hopper design was based on the angle of repose which determines movement of materials (Aremu et al., 2015). The side’s slope of the hopper was designed to allow the bulky materials to fall free without need of an external force. The proposed design machine capacity was 100 kg hour⁻¹ because the target beneficiaries are small scale farmers. The total volume required was calculated to be 0.28 m³ from considering the density of Bambara groundnuts pods at a 6% moisture content (MC). From calculations the triangular prism hopper could only handle 0.01 m³ per fill meaning that the machine had to be filled 28 times to achieve the design machine capacity. The length (l) and breadth (b) of the hopper were set at 420 and 130 mm respectively. The height of the triangular prism was calculated to be 200 mm from Equation 1.

\[ v = \frac{1}{2} \times b \times h \]  
(1)

Where \( v \) = volume \( (m^3) \); \( l \) = length \( (m) \); \( b \) = breadth \( (m) \) and \( h \) = height \( (m) \).

The hopper was welded on top of the housing. The technical drawing of the hopper and the semi-circular cylinder are shown in Figure 2.

Determination of the required power
The total shelling power is combination of the required power for cracking kernels \( (P_s) \) and the power needed to drive the shelling shaft \( (P_o) \).

Required power for cracking kernels \( (P_s) \)
The average force required for cracking Bambara groundnut pods and nuts at 6% moisture content was 32 ±12 and 73.74 ± 16.3 N, respectively based on experiments. The power calculations were based on the physical properties of Bambara groundnuts at 6% moisture content. The assumption made was that the shelling shaft had a diameter of 25 mm. Several literature reports that 250 to 350 rpm is the most efficient shelling speed for different varieties of groundnuts. Therefore, in this prototype design, the shelling speed
was set at 250 rpm to minimize groundnuts damages (Srina et al., 2021). The angular velocity ($w$) was calculated to be 26.19 rad.s$^{-1}$ from Equation 2 (Ogunlade et al., 2014; Raghtate and Handa, 2014).

$$w = \frac{2\pi N}{60}$$

(2)

where $w$ = angular velocity (m.s$^{-1}$), and $N$ = speed of the shaft (rpm).

The torque of the shelling spikes was calculated to be 15 Nm using equation 3 (Ogunlade et al., 2014). The required shelling power was calculated to be 601.8 W from Equation 4 (Ogunlade et al., 2014). A safety factor of 1.5 is used if the chosen shaft key is rectangular according to Ogunlade et al. (2014).
The static vertical moment diagram for the shelling mechanism.

\[ T = F \times r \times n_s \times n_a \quad (3) \]

Where \( T \) = shaft torque (Nm); \( F_{av} \) = average crack force (N); \( n_a \) = number of active row per time; \( n_s \) = number of active spikes, and \( r \) = radius of the shaft (m).

\[ P_s = TW\times SF \quad (4) \]

where \( P_s \) = power required to shelling Bambara groundnuts (W), \( T \) = shaft torque (Nm), and \( SF \) = safety factor.

**Power required to drive the spikes and shelling shaft (P_D)**

In this research, the shelling mechanism used was vertical spikes welded in a shaft. This combination was chosen because Oluwole et al. (2007) found that using an impact force in shelling was better than using rollers and a drum. Due to variation of dimensions, some of the groundnut pods were damaged or un-shelled when a roller mechanism was used. The shelling mechanism was made up of four rows of shelling vertical-spikes which were welded on the shaft. The average length of Bambara groundnuts seeds ranges 10.1 to 11.81 mm (Mpotokwane et al., 2008). Therefore, spaces between spikes were set at 11 mm to allow only the shelled groundnuts to pass through. The mass of the spikes was calculated from density formula:

\[ V_s = \pi r^2 h \quad (5) \]

Where \( V_s \) = volume of each spike (m³), \( r \) = radius of the Shaft (m), and \( h \) = spikes height (m).

The total mass of the spike was calculated from density formula:

\[ \rho = \frac{m}{V} \quad (6) \]

\[ m = \rho \times V \]

Total weight = mass of each \times number of spikes \quad (7)

The combined weight of the shaft and spikes was 45 N, and it was obtained by multiplying the mass and gravity acceleration constant (Alonge et al., 2017). The torque of the shaft with the spikes was calculated to be 0.56 Nm from Equation 8 (Hassan et al., 2009). Thus, the power required to drive the shelling mechanism was computed to be 22 W from Equation 9 (Hassan et al., 2009).

\[ T_D = W_D \times R_D \quad (8) \]

where \( T_D \) = torque (Nm); \( W_D \) = mass of shaft and spikes (N), and \( R_D \) = radius of shaft and spikes (m).

\[ P_D = \omega_D \times T_D \times FS \quad (9) \]

Where \( P_D \) = power required to drive shaft (W), and \( \omega_D \) = angular velocity (rad. \( s^{-1} \)).

The combined power was calculated to be 623.8 watts from Equation 10. The smallest local available motor selected was a 1.1 kW at 1390 rpm speed against the required rotational speed of 250 rpm. Therefore, speed reduction was required, and two pulleys and belt were introduced to reduce the speed from 1390 rpm (motor speed) to 250 rpm.

\[ P = P_S + P_D \quad (10) \]

**Shaft sizing**

Shaft sizing heavily depends on the axial loads, torsion and bending. These parameters have an impact on the life expectancy of the bearings which support the shaft in both ends (Hassan et al., 2009). In this research, the axial loads on the shaft included weight of the spikes and driven pulley. Figure 3 represent the static force diagram of the shaft with maximum vertical moment of 4.30 Nm. There was a horizontal force acting on the shaft. Therefore, the resultant moment \( (M_{rr}) \) and torsional moment \( (M_t) \) were calculated to be 4.30 and 23.03 Nm from Equations 14 and 15 respectively (Ogunlade et al., 2014).

\[ M_{max} = \sqrt{M_{rr}^2 + M_t^2} \quad (14) \]
Where $M_{\text{max}}$ = resultant bending moments; * $M_x$ = maximum horizontal bending moments diagram (Nm), and $M_y$ = maximum vertical bending moments (Nm).

$$M_t = \frac{P_s \times 60}{2 \pi N_1}$$  \hspace{1cm} (15)

Where $M_t$ = Torsional moments (Nm); $P_s$ = power required for shelling Bambara groundnuts (W), and $N_1$ = speed of small pulley (rpm).

The shaft was supported by two bearings to ensure that vibration and movement were minimized. The combined fatigue factor ($k_b$) and torsional moment factor ($k_t$) were set to be 2.0 and 1.5, respectively (Hassan et al., 2009). The allowed bending stress ($\gamma_d$); and safety factor (SF) for the shaft with keyways were 40 Nm.m$^{-2}$ and 1.5 respectively (Hassan et al., 2009). The shaft diameter was calculated to be 24 mm from Equation 16 (Olaoye and Adekanye, 2018). The standard available shaft size of 25 mm diameter was selected for this study based on the power calculations above. The spikes were then welded on the shelling shaft. The detailed drawing of the shelling shaft can be seen in Figure 4.

$$d_{\text{shaft}} = \left( \frac{16}{n_0} \right) \left( \left( k_b M_{\text{max}} \right)^2 + \left( k_t M_t \right)^2 \right)^{0.5} \times SF$$  \hspace{1cm} (16)

Where $d_{\text{shaft}}$ = diameter of the shelling shaft (m); $k_b$ = combine shock and fatigue factor applied in bending moment; $k_t$ = combine shock and fatigue factor applied on torsional moment, $M_{\text{max}}$ = resultants bending moments (Nm), $M_t$ = maximum torsional moment (Nm), $\gamma_d$ = allowable stress for steel shaft , and FS = safety factor.

The shaft and the driven pulley were connected by a rectangular sunk key. The width and thickness of keys were calculated to be 6.25 and 4.17 mm from Equations 17 and 18 respectively (Khurmi and Gupta, 2005).

$$w = \frac{d}{4}$$  \hspace{1cm} (17)

where $w$ = weight of the shaft (mm), and $d$ = diameter of the shaft (mm).

$$t = \frac{d}{6}$$  \hspace{1cm} (18)

where $t$ = thickness of key (mm), and $d$ = diameter of the shaft (mm).

**Design of frame structure**

A frame was selected to carry the whole load of the machine. The frame was made from a square tube with dimensions of 38 mm (length), 38 mm (height) and 2 mm (thickness). The strength and stability of the frame was checked against buckling due the applied load (SAISC, 2013). The total combined weight for the hopper and shelling mechanism was calculated to be 5.95 kg while the combined weight of the other components was 411.16 N. The frame calculations were according to the procedure outlined in the South African Steel Construction Handbook (SAISC, 2013).
Equation 19 to 24 was used to check the stability of the frame (SAISC, 2013). The sectional area of the frame of 38×38×2 mm square tube was calculated to be 148 mm$^2$ from Equation 19. Figure 5 shows detailed drawing of the frame.

$$A = (2a-t)$$  \hspace{1cm} (19)

Where $A$= area of the section ($\text{mm}^2$); $t$= thickness ($\text{mm}$) and $a$= width ($\text{mm}$).

The natural axis was calculated to be 27.75 mm from the Equation 20.

$$y = a - \frac{a^3 + at^2}{2(a-2t)}$$  \hspace{1cm} (20)

Where $y$=neutral axis ($\text{mm}$).

Moment of inertia ($I$) for the square tube of 38×38×2 mm was calculated to be 21,149 mm$^4$.

$$I = \frac{1}{3}(ty^3 + a(a-y)^3 - (a-t)(a-y)^2 - t^3)$$  \hspace{1cm} (21)

Where $I$=moments of inertia ($\text{mm}^4$)

The section modulus ($Z$) and radius of gyration ($k$) was calculated to be 762 mm$^3$ and 12 mm.

$$Z = \frac{I}{y}$$  \hspace{1cm} (22)

$$k = \frac{r}{\sqrt{A}}$$  \hspace{1cm} (23)

The total load that created buckling or crippling was calculated to be 35,456 N from Equation 24. The crippling or buckling load was found to be greater than the total load acting on the frame which is 3,800 N (SAISC, 2013). Therefore, the frame was able to hold the components without any failure.

$$W_{cr} = \frac{cm^2EAk^2}{L^2}$$  \hspace{1cm} (24)

**Sheller performance evaluations**

Bambara groundnuts samples were obtained from a local market in Mpumalanga province, South Africa. The groundnuts were cleaned, and foreign materials were removed before the shelling process started. Initial moisture content was determined using the standard oven method, where the groundnuts samples were oven-dried for 3 h at 130°C (Alonge et al., 2016; Aviare et al., 2012). The initial moisture content was determined as 6% using Equation 25 and a calculated amount of water was added (Equation 26) to the groundnuts. The water was added to the samples to bring moisture content to the required different levels of 6, 15 and 20%.

$$M_{cw} = \frac{W_i - W_d}{W_i} \times 100$$  \hspace{1cm} (25)

Where $M_{cw}$= moisture content (%); $W_i$= initial mass (kg) and $W_d$= final mass (kg).

$$Q = \frac{W_f(M_i - M_f)}{100M_i}$$  \hspace{1cm} (26)

where $W_i$= initial mass (kg); $M_i$= initial moisture (%) and $M_f$= required moisture (%).
The prototype was tested for three performance evaluations namely, shelling efficiency, grain damage or mechanical damage, and machine capacity (Nwigbo et al., 2008; Raghtate and Handa, 2014; Srilal et al., 2021). Shelling efficiency is defined as the ratio of shelled groundnuts to the total mass of groundnuts fed into the hopper (Srilal et al., 2021). Equation 27 was used to calculate the shelling efficiency of the prototype (Atiku et al., 2004).

\[ \eta_s = \left( \frac{N_1 + N_2}{N_T} \right) \times 100 \]  

Where \( \eta_s \) = shelling efficiency (%), \( N_1 \) = number of pods that were shelled and unbroken (g), \( N_2 \) = number of broken seed (g), and \( N_T \) = total number of groundnuts fed to shelling chamber(g).

The mechanical damage was calculated as ratio of the number of broken nuts to the number of groundnuts fed onto the system machine (Srilal et al., 2021). Equation 28 is used to calculate mechanical damage (Srilal et al., 2021). The grain damage is normal expressed as percentage.

\[ \eta_p = \left( \frac{w_j}{w_T} \right) \times 100 \]  

Where \( \eta_p \) = mechanical damage (%); \( w_j \) = total number of groundnuts (g), and \( w_r \) = number of pods fully with broken nuts (g).

The machine performance was evaluated by measuring the weight of groundnuts shelled per unit time. Equation 29 was used to calculate the machine capacity (Olaoye and Adekanye, 2018).

\[ \text{Capacity} = \frac{Q_s}{T_m} \]  

Where \( Q_s \) = weight of shelled groundnuts (kg), and \( T_m \) = shelling time (s).

**RESULTS AND DISCUSSION**

**Shelling efficiency**

The findings indicate that there was a linear relationship between shelling efficiency and moisture content. The shelling efficiency of this prototype declined from 71.7 to 21.8% as moisture content rose from 6 to 20% at the significance levels of 5%. The Bambara groundnuts are shelled by introducing impact forces between the groundnut kernels and spikes. As the moisture content increased, contact time between the spikes and kernels also increased resulting in impact force reduction. Therefore, the shelling efficiency declined as moisture content rose as seen in Figure 6. A similar finding was reported by Atiku et al. (2004), where a bambara groundnuts sheller was designed and tested, and achieved a maximum shelling efficiency of 80% at a feed rate of 93.6 kg.hour\(^{-1}\). A horizontal centrifugal Bambara sheller was also designed and tested by Alonge et al. (2017) and similar observations were made in that shelling efficiency declined with increased moisture content of groundnuts. As a way of improving efficiency, Oluwole et al. (2007) increased the number of impellers on the shaft and the highest value was obtained with nine. This shows that increasing the number of spikes could potentially improve the shelling efficiency of this prototype. Despite the low shelling efficiency compared to the prototype design by Oluwole et al. (2007), Alonge et al. (2017) and Atiku et al. (2004), this shelling mechanism...
has the potential to be improved and implemented by small scale farmers.

**Mechanical damage**

The results show that there is reduction in grain damage as the moisture content increases. The grain damage decreased from 3.66 to 1.46% as the moisture content increased from 6 to 20% as presented in Figure 7. The study design specification stated that the mechanical damage should not exceed 5%, which was achieved during the evaluations. The expectation was that as the moisture content rose, more nuts would break due to the soft skin of the groundnuts at high moisture content. However, in this study, the results showed that as the moisture increased, the pods became more resistant to the impact force due to the high contact time between spikes and kernels. As moisture increased the pods became more sponge-like, which prevented the seed from experiencing mechanical damage. Similar results were also reported by Oluwole et al. (2007) where a centrifugal Bambara groundnut sheller was designed, constructed, and evaluated providing a similar trend. Marketability of the groundnuts correlates with the percentage of the undamaged nuts the lower the percentage the higher the marketability. Therefore, due to the low mechanical damage observed in this study, this prototype can be promoted for implementation by small scale farmers as local consumers and market prefer to consume or purchase nuts that are undamaged.

**Machine capacity**

The design output capacity of the prototype was specified to at least 100 kg.hr⁻¹. During evaluation of this prototype, the results showed that the output capacity declined as the moisture content increased. The machine capacity declined from 145.6 to 80.1 kg.hour⁻¹ as the moisture content decreased from 6 to 20% as represented in Figure 8. The decline in machine capacity was caused by friction between groundnuts and the hopper surface at high moisture content. When the moisture content rose, the groundnuts experienced more friction as they rolled down the hopper. As a result, the machine had a lower machine capacity for high moisture content scenarios. This trend was also reported by Atiku et al. (2004). The maximum machine capacity was 145.6 kg.hour⁻¹ at 6% moisture content. While the design specification was to shell at least 100 kg.hour⁻¹. Therefore this prototype met the design specifications. During the shelling process, it is recommended that farmers shell the groundnuts at 6% moisture. Farmers can then add moisture after shelling to the recommended storage levels of 12 to 14%.

**Conclusion**

A vertical-spikes Bambara groundnuts shelling machine was designed, constructed and evaluated. The designed prototype consisted of a hopper, shelling shaft, transmission system, frame and a motor. The machine was evaluated for shelling efficiency, mechanical
damages, and machine capacity. The results show that shelling efficiency drop as moisture content increases. On the other hand, the mechanical damage and machine capacity also decreased from 3.66 to 1.45%, and 145.6 to 80.1 kg hour⁻¹, respectively. The best performance was recorded at 6% (w.b) moisture content. The shelling mechanism is affordable and requires less maintenance during operation. Therefore, this prototype can be viewed as feasible for implementation by small scale farmers.

CONFLICT OF INTERESTS

The authors have not declared any conflicts of interests.

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