SHELLING AND CHARACTERISATION OF THE TECHNICAL PARAMETERS OF A SHEA NUT (Vitellaria paradoxa) SHELLING MACHINE IN CAMEROON

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ABSTRACT

Producers of shea kernels encounter difficulties in processing the nuts. This leads to greater losses of raw material and a reduction in the yield of shea butter, as processing is generally done manually by smallholders, who produce more shea kernels in local areas. Added to this is the arduous work involved in shelling, due to the lack of a shelling machine adapted to their level of production. This study was, therefore, carried out to improve local shea butter production capacity. The huller was designed using data on the physical, gravimetric, geometric and frictional properties of shea nuts, before being built and tested. The hopper has an angle of inclination of 62.64°; a concave clearance of 3.6 cm and a winnowing air flow rate of 0.53 m³/s. The machine has an hourly capacity of 136 kg/h. The performance test showed that moisture content had a significant influence on hulling efficiency, cracking rate and machine output. The best cracking rate of 3.68±0.74% was obtained with a moisture content of 10.24%. The hulling efficiency obtained with the above content is 92.43±1.05%, a cleaning efficiency of 78.30±0.55% and a machine yield of 88.83±0.38%. Water contents of <10.24% are ideal for better shelling efficiency.

Key words: shea nuts, Shelling machine, Technical characteristics, Physical, geometric and gravimetric properties

INTRODUCTION

The shea tree (Vitellaria paradoxa) of the Sapotaceae family is a plant whose fruit contains a fat called shea butter. Shea butter obtained from the kernels is mainly used in traditional medicine in many rural areas (Leakey, 1999). In recent years, the growing consumption of shea butter around the world has led to a concerted effort by industry players to increase production (Coulibaly et al., 2004). The fleshy fruit of the shea tree contains a kernel with a fat content of 40-50%, which when extracted makes up shea butter (Diaallo, 1988). This edible and pharmaceutical oil is used in cosmetics, in the manufacture of soap and various toilet milks, and in the candle industry in several developed countries (Kapseu et al., 2005; Womeni et al., 2006). However, developing African countries, which are the main producers of shea kernels, process them less. Cameroon is not excluded because shea kernels produced in northern regions are less processed locally. Yet the area is ideal for their production. Artisanal processing of shea kernels is holding back production growth (Dandjouma et al., 2009). Traditionally, shea kernels are hulled by pounding the nut in a mortar or with a stone (Ahouansou et al., 2008). These different techniques are tedious and time-consuming, and expose female producers to aches and pains and the risk of abrasions. In addition, these hulling methods do not allow producers to process their entire product, which leads to post-harvest losses of around 40%, as is the case for most tropical agricultural products (Maldangoi et al., 2003). These losses are due to the lack of development of means of processing and preserving these products (Nkouam, 2007). To avoid losses during production periods, it is essential to shell the kernels in order to extract the lipids. However, virtually no studies have been carried out on the mechanised shea nut shelling process in Cameroon. There is, therefore, a need to improve the kernel shelling process and reduce the risks to the subsequent quality of the butter. Such an improvement can be envisaged by controlling the necessary moisture content of the kernels subjected to hulling. The aim of this work is to design, build and evaluate the performance of the shea kernel hulling machine. In order to determine the influence of the physical, geometric, gravimetric and frictional properties of the shea kernels with the aim of improving the shea butter production yield and the quality of the final product.

MATERIALS AND METHODS

Shea Nut Collection Area

The shea nuts used to test the machine were collected at in Bangou in western region Cameroon and in four production areas in northern region Cameroon: Rabingha, Djefatou, Laïndé-Massa and Gashiga.

The statistical analysis adopted for the technical parameters of the shea nut shelling machine evaluation was a $4 \times 3 \times 3$ factorial experiment in Completely Randomized Design, with three replicates using Statistical Products and Service Solutions (SPSS) 18.0. Analysis of variance (ANOVA) was used to analyze the significance of each of the factors on each of the performance indices.

Characterisation of the Physical and Geometric Properties of the Shea Nut

Determination of the physical properties

The 25 kg samples were placed in a dehydrator at $105^\circ$C for 72 hours until they reached a constant weight and weighed using a ROHS balance, accurate to 0.01g. The water content of the nuts and almonds is assessed in accordance with ISO standard 662 of 1998. Weight loss on final drying is recorded as weight and weighed using a ROHS balance, accurate to 0.01g. The water content of the nuts and almonds was determined from the equilibrium position, which is reached when the weight of the samples remains unchanged for 3 hours after each weighing (AOAC, 1984). The moisture content of the nut is calculated by equation 1.

$$MC = \left(\frac{W_{a} - W_{d}}{W_{d}}\right) \times 100 \quad (1);$$

where $MC$ is moisture content (%), $W_{a}$ is weight of shea nuts before drying (g), and $W_{d}$ is weight of shea nuts after drying in a dehydrator (g).

Determination of geometric properties

Samples of 1000 nuts from the five production zones were arbitrarily taken, i.e., 200 nuts per production zone, given the wide variety of geometric shapes of the different nuts. Dimensions were determined in accordance with the ISO 520 standard. A digital caliper with a resolution of 0.02 mm was used to measure the major diameter (length), intermediate or equatorial diameter (width) (b) and minor diameter (thickness) of each nut (Amoah, 2012). These measurements were made on a sample of 100 nuts taken at random from the stock. Since shea nuts and kernels are oblong in shape, the dimensions were determined from the equilibrium position, which is often either the germ face or the opposite face (Ahouansou et al., 2008).

The arithmetic mean diameter of shea nuts was determined using equation 2 (Mohsenin, 1980):

$$D_{a} = \left(\frac{a+b+c}{3}\right) \quad (2);$$

where $D_{a}$ is arithmetic mean diameter of the nut (mm), $a$ is length of nut (mm), $b$ is equatorial diameter of the nut (mm), and $c$ is width of the nut (mm).

Equation 3 was used to determine the arithmetic mean diameter (Aliyu et al., 2017):

$$D_{g} = \left(\frac{a \times b \times c}{3}\right)^{\frac{1}{3}} \quad (3);$$

where $D_{g}$ is arithmetic mean diameter of the nut (mm), $a$ is length of nut (mm), $b$ is equatorial diameter of the nut (mm), and $c$ is width of the nut in centimetres (mm).

Equation 4 was used to determine the geometric mean diameter (Aliyu et al., 2017):

$$\varnothing = \frac{\left(a \times b \times c\right)^{\frac{1}{3}}}{a} \quad (4);$$

where $\varnothing$ is geometric mean diameter (mm), $a$ is length of nut (mm), $b$ is equatorial diameter of the nut (mm), and $c$ is width of nut (mm).

Equation 5 was used to determine the surface area of the shea nut (Dauda et al., 2019):

$$S = \pi \times (D_{g})^{2} \quad (5);$$

where $S$ is surface area of the nut (mm$^2$) and $D_{g}$ is geometric mean diameter (mm).

Since the shea nut is an elongated ellipsoid, its unit volume was determined using the axial dimensions of the kernel by equation 6 (Stroshine, 1998):

$$V = \pi \times \left(\frac{a \times b \times c}{6}\right) \quad (6);$$

where $V$ is unit volume of the nut, $a$ is length of nut (mm), $b$ is equatorial diameter of the nut (mm), and $c$ is width of nut (mm).

The aspect ratio is the ratio between the length and width of the shea nut. It was calculated using equation 7 (Sharma et al., 2011):

$$R = \left(\frac{b}{a}\right) \times 100 \quad (7);$$

where $R$ is aspect ratio, $a$ is length (mm), and $b$ is equatorial diameter (mm).

Characterisation of Gravimetric and Frictional Properties of Shea Nuts

Characterisation of the gravimetric properties

A sample of 100 nuts arranged in 10 heaps of 10 nuts each was weighed using a ROHS electronic balance accurate to 0.01g. The average obtained was multiplied by 100 to obtain the mass of 1000 shea nut units accurate to 0.01g. The average bulk density was calculated for each replicate using equation 8:

$$\rho_a = \left(\frac{m_a}{V_{a}}\right) \quad (8);$$

where $\rho_a$ is apparent density (kg m$^{-3}$), $m_a$ is sample weight (kg), and $V_{a}$ is volume of the sample (m$^3$).

The actual density was determined by the water displacement method and calculated using equation 9 (Olajide et al., 2000):

$$\varphi_r = \left(\frac{m_r}{V_r}\right) \quad (9);$$

where $\varphi_r$ is core density (kg m$^{-3}$), $V_r$ is sample weight (kg), and $m_r$ is volume of the sample (m$^3$).
Porosity was calculated from the apparent and real densities using equation 10 (Mohsenin, 1980):
\[
\varepsilon = 1 - \left( \frac{\rho_a}{\rho_r} \right) \times 100 \tag{10}
\]
where \(\varepsilon\) represents porosity (%), \(\rho_a\) is apparent density (g cm\(^{-3}\)), and \(\rho_r\) is real density (g cm\(^{-3}\)).

**Determination of frictional properties**
The height of the pile was measured using the depth gauge on the caliper and the angle of repose \(\Theta\) calculated using equation 11 (Karababa, 2006):
\[
\theta_f = \tan^{-1} \left( \frac{2h}{D} \right) \tag{11}
\]
where \(\theta_f\) is angle of repose in degrees, \(H\) is heap height (mm), and \(D\) is diameter of the circular plate (mm).

**Design and Sizing of the Various Components of the Shea Nut Sheller**
Analysis of the physical, geometric, gravimetric and frictional properties of the shea nut were used to determine the dimensions of the various technical characteristics of the sheller: the concave clearance of the beating drum and its concave radius, the angle of inclination of the hopper, the ventilation air flow rate and the power of the motor (Oluwole et al., 2004; Aviara et al., 2005). The huller performance test was carried out by determining shelling efficiency, recovery efficiency of shelled kernels, cracking rate, hourly capacity of the sheller and electrical energy consumption.

**Centrifugal force of the beater**
The centrifugal force was determined by using equation 12 (Olakanni, 2004):
\[
F_c = M_L \times R_D \times W_D^2 \tag{12}
\]
where \(F_c\) centrifugal force generated in the internal basket (N), \(M_L\) is mass of the hulling blade (kg), \(W_D\) is angular speed of the drum (rad sec\(^{-1}\)), and \(R_D\) is drum radius (m).

**Total force on the beater shaft**
The total force on the beater shaft in the hulling unit was calculated using equation 13 (Ibrahim et al., 2016):
\[
F_{TD} = (F_c + (M_M + M_D) \times g) \tag{13}
\]
where \(F_{TD}\) is total force on hulling unit shaft (N), \(M_M\) is mass of the husking drum (kg), \(M_D\) is weight of the crank on the hulling shaft (kg), and \(g\) is acceleration due to gravity (N kg\(^{-1}\)).

**Total force on cleaning unit shaft**
The total force on the tree of the pulped nut cleaning unit was calculated thus (Ibrahim et al., 2016).
\[
F_{TN} = (M_P + M_{PN}) \times g \tag{14}
\]
where \(F_{TN}\) is total force on cleaning unit shaft (N), \(M_P\) is blade mass in the cleaning unit (kg), \(M_{PN}\) is mass of the pulley on the cleaning unit (kg), and \(g\) is acceleration due to gravity (N kg\(^{-1}\)).

**Gate ventilation air flow rate**
The airflow rate produced by the centrifugal fan was estimated based on the air velocity required for cleaning, duct width and duct depth using equation 15 (Dziurzynski et al., 2017):
\[
Q = V \times S \tag{15}
\]
where \(Q\) is air flow rate (m\(^3\) s\(^{-1}\)), \(V\) is speed required for cleaning (m s\(^{-1}\)), and \(S\) is surface area of the nut (m\(^2\)).

**Blower motor power requirement**
The power required for effective cleaning was determined using equation 16:
\[
P_N \frac{2\pi \times N_N \times F_{TN} \times R_V}{60} \tag{16}
\]
where \(P_N\) is power required to drive the fan (kW), \(N_N\) is speed of rotation of the fan pulley (R min\(^{-1}\)), \(F_{TN}\) is total force on cleaning unit shaft (N), and \(R_V\) is fan radius (m).

**Hopper volume**
The volume of the hopper was obtained thus:
\[
V = \frac{m}{\varphi_r} \tag{17}
\]
where \(V\) is hopper volume (m\(^3\)), \(\varphi_r\) is real density (g cm\(^{-3}\)), and \(m\) is mass of shea nuts (g).

**Hopper tilt**
The angle of inclination of the hopper was calculated by using equation 18:
\[
\theta = \tan^{-1} \left( \frac{2h}{l_1 - l_2} \right) \tag{18}
\]
where \(\Theta\) is angle of inclination of hopper (rad), \(h\) is height of the triangle (m), \(l_1\) is length of the lower part of the hopper (m), and \(l_2\) is width of the upper part of the hopper (m).

**Concave clearance**
The design of the concave clearance of the hulling unit is one of the most important aspects in the design of a hulling machine, and this was determined using Equation 19 after Onyechi et al., 2014:
\[
C_c = \frac{a + b}{2} \tag{19}
\]
where \(C_c\) is concave clearance (mm), \(a\) is main diameter of the shea nut (mm), and \(b\) is small diameter of the shea nut (mm).

**Concave radius**
Equation 20 was used to calculate the concave radius of the beater drum:
\[
R_c = R_D + C_c \tag{20}
\]
where \(R_c\) is concave radius (mm), \(R_D\) is drum radius (mm), and \(C_c\) is concave clearance (mm).

**Sheller Performance Test**
Parameters measured during the tests
Table 1 shows the various parameters in the sheet for the data used to evaluate machine performance.
Table 1: Parameters measured during the tests machine performance

<table>
<thead>
<tr>
<th>Try 1</th>
<th>Try 2</th>
<th>Try 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content</td>
<td>Mₜ₁, Mₜ₂, Mₜ₃</td>
<td>Mₜ₁, Mₜ₂, Mₜ₃</td>
</tr>
<tr>
<td>Number of shea nuts</td>
<td>Nₜ₁, Nₜ₂, Nₜ₃</td>
<td>Nₜ₁, Nₜ₂, Nₜ₃</td>
</tr>
<tr>
<td>Number of shelled nuts</td>
<td>N₉₁, N₉₂, N₉₃</td>
<td>N₉₁, N₉₂, N₉₃</td>
</tr>
<tr>
<td>Number of unshelled nuts</td>
<td>N₀₁₀₀₁, N₀₁₀₀₂, N₀₁₀₀₃</td>
<td>N₀₁₀₀₁, N₀₁₀₀₂, N₀₁₀₀₃</td>
</tr>
<tr>
<td>Number of broken nuts</td>
<td>N₅₁, N₅₂, N₅₃</td>
<td>N₅₁, N₅₂, N₅₃</td>
</tr>
<tr>
<td>Total weight of nuts (kg)</td>
<td>M₁₅₁, M₁₅₂, M₁₅₃</td>
<td>M₁₅₁, M₁₅₂, M₁₅₃</td>
</tr>
<tr>
<td>Mass of shelled walnuts (kg)</td>
<td>M₀₁₀₀₁, M₀₁₀₀₂, M₀₁₀₀₃</td>
<td>M₀₁₀₀₁, M₀₁₀₀₂, M₀₁₀₀₃</td>
</tr>
<tr>
<td>Separate hull mass (kg)</td>
<td>Mₙ₁, Mₙ₂, Mₙ₃</td>
<td>Mₙ₁, Mₙ₂, Mₙ₃</td>
</tr>
<tr>
<td>Shelling time</td>
<td>D₀₁, D₀₂, D₀₃</td>
<td>D₀₁, D₀₂, D₀₃</td>
</tr>
</tbody>
</table>

Shelling efficiency

The shelling efficiency was determined using equation 21 (Gbabo et al., 2013):

\[ E_D = \frac{N_D}{N_T} \times 100 \]  

where \( E_D \) is shelling efficiency (%), \( N_D \) is number of shelled nuts, and \( N_T \) is total number of shea nuts.

Cleaning efficiency

The cleaning efficiency was determined by equation 22 (Gbabo et al., 2013):

\[ E_N = \frac{M_C}{M_T} \times 100 \]  

where \( E_N \) is cleaning efficiency (%), \( M_C \) is mass of hulls separated (g), and \( M_T \) is total mass of hulls (g).

Recovery efficiency of shelled almonds

Equation 23 was used to determine the recovery efficiency of shelled kernels (Gbabo et al., 2013).

\[ E_R = \frac{N_P}{N_T} \times 100 \]  

where \( E_R \) is recovery efficiency (%), \( N_P \) is number of nuts lost, and \( N_T \) is total number of shea nuts processed at a time.

Breakage rate

The breakage rate is the ratio between the number of broken sheaths (\( N_B \)) and the number of seeds in the treated sample \( N_T \). It was calculated using equation 24:

\[ T_B = \frac{N_B}{N_T} \times 100 \]  

where \( T_B \) is breakage rate (%), \( N_B \) is number of broken nuts, and \( N_T \) is total number of shea nuts processed at a time.

Machine efficiency (RM)

The efficiency of the machine was determined using equation 25:

\[ Rm = \frac{N_{DN} \times E_D}{N_D} \times 100 \]  

where \( Rm \) is machine efficiency (%), \( N_{DN} \) is number of unbroken shelled nuts, \( E_D \) is shelling efficiency, and \( N_D \) is total number of shelled nuts.

Percentage of unshelled seeds

Equation 26 was used to determine the percentage of unshelled seeds:

\[ P_{ND} = \frac{N_{ND}}{N_T} \times 100 \]  

where \( P_{ND} \) is percentage of unshelled seeds, \( N_{ND} \) is number of unshelled seeds, and \( N_T \) is total number of seeds.

Percentage of partially shelled seeds

The percentage of partially shelled seeds is determined by using equation 27:

\[ P_{PD} = \frac{N_{PD}}{N_T} \times 100 \]  

where \( P_{PD} \) is percentage of partially shelled seeds, \( N_{PD} \) is number of partially shelled seeds, and \( N_T \) is number of total sentences.

Hourly machine capacity

The hourly capacity of the huller is the average quantity (in kg) of almonds hulled in 1 h of operation. It was determined using equation 28:

\[ C_h = \frac{M_{ND} \times 60}{M_D} \]  

where \( M_{ND} \) average of shelled nuts (kg), \( C_h \) s hourly capacity (kg), and \( M_D \) is weight of shelled nuts (kg).

Real capacity

The actual capacity of the huller is the actual quantity (in kg) of kernels hulled in a specific time of operation of the machine. It is determined using equation 29:

\[ C_v = \frac{M_D}{t} \]  

where \( C_v \) is actual capacity (kg), \( M_D \) is weight of shelled nuts (kg), and \( t \) is actual shelling time (h).

RESULTS AND DISCUSSION

Analysis of the Physical Properties of Shea Nuts

Table 2 presents the results of the physical properties of shea nuts. With water content of shea nuts ranged from 6.40% to 10.24%, by shaking the shea nuts with this content, it is observed that the kernel shakes in the nut. This shows that the nuts have dried sufficiently to loosen the kernel from its shell, which makes shelling easier. On the other hand, with water contents ranging from 10.24% to 21.34% the kernel does not shake enough inside the nut. This shows that the kernel is not sufficiently detached from the nut, which will make shelling more difficult and reduce shelling efficiency. These results are close to a minimum moisture content of 8.5% obtained by Ogbole and Ademoh (2021). Shea nuts with a moisture content above 10.24% should be dried further to improve shelling efficiency. The average
weight of 1,000 nuts is 6,007 g (Table 2), which is less than that of nuts harvested in Nigeria (8,000 g) (Aviara et al., 1999, 2000) and more than that of Burkina Faso (2,490 g). In Burkina Faso, it varies between 1170 and 5320 g (Yé and Destain, 2004). The variety of the seed, on one hand, and the agro-climatic conditions of production on the other hand, could explain the difference recorded between regions and within the same zone. The mass areas of the nuts and kernels (0.37 and 0.303 m$^2$ kg$^{-1}$, respectively) make it possible to size the parameters of the huller by the desired throughput and hourly capacity of the equipment.

**Analysis of the Geometric Properties of Shea Nut**

Table 3 shows an analysis of the geometric properties of shea nuts. These parameters are useful for determining the concave clearance. The results show that the length of the nut varies from 24.07 to 44.43 mm with an average value of 35.08±0.87 mm and the average value of its width being 22.87±0.45 mm. The thickness, however, varies from 11.41 to 24.36 mm. The mean values for the arithmetic and the geometric mean diameter are 25.67 and 24.73 mm, respectively. These results are higher than the arithmetic mean diameter of 19.74 mm and geometric mean diameter of 19.28 mm obtained by Seweh et al. (2015) on almonds from Ghana. These differences can be explained by the geographical variables specific to each locality or region, but also by the characteristics of the trees. The differences in size are thought to be partly linked to agricultural practices, which favour flowering and fruiting and seed exchanges (Kelly, 2005). They could also be due to a combination of edaphic, climatic and human factors. Rainfall seems to have a decisive effect on nut and kernel size.

**Table 2: Physical properties of shea nuts**

<table>
<thead>
<tr>
<th>Properties</th>
<th>Number of samples</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit weight (g)</td>
<td>50</td>
<td>3.8</td>
<td>9.45</td>
<td>6.83±0.37</td>
</tr>
<tr>
<td>1000 weight (g)</td>
<td>10</td>
<td>5531</td>
<td>7556</td>
<td>6456±378.07</td>
</tr>
<tr>
<td>Water content (%) at 105°C</td>
<td>3</td>
<td>21.34</td>
<td>6.40</td>
<td>10.24±1.26</td>
</tr>
</tbody>
</table>

**Table 3: Geometric properties of the shea nut**

<table>
<thead>
<tr>
<th>Properties</th>
<th>Number of samples</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (mm)</td>
<td>100</td>
<td>24.07</td>
<td>44.43</td>
<td>35.08±0.87</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>100</td>
<td>17.22</td>
<td>28.50</td>
<td>22.87±0.45</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>100</td>
<td>11.41</td>
<td>24.36</td>
<td>19.06±0.47</td>
</tr>
<tr>
<td>Arithmetic diameter (mm)</td>
<td>100</td>
<td>17.567</td>
<td>32.43</td>
<td>25.67±0.47</td>
</tr>
<tr>
<td>Geometric diameter (mm)</td>
<td>100</td>
<td>20.36</td>
<td>30.04</td>
<td>24.73±0.40</td>
</tr>
<tr>
<td>Surface area (mm$^2$)</td>
<td>100</td>
<td>1301.40</td>
<td>2832.74</td>
<td>1933.72±62.20</td>
</tr>
<tr>
<td>Sphericity</td>
<td>100</td>
<td>0.69</td>
<td>0.70</td>
<td>0.71±0.01</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>100</td>
<td>47.05</td>
<td>88.67</td>
<td>66.05±1.84</td>
</tr>
<tr>
<td>Unit volume (mm$^3$)</td>
<td>100</td>
<td>4415.72</td>
<td>14180.61</td>
<td>8077.97±388.30</td>
</tr>
</tbody>
</table>

**Table 4: Gravimetric properties of shea nuts**

<table>
<thead>
<tr>
<th>Properties</th>
<th>Number of samples</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual density (kg m$^{-3}$)</td>
<td>3</td>
<td>461.42</td>
<td>498.66</td>
<td>481.65±21.31</td>
</tr>
<tr>
<td>Bulk density (kg m$^{-3}$)</td>
<td>3</td>
<td>246.36</td>
<td>293.69</td>
<td>271.43±26.92</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>3</td>
<td>41.104</td>
<td>46.608</td>
<td>43.65±6.09</td>
</tr>
</tbody>
</table>

**Table 5: Frictional properties of shea nuts**

<table>
<thead>
<tr>
<th>Properties</th>
<th>Number of samples</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of friction (stainless steel)</td>
<td>5</td>
<td>0.276</td>
<td>0.293</td>
<td>0.284±0.28</td>
</tr>
<tr>
<td>Angle of repose</td>
<td>5</td>
<td>24.26</td>
<td>32.24</td>
<td>28.25±0.22</td>
</tr>
</tbody>
</table>

**Analysis of the Gravimetric Properties of Shea Nuts**

The gravimetric properties obtained (Table 4) were used to determine the air flow rate required to separate the kernels from the shell and undesirable matter. This Table 4 shows that the mean value of true density is 481.65±21.31 kg m$^{-3}$ while that of bulk density is 271.43±26.92 kg m$^{-3}$ and that of kernel porosity is 43.65±6.09. These results are lower than those obtained by Seweh et al. (2015) who obtained an average true and bulk density 1096 and 682 kg m$^{-3}$, respectively and a porosity of 38.929%. These differences are probably due to the difference in water content after dehydration.

**Analysis of the Frictional Properties of Shea Nuts**

The frictional properties obtained in Table 5 were used to size the angle of inclination of the hopper. The results show that the coefficient of friction of the shea nuts on the stainless steel is 0.28. The angle of inclination of the hopper must be greater than or equal to 28.25° for the shea nuts to orientate easily towards the beater drum of the sheller.

**Production and Testing of the Shea Nut Sheller**

Figure 1 shows the various parts of the husking machine. Figure 1a shows the throttle valve for adjusting the winnowing air flow, Figure 1b shows the beater roller and the concave gap, Figure 1c shows the nuts inserted in the concave gap, and Figure 1d shows an overall view of the hulling machine.

**Shelling and Cleaning Efficiency as a Function of Shea Nut Moisture Content**

Figure 2 shows hulling and cleaning efficiency as a function of moisture content. The results of the machine performance tests (Figure 2) show that the
highest values of shelling and cleaning efficiency are respectively 97.46±1.06% and 87.48±1.06% obtained with a moisture content of 6.40% while the lowest are, respectively, 94.20±1.05% and 82.48±0.55% obtained with a moisture content of 21.34%. These efficiencies are higher than those obtained by Oluwole et al. (2004), who had hulling and cleaning efficiencies of 93% and 82%, respectively; and also higher than those obtained by Ibrahim et al. (2016), with hulling and cleaning efficiencies of 94.31% and 69.56% respectively at a moisture content of 8.23%. This difference is thought to be due to the difference in water content during shelling, which favours separation between the shea kernel and the shell.

The shape of the hulling and cleaning efficiency curves (Figure 2) shows that hulling efficiency is higher when the nut is less moist. Similar observations were made in the studies by Oluwole et al. (2004) and by Fadele et al. (2016) on moringa seeds. Water contents of < 10.24% are recommended to maximise the efficiency of shea nut shelling and hull cleaning.

Yield and Cracking Rate as a Function of Moisture Content
Figure 3 shows the machine's yield and cracking rate as a function of moisture content. The best yield (88.83±0.38%) and cracking rate (3.60±0.60%) were obtained with a moisture content of 6.40% while the worst (76.45±0.84% and 20.67±0.74%, respectively) were with a moisture content of 21.34%. Also, breakage rate decreases while machine performance increases with increasing moisture content (Figure 3), similar to the findings of Oluwole et al. (2004) and Ibrahim et al. (2016). In order to minimise the rate of cracking of shea nuts during shelling, their moisture content should be less than 10.24%.

Hulling Efficiency and Breakage Rate as a Function of Concave Clearance
Figure 4 shows that the variability of dimensions, particularly the thickness and width of nuts and kernels, means that the concave clearance must be adjusted to accommodate the nuts during shelling. The cracking rate and shelling efficiency depend largely on this setting. The results show that for concave clearances of between 36 and 40 mm, all the nuts are shelled with an efficiency of between 96.48% and 92.14%, while the best cracking rate of 3.95 % is obtained with a concave clearance of 36 mm. However, with concave clearances greater than 36 mm, hulling efficiency is reduced to 47.23. Further analysis is still required to ensure that the equipment achieves an optimum hulling rate, while ensuring a low rate of kernel shattering. One possible solution is to calibrate the nuts before hulling.

Cleaning Efficiency as a Function of Winnowing Air Flow Rate
Figure 5 shows the influence of the winnowing air flow rate on hull cleaning efficiency. The highest efficiency (87.48%) was obtained with a winnowing air flow rate of 0.53 m$^3$ s$^{-1}$. When the winnowing air flow rate is low (0.18 to 0.31 m$^3$ s$^{-1}$), the cleaning efficiency drops considerably to 76.33%. Also, when the winnowing air flow rate is too high (0.88 to 0.98 m$^3$ s$^{-1}$), cleaning efficiency decreases because the shelled kernels and shells are all propelled together by the fan force. For optimum hull cleaning efficiency, the winnowing air flow rate should be 0.53 m$^3$ s$^{-1}$.

Statistical Analysis
The ANOVA (Table 6) shows that there is a significant difference in hulling efficiency and machine output between moisture contents of 21.34% and 6.40%; however, these efficiencies try to stabilise from a content of 10.24% downwards, as no significant difference is found between 10.24% and 6.40%.
The variation in content did not make a significant difference to cleaning efficiency, as shown in Table 6. This could be explained by the small variation in hull weight with humidity. It was observed that the moisture content had a significant influence on the cracking rate of the kernels, since at different moisture contents there was a significant difference in the percentages. This could be explained by the hardening capacity of the kernel at low moisture content. The drier the kernel, the more resistant it is to breaking under the action of any force. Moisture contents of less than 21.34% are sufficient for a better cleaning rate of the shea nuts after shelling, while the winnowing air flow must be 0.53 m$^3$ s$^{-1}$.

Table 6: Results of the analysis of variance performed using SPSS software

<table>
<thead>
<tr>
<th>Features</th>
<th>Moisture content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shelling efficiency</td>
<td>21.34</td>
</tr>
<tr>
<td>Cleaning efficiency</td>
<td>94.30*</td>
</tr>
<tr>
<td>Breakage rate</td>
<td>96.46*</td>
</tr>
<tr>
<td>Performance</td>
<td>97.48*</td>
</tr>
<tr>
<td>Shelling efficiency</td>
<td>6.40</td>
</tr>
<tr>
<td>Cleaning efficiency</td>
<td>96.46*</td>
</tr>
<tr>
<td>Breakage rate</td>
<td>97.48*</td>
</tr>
<tr>
<td>Performance</td>
<td>88.83*</td>
</tr>
</tbody>
</table>

X Y$^*$: Difference not significant; X' Y$^*$ or X Y$^*$ or X' Y$^*$: Significant difference
CONCLUSION

The aim of this study was to characterise shea nuts, and then to design, build and evaluate the performance of a shea kernel (Vitellaria paradoxa) sheller. Shea nuts have an angle of repose of 28.25° and a coefficient of friction of 0.28 on stainless steel. These characteristics resulted in a huller with a concave clearance of 3.60 cm and a winnowing air flow rate of 0.53 m³/s⁻¹. The huller performance test gave a hulling efficiency of 96.44%, and a cracking rate of 3.68%. The best efficiency of 88.83% was obtained at moisture contents below 6.40%. The machine has an hourly capacity of 136 kg h⁻¹. For best shea nut shelling efficiency, the moisture content should be less than 10.24%, while the concave clearance should be 3.60 cm to minimise cracking. Furthermore, with water contents of less than 21.34%, a winnowing air flow rate of 0.53 m³/s⁻¹ is required for better cleaning efficiency.

REFERENCES


