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

[1]Noubissi G., [1]Djousse B.M.K., [1]Tangka K.J., [2,4]Tchinda R. and [2,3]Tchoffo M.

[1]Agricultural Engineering Research Unit, Rural Engineering Department,
Faculty of Agronomy & Agricultural Sciences, University of Dschang, BP 222, Dschang, Cameroon
[2]Department of Physics, Faculty of Science, University of Dschang, BP 67, Dshang, Cameroon
[3]Center for Studies & Research in Agronomy & Biodiversity,
Faculty of Agronomy & Agricultural Sciences, University of Dschang, BP 222, Dschang, Cameroon
[4]Fotso Victor University Institute of Technologies (IUT-FV) in Bandjoun, University of Dschang

Corresponding author's email: noubissigabriel@yahoo.fr

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 m^3/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 (Diallo, 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 (Maldangoï *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.

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MATERIALS AND METHODS

Shea Nut Collection Area

The shea nuts used to test the machine were collected at in Bangoua 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 × 3 × 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°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 moisture content using the method recommended by the AOAC (1984). The moisture content of the nut is calculated by equation 1.

$$MC = \left(\frac{W_w - W_d}{W_d}\right) * 100 \quad (1);$$

where MC is moisture content (%), W_w 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):

$$\boldsymbol{D_g = (a * b * c)^{\frac{1}{3}}} \quad (3);$$

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):

$$\emptyset = \frac{(\boldsymbol{a*b*c})^{\frac{1}{3}}}{\boldsymbol{a}} \quad (4);$$

where $\emptyset$ 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):

$$S = \pi * (Dg)^2 \quad (5);$$

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):

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

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):

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

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 (Sirisomboon *et al.*, 2007). The average bulk density was calculated for each replicate using equation 8:

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

where ρ_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 φ_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):

$$\varepsilon = 1 - \left(\frac{\rho_a}{\rho_r}\right) * 100 \qquad (10);$$

where ε represents porosity (%), ρ_a is apparent density (g cm^{-3}), and ρ_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 Θ_f calculated using equation 11 (Karababa, 2006):

$$\theta_f = \tan^{-1}\left(\frac{2*H}{D}\right) \qquad (11);$$

where Θ_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 (Olakanmi, 2004):

$$F_C = M_L * R_D * W_D^2 \qquad (12);$$

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):

$$F_{TD} = (F_C + (M_M + M_D) * g) \qquad (13);$$

where F_{TD} is total force on hulling unit shaft (N), M_D is mass of the husking drum (kg), M_M 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).

$$F_{TN} = (M_P + M_{PN}) * g) \qquad (14);$$

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):

$$Q = V * S \qquad (15);$$

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:

$$P_N \frac{2\pi * N_N * F_{TN} * R_V}{60} \qquad (16);$$

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:

$$V = \frac{m}{\varphi_r} \qquad (17);$$

where V is hopper volume (m^3), φ_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:

$$\theta = \tan^{-1}\left(\frac{2h}{l1 - l2}\right) \qquad (18);$$

where Θ is angle of inclination of hopper (rad), h is height of the triangle (m), $\boldsymbol{l1}$ is length of the lower part of the hopper (m), and $\boldsymbol{l2}$ 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):

$$C_c = \frac{a+b}{2} \qquad (19);$$

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:

$$R_c = R_D + C_c \qquad (20);$$

where $\boldsymbol{R_c}$ is concave radius (mm), $\boldsymbol{R_D}$ is drum radius (mm), and $\boldsymbol{C_c}$ 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

	Try 1			Try 2			Try 3		
Moisture content	M_{C1}	M_{C2}	M_{C3}	M_{C1}	M_{C2}	M_{C3}	M_{C1}	M_{C2}	M_{C3}
Number of shea nuts	N_{T1}	N_{T2}	N_{T3}	N_{T1}	N_{T2}	N_{T3}	N_{T1}	N_{T2}	N_{T3}
Number of shelled nuts	N_{D1}	N_{D2}	N_{D3}	N_{D1}	N_{D2}	N_{D3}	N_{D1}	N_{D2}	N_{D3}
Number of unshelled nuts	N_{ND1}	N_{ND2}	N_{ND3}	N_{ND1}	N_{ND2}	N_{ND3}	N_{ND1}	N_{ND2}	N_{ND3}
Number of broken nuts	N_{B1}	N_{B2}	N_{B3}	N_{B1}	N_{B2}	N_{B3}	N_{B1}	N_{B2}	N_{B3}
Number of unbroken nuts	N_{NB1}	N_{NB2}	N_{NB3}	N_{NB1}	N_{NB2}	N_{NB3}	N_{NB1}	N_{NB2}	N_{NB3}
Total weight of nuts (kg)	M_{T1}	M_{T2}	M_{T3}	M_{T1}	M_{T2}	M_{T3}	M_{T1}	M_{T2}	M_{T3}
Mass of shelled walnuts (kg)	M_{ND1}	M_{ND2}	M_{ND3}	M_{ND1}	M_{ND2}	M_{ND3}	M_{ND1}	M_{ND2}	M_{ND3}
Separate hull mass (kg)	M_{C1}	M_{C2}	M_{C3}	M_{C1}	M_{C2}	M_{C3}	M_{C1}	M_{C2}	M_{C3}
Shelling time	D_{D1}	D_{D2}	D_{D3}	D_{D1}	D_{D2}	D_{D3}	D_{D1}	D_{D2}	D_{D3}

Shelling efficiency

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

$$E_D = \frac{N_D}{N_T} * 100 \quad (21);$$

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):

$$E_N = \frac{M_C}{M_T} * 100 \quad (22);$$

where $\boldsymbol{E_N}$ is cleaning efficiency (%), $\boldsymbol{M_C}$ is mass of hulls separated (g), and $\boldsymbol{M_T}$ 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).

$$E_R = \frac{N_P}{N_T} * 100 \quad (23);$$

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:

$$T_B = \frac{N_B}{N_T} * 100 \quad (24);$$

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:

$$Rm = \frac{N_{DN} \times E_D}{N_D} * 100 \quad (25);$$

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 unhulled seeds

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

$$P_{ND} = \frac{N_{ND}}{N_T} * 100 \quad (26);$$

where P_{ND} is percentage of unhulled seeds, N_{ND} is number of unhulled 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:

$$P_{ND} = \frac{N_{PD}}{N_T} * 100 \quad (27);$$

where P_{ND} 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:

$$C_h = \frac{M_{ND} * 60''}{M_D} \quad (28);$$

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:

$$C_V = \frac{M_D}{t} \quad (29);$$

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.

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

Table 2: Physical properties of shea nuts

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

Table 3: Geometric properties of the shea nut

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

Table 4: Gravimetric properties of shea nuts

Properties	Number of samples	Minimum	Maximum	Average
Actual density (kg m^{-3})	3	461.42	498.66	481.65±21.31
Bulk density (kg m^{-3})	3	246.36	293.69	271.43±26.92
Porosity (%)	3	41.104	46.608	43.65±6.09

Table 5: Frictional properties of shea nuts

Properties	Number of samples	Minimum	Maximum	Average
Coefficient of friction (stainless steel)	5	0.276	0.293	0.284 ± 0.28
Angle of repose	5	24.26	32.24	28.25 ± 0.22

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.

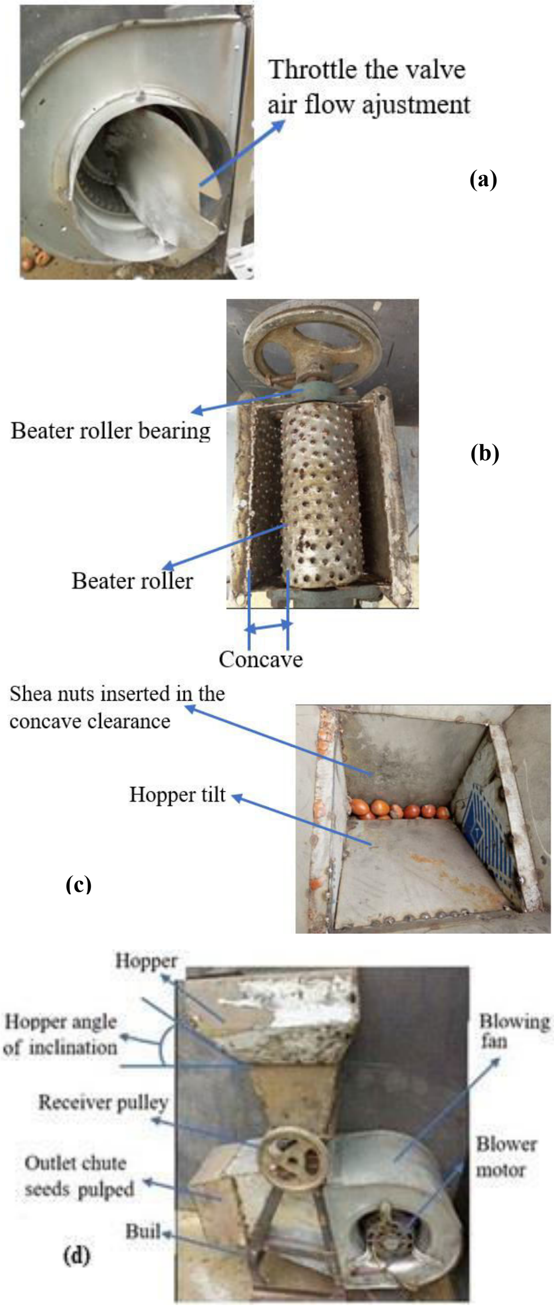

Figure 1: Overall view of the shea nut sheller produced by the company

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 6.4% 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. Tthe 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 efficiences try to stabilise from a content of 10.24% downwards, as no significant difference is found between 10.24% and 6.40%.

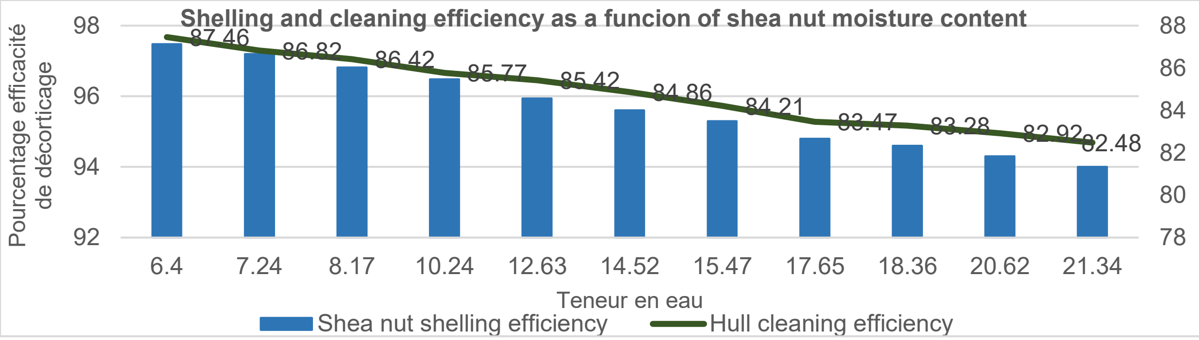

Figure 2: Shelling and cleaning efficiency as a function of the water content of shea nuts

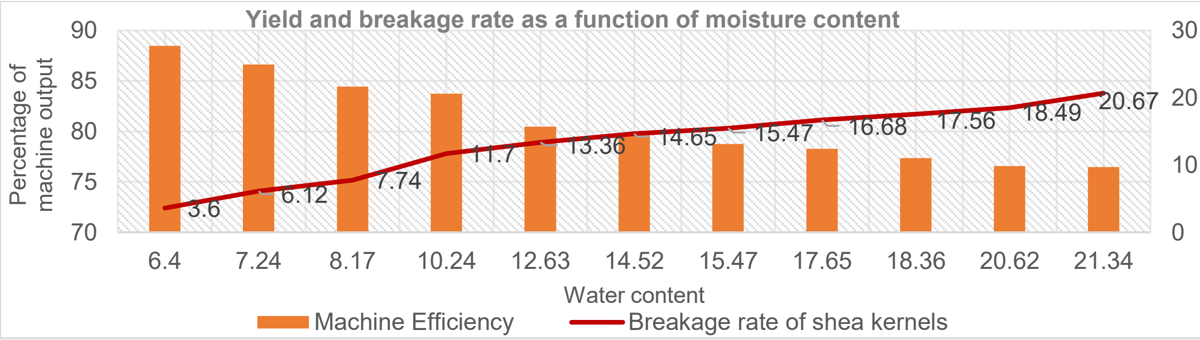

Figure 3: Curve of yield and breakage rate as a function of moisture content

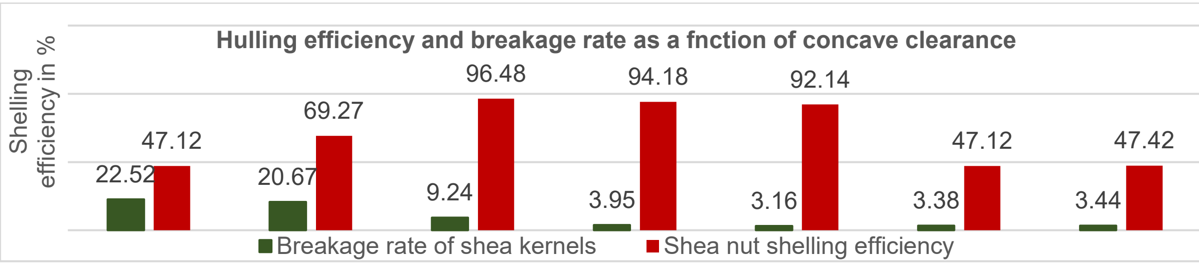

Figure 4: Hulling efficiency and breakage rate as a function of concave clearance

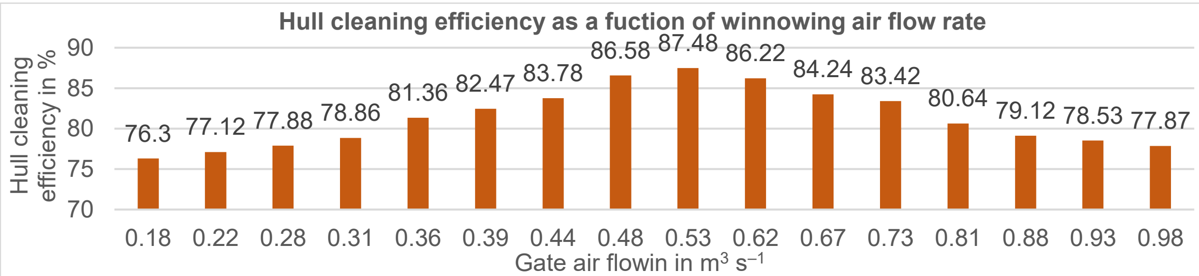

Figure 5: Cleaning efficiency as a function of gate air flow rate

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

Features	Moisture content (%)		
	21.34	10.24	6.40
Shelling efficiency	94.30^{a}	96.46^{ab}	97.48^{b}
Cleaning efficiency	82.48^{a}	83.47^{a}	87.46^{a}
Breakage rate	3.60^{a}	12.70^{b}	20.67^{c}
Performance	76.45^{a}	81.75^{ab}	88.83^{b}

X^a Y^a - Difference not significant; X^a Y^b or X^a Y^c or X^b Y^c - 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 $m^3\ s^{-1}$. 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 $m^3/s\ s^{-1}$ is required for better cleaning efficiency.

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