Design and preliminary evaluation of a dry cowpea dehulling machine

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Abstract: Cowpea dehulling is an important operation in the processing of cowpea. Traditional cowpea dehulling methods recognize the soaking of cowpea in water for a significant amount of time before manual abrasion is carried out either through the use of mortar and pestle, hands, or legs. Existing mechanical alternatives also require prolonged soaking of cowpea before dehulling occurs in addition to being expensive and beyond the reach of many rural populations. This study designed and fabricated a dry cowpea dehulling machine using engineering principles and with locally available materials. Components of the machine include the hopper, power transmission drive, dehulling chamber, polishing chamber, sieves, discharge chute, and agitator. Dry cowpea varieties of Brown Drum (15%Mc dB) and *Oloyin* (17.5%Mc dB) cowpea weighing 500 g each were fed into the machine at a constant speed of 358 rpm. Preliminary tests showed the "Brown Drum" cowpea variety recorded a maximum dehulling efficiency of 97.43% in 7 minutes while the *Oloyin* variety was completely dehulled in 8 minutes at 98.75% efficiency. The throughput capacity recorded was 450 kg hr^{-1} and this machine raises the possibility of producing dry dehulled cowpea for domestic and industrial end-users.
Keywords: dry cowpea de-hulling, processing, value addition, machine design and energy efficient.

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1 Introduction

Cowpea (*Vigna unguiculata* L.) is a popular leguminous crop in Africa which is commonly known as 'beans' in Nigeria (Ogunnigbo et al., 2018), and black eyed-peas in America (Kamaldeen et al., 2017). It is one of the most protein-rich indigenous crops in Africa that provides food, and fibre for people, and livestock and greatly enriches the soil through nitrogen-fixing activity (Kamaldeen et al., 2017). In Nigeria as well as most West African countries, cowpea is eaten in various forms: as porridge along with fried or boiled yam or plantain; as bean cake called *akara* or *kosei* among Yoruba and Hausa respectively (Ukam, 2015). It is also consumed as *moin – moin* which is prepared by steam–cooking wet–milled cowpea mixed with cooking ingredients (Ogunnigbo et al., 2018) or used in the preparation of a local stew called *Gbegiri* (Babatunde, 1995), which is consumed in most parts of southwestern Nigeria.

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Despite the widespread use of cowpea as a nutritional mainstay of many Nigerians, its dehulling is still carried out manually (Egbe and Roland, 2016). The operation generally requires soaking the cowpeas in water for 2 to 10 minutes (Olotu et al., 2013) draining and rubbing between the palms, or beating with wooden pestle and mortar which housewives and food vendors carry out daily (Purseglove, 1968). These processes are laborious and time consuming (Reichert et al., 1979; Sefa-Dedeh and Stanley, 1979).

Mechanically, several attempts have been made to improve the dehulling of cowpea at the small-scale level. Reichert et al. (1979) obtained dehulling efficiencies of 86% and 96% when they comparatively evaluated two methods of cowpea dehulling using a hill grain thresher and a rubber coated barley roller after the cowpeas were soaked in water from between 12-15 minutes. Audu et al. (2004) developed a concentric cylindrical locust bean dehuller and the evaluation revealed a significant correlation between throughput capacity and increased moisture content of the bean. A similar result that was also obtained by Olajide et al. (2019). Adejuyigbe and Bolaji (2005) designed and evaluated the performance of a beans dehuller with well soaked beans. They recorded a dehulling efficiency of 75.1% and a capacity of 3.67 kg hr^{-1} respectively during the testing. Olaoye and Olotu (2015), designed and evaluated a hydro separating cowpea dehuller where a water tank was incorporated into the dehulling process as a means of eliminating soaking before dehulling. The capacity of the machine when tested was 18 kg hr^{-1}. Egbe and Roland (2016), developed a wet legume dehulling machine using the principle of shear and friction to dehull cowpea and soya beans soaked for between 6 -30 minutes. These procedures were not only time and energy consuming, the dehulled beans were not suitable for long term storage. Also, the nutritional and taste quality of the soaked cowpea were adversely impacted while waste water from the soaked cowpea polluted the environment, Furthermore, little attempt has been made to dehull cowpea in its dry state without subjecting it to any soaking process. Hence, this study developed a dry dehulling of cowpea using locally available materials. The specific objectives include the design and fabrication of the cowpea dehulling machine and preliminary testing to determine its efficiency after the fabrication.

2 Materials and methods

Paramount in the list of engineering properties of cowpea needed for its effective dehulling is the abrasive/shear force. The engineering properties of the popular cultivars Sampea 7 and Tvx3236 of cowpea were taken into consideration in the design of this machine (Egbe and Roland, 2016) and the five cowpea varieties of IT 716, Sokoto Red (SR), Ife Brown (IB), White (WH), and Oloka as reported by Faleye et al. (2013). The objective of dehulling is to remove all the pericarp and testa layers of the grain with minimal loss of endosperm and germ, and to achieve this with a minimum amount of energy and time (Bassey and Schmidt, 1989).

2.1 Design calculations

2.1.1 Torque requirement

Given an abrasive force F_b (N), the dehulling/striping torque required is given by Egbe and Roland (2016):

$$T = F_b \times D_g \tag{1}$$

where, F_b is the abrasive force (N)

T is the Torque requirement (Nm)

D_g is the geometric mean diameter of the seed (mm).

Maximum abrasive force required to dehull cowpea varieties Tvx 3236 and sampea 7, at a feed rate of 20 seeds per minute was given as 92.56 N and 64.55 N (Chukwu and Sunmonu, 2010; Egbe and Roland, 2016). The average abrasive force for feed rate of 500 seeds per second would become 1571.1 N (Egbe and Roland, 2016). If the diameter of cowpea seed was 6.75 mm (Chukwu and Sunmonu, 2010), therefore, the average dehulling torque becomes, 1571 × 6.75/1000 = 10.604 Nm for a feed rate of 500 seeds per seconds (Egbe and Roland, 2016).

2.1.2 Power requirement

Effective power for dehulling is given by (Egbe and Roland, 2016)

$$P_D = T\omega_2 \quad (2)$$

where, P_D is the power requirement (Watts)

T is the dehulling torque (Nm)

and ω_2 is the angular speed for effective dehulling (rad s^{-1}).

For a feed rate of 500 seeds per second which is 10.604 Nm (Egbe and Roland, 2016) and

effective dehulling speed of 438 rpm, (ω_2 = 45.87 rad s^{-1}) (Chukwu and Sunmonu,2010),

the power requirement is 486.40 watts.

For this purpose, a variable speed gasoline powered motor of 5.5 hp was purchased to power the dehulling operation. The gasoline engine supplied for this work has an output speed of 1200 rpm, 19 mm shaft diameter, pulley diameter of 50 mm.

2.1.3 Hopper design

The hopper design was based on the volume of frustum.

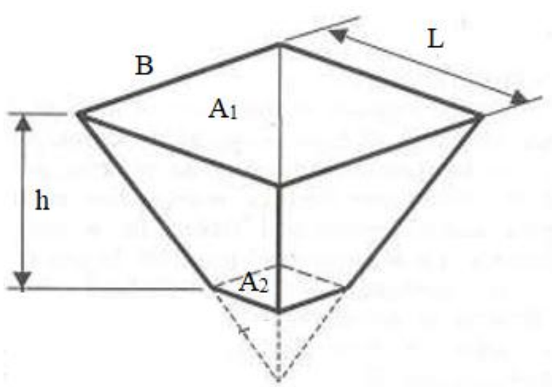


Figure 1 Frustum of the hopper

The volume of frustum can be obtained from Equation 3.

$$V = \frac{\square}{3}\left(A_1 + A_2 + \sqrt{A_1 A_2}\right) \quad (3)$$

where, V is the volume of the frustum in m^3, h is the height of the frustum in m, A_1 is the area of upper base in m^2 and A_2 is the area of the lower base in m^2.

Rectangular method was used to find the areas since both upper and lower base are rectangular.

$$A = L \times B \quad (4)$$

where, A is in m^2

L and B are the length and the breadth of the frustum in m respectively.

Therefore;

A_1 = 0.320 × 0.050m = 0.016 m^2

A_2 = 0.195m × 0.040m = 0.0078 m^2

h = 0.355m

Therefore,

$$V = \frac{0.355}{3}\left[\begin{matrix}(0.016\,m^2 + 0.0078\,m^2\,) + \\ \sqrt{0.016\,m^2 \times\, 0.0078 m^2}\end{matrix}\right] = 0.0041\ m^3$$

2.1.4 Volume of the dehulling chamber

The geometry of the dehulling chamber (V_{dc}) is chosen to be a cylinder. Thus, the volume is given by:

$$V_{dc} = \pi r_{dc}^2 L_{dc} \quad (5)$$

where, r_{dc} is the radius of dehulling chamber (mm) and L_{dc} is the length of the dehulling chamber (mm).

2.1.5 Belt drive calculations

The belt drive configuration selected is an open system. Thus, according to Khurmi and Gupta (2005), the diameter of the pulley is given by

$$\frac{N_1}{N_2} = \frac{D_1}{D_2} \quad (6)$$

where, N1 is the speed of the motor(rpm), N2 is the speed of the shaft(rpm), D1 is the diameter of the motor pulley(mm) and D2 is the diameter of the shaft pulley(mm).

There are various types of belts, however; type A V-belt was chosen because of its ability to withstand heat and difficult operating conditions.

2.1.6 Belt length determination

Billah et al. (2008) stated that the length of a belt can be determined using the equation below as seen in Figure 2

$$L = 2C + \frac{\pi}{2}(d + D) - \frac{(D-d)(D+d)}{4C} \quad (7)$$

where, L is the total length of the belt (mm), d is the diameter of the drive pulley (mm) and

D is the diameter of the driven pulley (mm) and C is the distance between the two pulleys (mm).

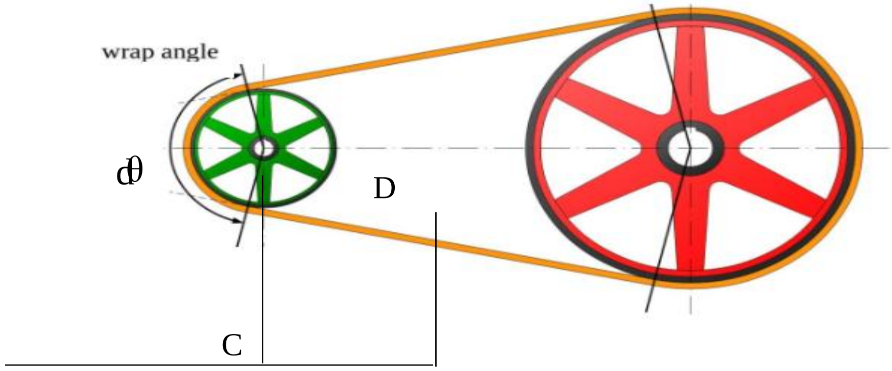


Figure 2 Open belt configuration

Source: Tec-science, (2018)

2.1.7 Angle of wrap

A standard belt A type grooving is selected, whereas the motor can be adjusted horizontally on its supporting slot in other to tension the belt. For the open belt:

$$\theta = 180 - 2sin^{-1}\left(\frac{D-d}{2C}\right) \qquad (8)$$

Where θ is the angle of wrap (in degrees)

d- diameter of drive pulley (mm)

D-Diameter of driven pulley(mm)

C- Total length of Belt (mm)

2.1.8 Belt tension ratio

Khurmi and Gupta (2005) gave the equation for calculating belt tension as:

$$P = (T1 - T2)\, v \qquad (9)$$

where, P is the power (Watts), T_1 is the tension on the tight side of the belt (N), T_2 the tension on the slack side of the belt (N), and v is the velocity of the belt (ms^{-1}).

Tension ratio for an open belt is then given as:

$$2.3\log\frac{T1}{T2} = \mu\theta \qquad (10)$$

where, μ is the coefficient of friction between the belt and the pulley (unitless) and θ is the angle of wrap in degrees. According to Khurmi and Gupta (2005), the coefficient of friction for mild steel pulley and rubber belt is given as 0.30.

2.1.9 Shaft design

The shaft diameter is calculated using the formula given by Khurmi and Gupta (2005).

$$d^3 = \frac{16\tau}{\pi S_s}\sqrt{(K_b \times BM)^2 + (K_T + TM)^2} \qquad (11)$$

d- diameter of shaft (mm)

τ-Maximum shear stress Mpa

S_S- Allowable Shear stress, Mpa

Bending Moment - Nm

Torsional moment- Nm

K_b - combined schock and fatigue factor for bending (1.5)

K_T- combined schock and fatigue factor for torsion (1.0)

A mild steel rod of diameter 30 mm and length 450 mm was selected for the shaft.

The weight of shaft will have effect on the critical speed of the critical shaft.

$$Critical\ Speed\ of\ Shaft\ (\acute{\omega}_s) = \frac{48 \times E \times I}{L^3} \qquad (12)$$

Where, $\acute{\omega}_s$ *is the critical speed* (rps)

E is Modulus of elasticity of steel, *(Nm^{-2})*

I is Moment of inertia ($\pi d^4/64$)

Where d – diameter in (mm)

and L is the Shaft length (mm).

2.1.10 Dehulling chamber design

The dehulling chamber is assumed to be a thin wall cylinder. Hence, the tangential stress perpendicular to the axis of the cylinder is

$$\sigma = \frac{pD_{dc}}{2t} \tag{13}$$

where, σ is the perpendicular of hoop stress (N mm^{-2}), assumed to be maximum tensile stress the cylinder is subjected, P is the internal pressure (Mpa), T is the thickness of dehulling chamber (mm), D_{dc} is the internal diameter of dehulling chamber (mm).

Also

$$\sigma = S_{all} = \frac{0.5S_y}{N} \tag{14}$$

where, S_{all} is the allowable shear stress(Nmm^{-2}), N is the factor of safety and S_y is the yield stress (Nmm^{-2}).

For this design a factor of safety of 2.5 was used in the design of the shaft.

2.2 Selection of materials and manufacturing technology

Stainless steel was used for the construction of both the hopper and for the dehulling and cleaning chambers; due to its corrosion resisting properties. Plain carbon steel was used for the shaft due to its moderate ductility and malleability which improves its workability and it is widely readily available and obtained at a cheaper price compared to other steel alloys. Angle iron of size 250 mm × 250 mm×3 mm was used for the frame of the dehuller and the electric motor stand. The other weight of the other components of the dehuller was considered before this was chosen. The major manufacturing technologies adopted were welding, cutting and bolting.

Electronic weighing scale was used to measure the weight of the test samples. Tachometer; used for ascertaining of the speed of the shafts while a gasoline powered variable speed engine served as the prime mover.

2.3 Principle of operation

The dry cowpea samples are fed into the machine through the hopper which pass into the dehulling chamber. The dehulling chamber is the unit where the hull of the seed is being removed. It consists of a rotating drum with dehulling disc, the seeds are dehulled using impact force. Inside the dehulling, there is a screen which allows the seed and the chaff to go through to the polishing hopper. The hopper then opened to allow dehulled cowpea pass through to the polisher. The polisher chamber is made up of brush arranged serially on the rotating shaft and net to allow the chaff pass through under the action of gravity as the brush rotates against the cowpea.

2.4 Performance evaluation

An optical tachometer was used to measure the speed of the dehulling pulley while the efficiency od the dehulling process was given by Ndirika and Onwualu (2016);

$$\delta = \frac{Dehulled\ Beans}{Undehulled\ Beans + Dehulled\ Beans} \times 100 \tag{15}$$

2.4.1 Dehuller Throughput (T_p)

The throughput of the dehuller can be evaluated using the following equation as stated by Ndirika and Onwualu (2016)

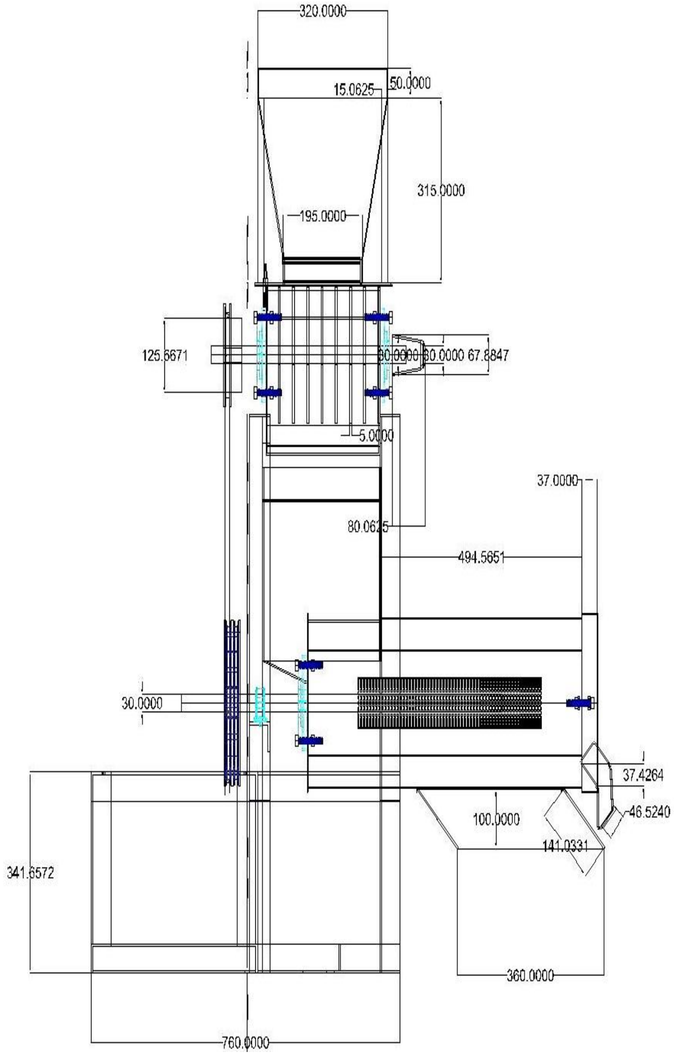
$$T_p = \frac{3.6M_t}{T_D}\ (kg\ h^{-1}) \tag{16}$$

where, M_t is the mass of sample before dehulling(kg), T_D is the time used for dehulling(min).

2.5 Test procedure and experimental set up

The procured samples were cleaned manually of any shaff and foreign material, samples were taen for moisture content evaluation. The machine was also tested at various speeds at no load to ensure the stability of bolted and welded joints. Afterwards, a total of 4 kg of Oloyin Cowpea variety divided into 8 samples of 500 g was fed into the machine at a constant speed of 358 rpm at time intervals of 3, 4, 5, 7 and 8 minutes respectively in a 2 ×6 factorial experiment. The effcieicy of dehulinh at the end of each time interval was recorded. The same procedure was carried out on the the Brown Drum variety.

The side view and the assembly of the developed machine are in Figure 3 while the fabricated machine is shown in Figure 4.



S/N	PARTS
1	HOPPER
2	DEHULLING DISC
3	DEHULLING CHAMBER
4	SHAFT CAP
5	POLISHING PULLEY
6	BEARING
7	POLISHING CHAMBER
8	THROUGH CHUT
9	DEHULLING PULLEY
10	BELT
11	SHAFT
12	SIEVE
13	FRAME

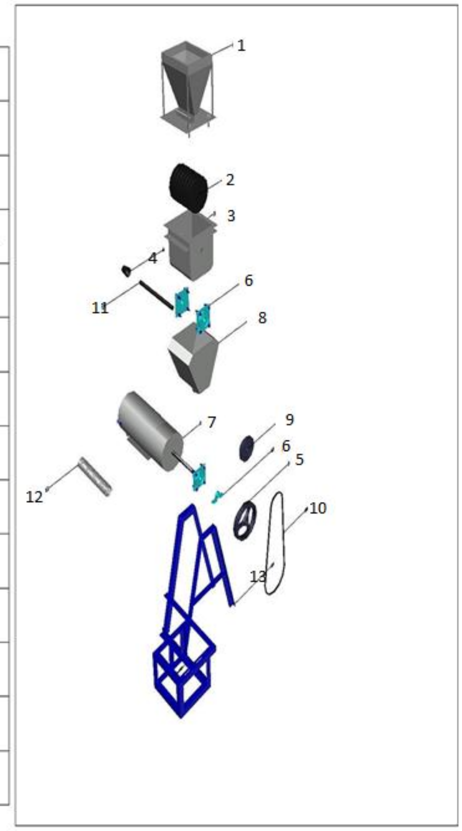


Figure 3 The side view and assembly drawing of the machine

The fabricated machine is shown in Figure 4.

Figure 4 The fabricated machine

3 Results and discussion

The results of the dehulling experiments are shown in Tables 1 and 2 for brown drum variety and oloyin variety respectively while the T-Test and the ANOVA results are shown in Tables 3 and 4 respectively. The transformation of the undehulled cowpea to the dehulled stage is shown in Figure 5.

Table 1 Result for dehulled brown-drum beans

Run time (min)	Weight of dry cowpea seed (kg)	Dehulled cowpea (kg)	undehulled cowpea (kg)	Hull weight (kg)	Percentage Loss %	Efficiency (%)
3	0.5	0.07	0.37	0.045	1.5	15.91
4	0.5	0.2	0.225	0.055	2	47.06
5	0.5	0.38	0.03	0.06	3	92.68
6	0.5	0.385	0.015	0.055	4.5	96.25
7	0.5	0.38	0.01	0.055	5.5	97.43
8	0.5	0.37	0.015	0.09	2.5	96.10

Table 2 Result for dehulled of the oloyincowpea

Run Time (min)	Weight of dry cowpea seed (kg)	Dehulled cowpea (kg)	Undehulled cowpea (kg)	Hull weight (kg)	Percentage Loss %	Efficiency (%)
3	0.5	0.05	0.415	0.01	2.5	10.75
4	0.5	0.15	0.31	0.02	2	32.61
5	0.5	0.36	0.085	0.025	3	80.90
6	0.5	0.405	0.025	0.035	3.5	94.19
7	0.5	0.42	0.005	0.045	3	98.82
8	0.5	0.395	0.005	0.05	5	98.75

Table 3 T-test for means (dehulling efficiency)

	Honey	Drum
Mean	74.24011	69.33663
Variance	1196.395	1453.363
Observations	6	6
Pearson Correlation	0.986294	
Hypothesized Mean Difference	0	
Df	5	
t Stat	1.722264	
P(T<=t) one-tail	0.072818	
t Critical one-tail	2.015048	
P(T<=t) two-tail	0.145636	
t Critical two-tail	2.570582	

Table 4 ANOVA of dehulling efficiency

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	72.13215	1	72.13215	0.054444	0.82021	4.964603
Within Groups	13248.79	10	1324.879			
Total	13320.92	11				

4 Discussion

From Tables 1 and 2, it is evident that the average time to achieve complete dehulling of the dry cowpea varieties was at 7 minutes. At Moisture contents of 17%, the maximum dehulling efficiencies recorded for brown drum and *Oloyin* variety of cowpea were 97.43% 98.82% at 7 minutes respectively whch compares favorably with 30 minutes recorded by Egbe and Roland (2016) and 15 minutes recorded by Olajide et al. (2019) in their studies with wet cowpea respectively. The highest amount of undehulled cowpea were recorded at 3 minutes for both brown drum beans and *Oloyin* cowpea. The T-test (tstat 1.722) revealed no significant difference between the dehulling eficiencies of the two varieties of cowpea. A situation which was further confirmed by the ANOVA table (P value- 0.82021). The throughout estimated during the runs showed that the machine was capable of producing 450 kg hr^{-1} of dry dehulled cowpea .

Figure 5 Showing the undehulled cowpea and the dehulled cowpea

5 Conclusion

The design, fabrication and preliminary testing of a cowpea dehuller was successfully carried out in this work. Preliminary evalaution showed that a throughput of 450 kg hr^{-1} and dehulling efficiency of 98.82% was achieved when the machine was run for 7 minutes. This study has established that development of high performance machines from locally available materials, with available technology for the dehullig of dry cowpea samples is possible and should be explored to further enhance the cowpea production value chain.

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