Development and assessment of Coffea Arabica and Coffea Canephorade-hulling machine

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Abstract: This work was aimed at the development and assessment of Coffea Arabica and Coffea Canephora de-hulling machine. Two units (de-huller and brusher) were incorporated in a single machine in order to remove the drudgery and constraints associated with the traditional de-hulling and separating method of both varieties of coffee seeds before it is processed into food condiment and flavoring agent. The response surface methodology (RSM) was employed to point out the relationship between the response functions and the process variables, of the de-hulling system for Coffea Arabica and Coffea Canephora. The performance rate of the machine was evaluated by varying the speed of rotation of the de-hulling shaft of the machine; 300, 400and 500r/min and moisture content; 10%, 15% and 20%, d.b. Based on these conditions, they worked optimally at the rate of 240kg/h. The result showed that the performance of the machine for Coffea Arabica and Coffea Canephora were (65.17%and 57.62%), (62.13% and 54.30%), (59.67% and 59.67%), (58.43% and 54.11%), (58.90% and 53.39%), (55.50% and 51.47%), (57.07% and 53.97%), (56.67% and 52.43%) and (56.23% and 52.19%) for (10%d.b, 300r/min),(15%d.b, 300r/min), (20%d.b, 300r/min), (10%d.b, 400r/min), (15%d.b,400r/min), (20%d.b, 400r/min), (10%d.b, 500r/min), (15%d.b, 500r/min), and (20%d.b, 500r/min),respectively. Therefore, the machine is recommended for small and medium scale farmers that are involved in coffee cultivation and processing.

Keywords: de-huller, de-hulling efficiency, moisture content and machine capacity.

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1 Introduction

Coffee is woody perennial evergreen shrubs growing well in the hot humid climate of the tropics. The plant is believed to be of Africa origin with some still found in wild population in Abyssian Plateaux. The two species largely cultivated are *Coffea Arabica* and *Coffea Canephora Pierre*, simply known as coffee arabica and coffee robusta. Other less extensively cultivated include C. Liberica, C. Abeokutae, C. Excelsa and C. cogenesis, Coste (1992) reported that species are different in their characteristics in terms of colour, branches, leaves, flowers, fruits and beans.

Coffee is one of the most important cash crops across the world and a major source of export earnings. It is second only to crude oil as the most important internationally traded commodity in monetary value (FAO, 2004). Kule (2010) reported that in spite of high export earnings from coffee globally, coffee produced in most African countries fetch low prices compared to coffee from other continents due to relatively lower quality coffee.

Reports have shown decline in coffee production over the period between 1960 and 2008 in Nigeria; from 50,000 bags (60kg/bag) in 1961 to 18,000 bags in 2008, with the highest production level of 95,000 bags in 1964, 1988 and 1990 (Williams, 2008). Over 80% of coffee from developing countries, particularly Nigeria, is produced by small scale farmers who lack adequate technical education and are faced with low market price leading to poor management, poor productivity and abandoned farms (Williams, 1989; Mutua, 2000 and Agbongiarhuoyiet al., 2006). Arabica coffee accounted for 4% of export in Nigeria, and less than 2% of world

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coffee in 1989; while other producing countries such as Ivory Coast have in recent time significantly increased their production level despite the collapse of world price of coffee, Nigeria no longer has a place at all in coffee production on a global scale (Williams, 1989). Arabica coffee provides employment for a lot of people in all producing countries. Muleta (2007)and Surendra (2002) reportedthatabout 33 million people in 25 African countries derived their livelihoods by growing coffee in subsistence level from about 4.5 million square kilometers of land. This necessitates the need for a low cost but efficient coffee de-huller.

De-hullingconsists of removing the pericarp from the grain. This is often accompanied by degerming (removal of the embryo). Shelling and de-hullingare generally carried out by women, and are very labor-intensive and time consuming (Fandohanet al., 2004). Shelling is traditionally done by hand, mortar and pestle or using a wooden stick (Houssou, 2000), whereas de-hullingis done by using stones or mortar and pestle. Despite these notable roles, coffee processing, harvesting and handling are still under manual method using such equipment as pestle and mortar. This situation calls for development of mechanical equipment to handle the operations mentioned above, of this economic crop (Olukunle and Akinnuli, 2012). Hence, this paper is aimed at developing a cost effective *Coffea Arabic* and *Coffea Canephora*de-hulling machine and to evaluate and compare the performance in de-hulling the two species.

2 Material and methods

2.1 Material selection

The *Coffea Arabica* and *Coffea Canephora* were selected for this study. The coffee seeds used were grown at the Cocoa Research Institute of Nigeria. The institute is located at 14 km from Ijebu-Ode Road, Idi-Ayunre, Oluyole Local Government Area, Ibadan, Oyo State. The seeds were manually cleaned to remove all foreign matter and broken seeds.

2.2 Design features of the machine

All parts of the coffee de-hullingmachine were constructed from stainless steel material, with the exception of the main frame that was developed from mild steel. The de-hulling cylinder and the brushing unit were constructed from stainless steel for hygienic and its resistance to corrosion purposes.

The major parts of the constructed machine were; frame, hopper, de-hullingunit, brushing unit and auger.

i. **De-hullingcylinder**

The de-hullingcylinder was made of stainless steel sheet rolled into a cylindrical shape with diameter of 80mm and total length of 520mm.

ii. **Brushing drum**

It was also made of stainless steel cut and rolled into a cylindrical tube of 170mm diameter with total length of 250mm.

3 Design calculations

3.1 Expression of the machine capacity in volumetric rate

The machine capacity in volumetric rate was done to determine the volume of coffee seedsthat can be de-hulled per hour(kg/h).

Note: The assumed machine capacity was 4kg/min (240kg/h).

According to Gbaboet al. (2013), the density (ρ)of coffee seed is 1219.3kg/m^3. The assumed mass of the machine was 4kg. Therefore;

$$Volume\ rate = \frac{4}{1219.3} = 0.00328\text{m}^3/min$$

Hence, to express in volumetric rate;

$$\text{Volumetric rate} = 0.00328\text{m}^3/min \times 60min$$
$$= 0.197\text{m}^3/\text{h}$$

3.2 Shaft diameter

The shaft was designed on the basis of strength, rigidity and stiffness. When designing the shaft, it was considered that it may be subjected to twisting and bending moments. Gbabo et al. (2013), reported that the Equation 1 and Equation 2 used for shaft design is given as;

$$\sigma = \frac{16\tau}{\pi ds^3} \quad (1)$$

$$ds = \sqrt[3]{\frac{16\tau}{\sigma\pi}} \quad (2)$$

$$ds = \sqrt[3]{\frac{16 \times 36.287 \times 10^3}{28\pi}}$$

$d = 18.758mm$

Where:

ds: Diameter of the shaft (m), and

τ: Torque of the shaft (36.287Nm).

σ: Maximum permissible work stress (N/m).

Therefore, the total shaft diameter;

$18.758 + 3.75 = 22.509mm$

However, $25mm$ diameter of shaft (ds)was chosen for the design by standard.

3.3 Weight of coffee seeds in de-hullingchamber

The Weight of coffee seeds in de-hullingchamber was calculated using the method reported by Adejuyigbe and Bolaji (2005) as following Equation 3, Equation 4 and Equation 5:

$$V_{dc} = \pi r_{dc}^2 l_{dc} \quad (3)$$

Where; $r_{dc} = 0.045m$ and $l_{dc} = 0.7m$.

$$V_{dc} = \pi \times 0.045^2 \times 0.7 = 0.004m^3$$

Also,

$$V_s = \pi r_s^2 l_s \quad (4)$$

$$V_s = \pi \times 0.013^2 \times 1.25 = 0.001m^2$$

Hence, $V_{cs} = V_{dc} - V_r$(5)

$$= 0.004m^3 - 0.001m^3 = 0.003m^3$$

The weight of coffee seed was expressed as Equation 6 and Equation 7;

$$W_{cs} = mg \quad (6)$$

Also;

$m = \rho V_{cs}$(7)

Since;

$$m = 1226.5 \times 0.003 = 3.67kg$$

Hence, weight of coffee seed;

$W_{cs} = 3.80 \times 9.81 = 37.278$N

Where:

r_{dc}: Radius of dehulling chamber (m)

l_{dc}: Length of dehulling chamber (m)

V_{dc}: Volume of de-hulling chamber (m^3)

V_s: Volume of Shaft in de-hulling chamber (m^3)

r_s: Radius of shaft (mm),

l_s: Length of shaft (mm)

W_{cs}: weight of coffee seeds (N),

m: Mass of coffee seeds (kg)

g: acceleration due to gravity (m/s).

ρ: Density of coffee seeds (kg/m^3),

3.4 Determination of screw auger diameter

The screw auger diameter was determined in other to know the actual minimum diameter required to be added to the shaft diameter. The screw diameter was determined using the Equation 8 below, used by Gbabo et al. (2013).

$$C_{MPH} = (D^2 - ds^2) \times p \times N \times 60 \quad (8)$$

$\Rightarrow 0.197 = (D^2 - 0.025^2) \times 0.02 \times 500 \times 60$

$D = 0.031$m

Where:

ds: Diameter of the shaft (0.025 m),

C_{MPH}: Capacity of the machine (0.197 m^3/h),

D: Diameter of screw auger(m),

p: Pitch of the auger (0.02 m),

N: Speed of the auger (500 r/min).

3.5 Power requirement of the shaft

The power requirement (P_s), was divided into three parts. Gbabo et al. (2013), reported the power requirement (P_s) with the equations expressed in Equation 9, Equation 10, Equation 11, Equation 12, Equation 13, Equation 14 and Equation 15.

i. Power required to drive shaft:

$$P_s = W_s \times R_s \quad (9)$$

$$W_s = mass \times force\ of\ gravity \quad (10)$$

$mass\ of\ the\ shaft = 3.85kg$

$W_s = 3.85 \times 9.81 = 37.77N$

$$R_s = \frac{ds}{2} = \frac{0.025}{2} = 0.0125\,m \quad (11)$$

$P_s = 37.77 \times 0.0125 = 0.472W = 0.000472kW$

Where:

ds: Diameter of the shaft (0.025 m), P_s: Power requirement of shaft (kW)

R_s: Radius of shaft (m). W_s: Weight of the shaft (N)

g: acceleration due to gravity (m/s). m: Mass of shaft (kg)

ii. Power required to de-hull the coffee seed:

$P_{dh} = \tau \times \omega$ (12)

$\tau = 36.287$Nm and $\omega = 52.30$rad/s

$P_{dh} = 36.287 \times 52.36 = 1.899$kW

Where:

ds: Diameter of the shaft (0.025 m), P_{dh}: Power requirement of de-hull(kW)

ω: Angular speed of the shaft (52.30 rad/s) τ: Torque of the shaft (36.287 Nm)

iii. Power required to drive the pulley:

$P_p = W_p \times R_p$ (13)

Mass of the pulley = 2kg

$W_p = mg = 2 \times 9.81 = 19.62N$ (14)

$P_p = 19.62 \times 0.075 = 1.472kW$

$Pt = P_s + P_{dh} + P_p$ (15)

= 0.000472 + 1.899 + 1.472 = 3.371kW

Hence, 5.5 petrol engine was used for the design.

Where:

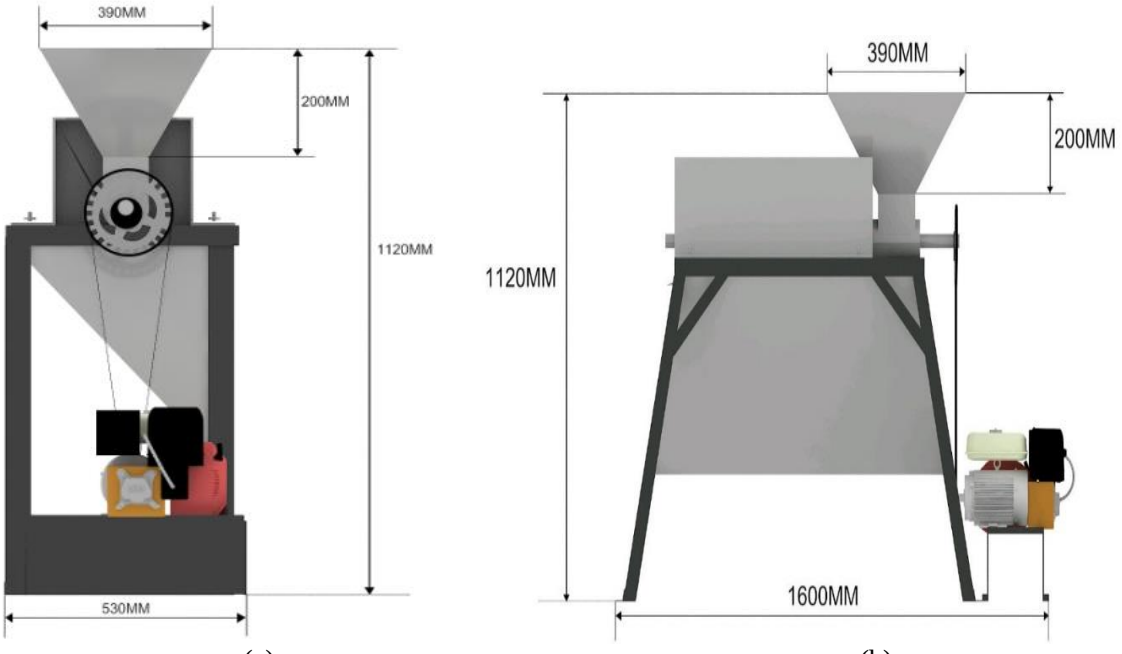
Pt: $Total\ Power$ (kW) P_p: Power requirement of pulley (kW)

R_p: Radius of pully (m). W_p: Weight of the pully (N)

g: acceleration due to gravity (m/s). m: Mass of pully (kg)

4 Experimental procedure

The machine was initially test-feed under no load condition as described by Gbabo et al.(2013) using a motor of 5.5hp with engine speed of 1500r/min and shaft speed of 300, 400 and 500r/min. This was done to assess the smoothness of the machine parts. After this was done, the performance test was as well conducted. See Figure 1 please.



(a) (b)

Figure 1 De-hullingMachine

The moisture content of the coffee seeds used for the experiment were 10%, 15% and 20% dry basis, considering the moisture content of freshly harvested coffee beans given by Narasimnaet al. (1994) as 18%-22%.

- The moisture content was varied as described by Chakraverty, (1988).
- The time of operation was taken using a stopwatch.
- The output of de-hulled and unde-hulled seeds from the outlets collected after each operation were weighed using a digital balance.
- The desired speed was achieved by using variable speed petrol engine (Honda engine GX 160 model, 5.5hpengine). While the speeds were varied by changing the engine (prime mover) speed until the desired speed was gotten. This was determined with the aid of a tachometer.

5 Performance evaluation

The machine was tested using PAE standard 221 (2005).

i. **De-hullingefficiency (%)**

This determines how efficient the machine performs, when operated.See Equation 16.

De-hullingefficiency

$$= \frac{mass\ of\ dehulled\ coffee\ bean}{total\ mass\ of\ coffee\ bean\ dehulled} \times 100 \qquad (16)$$

ii. Capacity of the machine(kg/h)

The capacity of the machine was calculated using Equation 17:

$$\text{Capacity of machine} = \frac{mass\ of\ output\ (kg)}{Duration\ of\ operation\ (h)} \qquad (17)$$

iii. **Moisture content**

The moisture content of the seeds (MC) was determined according to the ASAE S410.1 Method (ASAE, 1997). The moisture content of the unde-hulled coffee seeds was determined from a sample of 200 grams and was expressed as dry basis percentage (%, d.b.). The desired moisture content was obtained by drying the grains in a convection air oven at 130 ℃ and by spraying with pre-calculated amounts of distilled water, and then thoroughly mixing and sealing them in separate polyethylene bags. The samples were kept in a dry place for at least 72 h to allow a homogeneous moisture distribution.

The desired quantity of distilled water to be added, or moisture to be evaporated (seed to be dried), was calculated using following Equation 18 (Chakraverty, 1988):

$$W_m = W_1\left[\frac{\Delta M}{100 - M_2}\right] \qquad (18)$$

Where;

$\Delta M = M_2 - M_1$(for $M_2 > M_1$) and $\Delta M = M_1 - M_2$(for $M_1 > M_2$),

Where:

$W_m =$ Moisture to be added or removed (g), $W_1 =$ Initial weight of the seed at M_1(g),

$M_1 =$ Initial moisture content (wb), (%) $M_2 =$ Final or desired moisture content (w.b.), (%)

Kajunaet al. (2001) gave the expression for obtaining the amount of bone dry matter based on the initial moisture content of the sample using theEquation 19, Equation 20, Equation 21 and Equation 22 expressed below:

$$MC_{db} = \frac{100(\%MC_{wb})}{100 - (\%MC_{wb})} \qquad (19)$$

But;

$$MC_{db} = \frac{(M_w)}{(M_{dm})} \times 100\% \qquad (20)$$

$$M_w = \frac{MC_{db} \times M_{dm}}{100} \qquad (21)$$

$$M_{dm} = M_s - M_w \qquad (22)$$

Where:

MC_{db}: Moisture content (d.b.),(%) M_{dm}: Mass of bone dry matter, (g)

MC_{wb}: Moisture content (w.b.), (%) M_w: Mass of water, (g)

M_s: Mass of sample, (g)

6 Results and discussions

6.1 Determination of moisture content of coffee seeds:

The moisture content of *Coffea Arabicaand Coffea Canephora* seeds were determined in the laboratory using the conventional oven drying method and computed as represented in Table1 and Table 2 to give the following moisture content in dry basis: 11%, 13.85%, 13.48%, 11.3% and10.9%, and a mean moisture content of 12.23%. While the moisture content of *Coffea Canephora*in dry basis was: 13%, 13.31%, 11.58%, 12.3%and10.22%, and a mean moisture content of 12.26%.

Table 1Determination of moisture content of *Coffea Arabica*

Trials	Mass of Wet Product (g)	Mass of Dried Product (g)	Moisture Content (%, d.b.)
1	200	179.21	11.60
2	200	175.67	13.85
3	200	176.24	13.48
4	200	179.69	11.30
5	200	180.34	10.90
Sum	1000	891.15	61.13
Average	200	178.21	12.23

Table 2Determination of moisture content of *Coffea Canephora*

Trials	Mass of Wet Product (g)	Mass of Dried Product (g)	Moisture Content (%, d.b.)
1	200	175.64	13.87
2	200	176.51	13.31
3	200	179.24	11.58
4	200	178.09	12.30
5	200	181.46	10.22
Sum	1000	890.94	61.28
Average	200	178.19	12.26

6.2 Performance evaluation

The results of the performance test carried out on the *CoffeaArabic* and *CoffeaCanephora* de-hulling machine are shown in Table3 and Table4.

Table 3Design factors and responses as influenced by treatments of de-hulled*Coffea Arabica.*

X_1	X_2	Y_1	Y_2	Y_3	Y_4	Y_5
10	300	1955	945	2.97	658.25	65.17
15	300	1864	1021	2.34	796.58	62.13
20	300	1790	1113	2.61	685.82	59.67
10	400	1753	1160.2	2.41	727.39	58.43
15	400	1767	1121.6	2.27	778.41	58.9
20	400	1665	1240.3	2.43	685.19	55.5
10	500	1712	1199.5	2.12	807.55	57.07
15	500	1700	1200.4	2.34	726.5	56.67
20	500	1687	1216.43	2.07	814.98	56.23

Table 4Design factors and responses as influenced by treatments of de-hulled *CoffeaCanephora*

X_1	X_2	Y_1	Y_2	Y_3	Y_4	Y_5
10	300	1728.6	1189.14	2.81	705.55	57.62
15	300	1629	1210.32	2.88	565.63	54.3
20	300	1572.3	1302.6	2.12	741.65	52.41
10	400	1623.3	1293	2.45	662.57	54.11
15	400	1601.7	1281.43	2.42	661.86	53.39
20	400	1544.1	1369.89	2.17	711.57	51.47
10	500	1619.1	1287.11	2.28	710.13	53.97
15	500	1572.9	1325	2.34	672.18	52.43
20	500	1565.7	1352.04	2.11	742.04	52.19

Where;

X_1 = moisture content in dry basis (% d.b),

X_2 = speed of rotational machine's shaft (r/min),

Y_1 = de-hulled mass (1st feed)(g),

Y_2 =de-hulled mass(1st feed)(g),

Y_3 =de-hulled time(1st feed)(min),

Y_4 =de-hulled capacity (1st feed)(g/min),

Y_5 =de-hulled efficiency(1st feed)(%).

6.3 Effect of moisture content and speed of the shaft on the de-hulling efficiency of the machine

Figure 2 is the plot of treatment against de-hulling efficiency of the machine for *Coffea Arabica*. Based on the experimental data obtained, it was observed that as moisture content increased, the de-hulling efficiency reduced. The result showed that the de-hulling efficiency of the machine for *Coffea Arabica*was(65.17%and 57.62%), (62.13% and 54.30%), (59.67% and 59.67%), (58.43% and 54.11%), (58.90% and 53.39%), (55.50% and 51.47%), (57.07% and 53.97%), (56.67% and 52.43%)for (10%d.b, 300r/min), (15%d.b, 300r/min), (20%d.b, 300r/min), (10%d.b, 400r/min), (15%d.b,400r/min), (20%d.b, 400r/min), (10%d.b, 500r/min), (15%d.b, 500r/min), and (20%d.b, 500r/min), respectively.Similar findings were reported by Ringin (1982); Babale (1988) and Mohammed (1989)

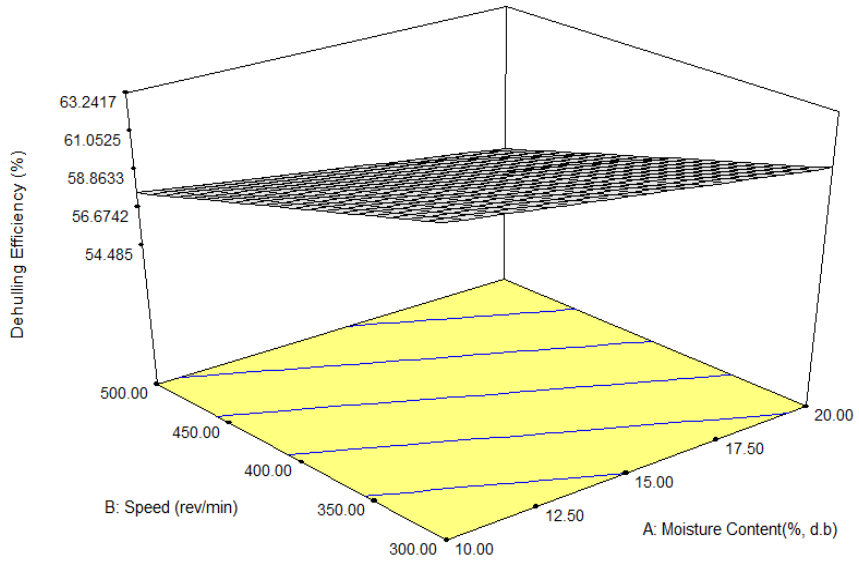


Figure 2 Effect of moisture content and speed on the de-hullingefficiency for*Coffea Arabica.*

The relationship between moisture content and speed of rotation is expressed as Equation 23. The ANOVA results reported in Table 5 shows that the rotational speed of the shaft is the only significant model term on dehulling efficiency ($p < 0.05$). Shittu (2012) also reported that the results of analysis of variance (ANOVA) carried out on the performance test results showed that seed moisture content and machine shelling speed have significant effect on both shelling efficiency and seed damage percentages at 1% level.

$$Dehulling\ Efficiency = +58.86 - 1.55X_1 - 2.83X_2 (R^2 = 0.8057) \quad (23)$$

Table 5 ANOVA for response surface linear model. Analysis of variance table [Partial sum of squares]

Source	Sum of Squares	DF	Mean Square	F Value	Prob.>F	
Model	62.48882	2	31.24441	12.44022	0.0073	Significar
A	14.32215	1	14.32215	5.702483	0.0542	
B	48.16667	1	48.16667	19.17796	0.0047	
Residual	15.06938	6	2.511564			
Cor. Total	77.5582	8				

The de-hulling efficiency of the machine for *CoffeaCanephora* was (56.23% and 52.19%) for (10%d.b, 300 r/min), (15%d.b, 300 r/min), (20%d.b, 300 r/min), (10%d.b, 400 r/min), (15%d.b,400 r/min), (20%d.b, 400 r/min), (10%d.b, 500 r/min), (15%d.b, 500 r/min), and (20%d.b, 500 r/min), respectively. The de-hullingefficiency obtained was similar to the result described by Gbabo et al. (2013). For *CoffeaCanephora*, mathematical expression of the relationship between the speed, and moisture content are presented in Equation 24and the response surface plots as shown in Figure 3. Furthermore, the ANOVA results reported in Table 6 indicates that the moisture content and rotational speed of shaft have significant effects on the dehulling efficiency.

$$Dehulling\ Efficiency = +53.54 - 1.61X_1 - 0.96X_2 (R^2 = 0.7943) \quad (24)$$

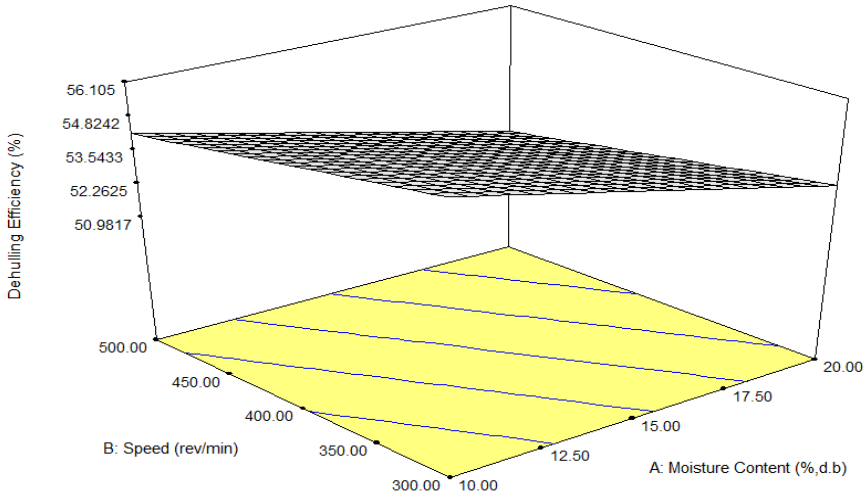


Figure 3Effect of moisture content and speed on the de-hullingefficiency for*Coffee Canephora*

Table 6 ANOVA for response surface linear model. Analysis of variance table [Partial sum of squares]

Source	Sum of Squares	DF	Mean Square	F Value	Prob.>F	
Model	20.94742	2	10.47371	11.58343	0.0087	Significant
A	15.45615	1	15.45615	17.09378	0.0061	
B	5.491267	1	5.491267	6.073085	0.0488	
Residual	5.425183	6	0.904197			
Cor. Total	26.3726	8				

7 Conclusions and recommendations

7.1 Conclusions:

The following conclusions were drawn from the results acquired, based on the investigation of the performance evaluation of a coffee de-hulling machine;

1. The moisture content, shaft speed and the interaction of moisture content and shaft speed were significant on the de-hulling mass for the various varieties at $p< 0.05$. As the speed increased, the mass of de-hulling coffee seed reduced, and increase in moisture content also led to a reduction of the de-hulling mass.

2. A higher de-hulling efficiency was recorded for the *CoffeeArabica* specie than the *CoffeeCanephora* specie.

3. The paired sample test between the de-hulling performance of *Coffee Arabica* and *Coffee Canephora*, showed that the de-hulling efficiency was significant.

7.2 Recommendations:

As a result of the research done on the design and performance evaluation of the coffee de-hulling machine, the following recommendations are suggested;

1. The length of the de-hulling chamber should be increased in the other to make certain an increase, of the retention time of the de-hulling machine.

2. The clearance between the auger and the wall of the de-hulling chamber should be made adjustable. This would improve the interaction between auger and seed, seed and seed, and seed and the barrel wall, thereby reducing the effect of the sharp variations of sizes coffee seeds of the same and different species.

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