DEVELOPMENT AND PERFORMANCE EVALUATION OF A CENTRIFUGAL AIR-FLOW GRAIN CLEANER

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ABSTRACT

Global demand for high-quality grain underscores the need for clean grains which is vital to food security. Contaminants such as broken cobs, grain dust, stones, and chaff are found in grains during harvest, handling, and storage operations. Manual winnowing is laborious and cannot meet the continuous demand for clean grains. The availability of grain cleaning machines will ensure a sustainable supply of clean grains while conserving human energy and improving food security.A centrifugal flow grain cleaner was developed with major components such as hopper, sieves, electric motor, and blower. Yellow maize variety (Swan 2) was used to test the centrifugal flow grain cleaning machine and trials were carried out in three replicates. It was tested at three moisture content (MC) levels of 15%, 17%, and 19% (wet basis) commonly found in grain markets in Ibadan, Nigeria. Three feed rates (FR) (180, 250, and 320 kg/hr) were used. Performance evaluation to determine the cleaning efficiency (EG), total efficiency (ET), and product purity (PP) level using NIS 320: 1997 Seed/Grain Standards and other relevant indices. Analysis of variance was carried out to assess the significance of the models developed using Design-Expert® software (Version 6.0.6 StatEase, Inc., Minneapolis, Minn.). Results showed that EG was within 98.3% to 98.9% across the MC and FR. The optimal ET was 85.5% at optimum operating parameters of 180 kg/hr FR, and 15% MC. The regression model developed for the relationship between MC and FR on EG was significant. Commercial production of the grain cleaner is viable due to its low cost, local technology and, increased demand for quality grains.

Keywords: Maize, moisture content, feed rate, machine efficiency, grain quality, grain cleaner

1. INTRODUCTION

Grains are crops rich in carbohydrates and also contain some amount of protein, fats, oil, and vitamins (Sarwar *et al*., 2013). Grains are cultivated for their kernels which are used majorly for food (Sokoto *et al*., 2016). Cereal belongs to the monocotyledon family Poaceae, which are grass crops that produce comestible grain seeds (Adebayo and Ibraheem, 2015). The most common cereal or grain crops grown in Nigeria include maize (also known as corn), rice, sorghum, cowpea, and wheat (Aremu *et al*., 2014). According to FAO, maize production in Nigeria was estimated at 10.2 million metric tons (FAOSTAT, 2020). However, cleaning and separation of grains from impurities is required before further processing can be carried out.

The need for clean and high-quality grains to food safety and human existence in a modern society cannot be overemphasized both in Nigeria and the rest of the world (Ismaila *et al*., 2010). This is because the fines in unclean grains are attractive to insects making the grains susceptible to contamination by molds and aflatoxins during storage. Toews and Subramanyam (2014) reported that cleaning of grains is essential before storage as it results in reduced costs related to aeration and insect management. Grains such as milled rice are frequently winnowed locally to separate grains from unwanted materials (Okunola *et al*., 2018), a process that is quite tedious and requires a long period (Okunola, 2011). Postharvest operations such as cleaning and milling of grains are carried out in developing countries such as Nigeria manually with hand and with some traditional methods (Ndukwu and Onyenwoke, 2014).

Aguirre and Garray (1999) reported that the speed, high labor requirement, air flow in different directions, and continuity of air current pose a limitation to the dependency on natural air current as a means of separation of chaff from bean seeds. Zhao *et al*. (1999) reported that the preliminary separation of grains from impurities (chaff and particles) was influenced by air velocity during grain conveyance on the sieve. Simonyan *et al*. (2006) also reported that the separating and cleaning process was affected by physical factors and can be grouped from literature into two namely: crop factor — grain variety, maturity stage, grain moisture content, grain size, and terminal velocity; mechanical factor — sieve hole diameter, frequency of sieve oscillations, air speed, and sieve slope. These factors are essential and critical to the performance of the machine.

Some of the mechanical factors influencing the rate of cleaning, separation, and total losses include sieve slope, air speed, and sieve oscillation (Ebaid, 2005). Ali *et al.* (2022) designed and assessed a small-scale machine for cleaning wheat grains. They concluded that the slope of the sieve unit and the reciprocating speed had the most significant effect on the maximum cleaning efficiency. Ghonimy and Rostom (2022) designed and evaluated the performance of a canola seed-cleaning machine. They concluded that an increment of the cylindrical sieve slope angle and flat sieve speed increases the percentage of canola seed losses during the cleaning process. Olaposi and Jerome (2023) developed and evaluated the performance of a combined maize shelling and cleaning machine. They concluded that the highest machine efficiency of 88% was attained at 500 rpm and 12% moisture content (MC) of shelled maize. Awady *et al*. (2003) and Ebaid (2005) reported that the cleaning efficiency and total loss increased with increasing sieve oscillation, sieve tilt angle, and air speed while working on rice and wheat grains respectively. Abdel *et al*. (2007) reported that less resident time of materials to be separated on the sieve during grain cleaning such as rice may be responsible for the decrease in cleaning efficiency with respect to increasing sieve oscillation movement. Zdzislaw (2013) reported that the angle of inclination of a separator screen or sieve is a vital consideration that determines the effectiveness and continuity of the separation process of cereal seeds. A common occurrence during separation may be clogging of the sieve opening by the presence of materials that are unable to pass through the openings. Okunola *et al*. (2015) varied the angle of tilt of the sieve between 3° to 8° and maintained a fan speed of 240 rpm during the machine test of a rice grain cleaner. They reported a total separation efficiency of 71% for paddy rice. Angelovič *et al.* (2019) reported that the level of cleanliness achieved by grain cleaners should not be the only factor determining the quality of the machine but also other factors such as performance and quantity of good grains lost.

Grain MC is an important consideration in the design of equipment for separation, cleaning, handling, conveying, processing and storing (Sobukola and Onwuka, 2011), as well as to accurately specify design considerations and avoid resources loss. The grain size and shape are relevant in separation of undesirable particles and in the fabrication of sizing and grading equipment (Mohsenin, 1970; Gursoy and Guzel, 2010). The drop height of the material mixture — grains, chaff, tiny broken cobs, and grain dust was recommended to be large enough to aid adequate exposure to the blowing or sucking air for effective cleaning (Caro *et al*., 2014). In addition, it allows for the provision of adequate height to enable the terminal velocity of the chaffs to be attained. They further recommended a drop height of 0.51 m which was found suitable for blowing away lighter impurities with required air velocity. The lighter chaffs are blown or sucked by the air speed generated from the blower due to the varying terminal velocities of the materials while the grains drop by gravity as a result of the higher terminal velocity of grains to the air velocity (Simonyan and Yiljep, 2008).

Food grains need to be cleaned as harvesting and postharvest handling methods add contaminants — chaff, dust, sticks, and leaves to grains (Ogunlowo and Adesuyi, 1999). Cleaning of about one kilogram of unclean grains using the winnowing method can take about seven to twelve minutes depending on some factors — winnower's handling skills, speed and stability of natural air current, and ratio of grain to unwanted materials (Muhammad et al. 2013). Grain cleaning process remains stressful in rural and farm settlement areas among farmers and individuals involved in farming activities (Okunola *et al.,* 2019). The design and construction of effective and efficient grain cleaning equipment will ensure the mitigation of problems arising from low quality grains. There is therefore the need to deploy grain cleaning machines at an affordable cost and with high efficiency, most especially at the farm level, to alleviate problems associated with impurities in grains before bagging, storage or transportation.

The objectives of this study were:
(1) to design and develop a grain cleaning machine, and (2) to evaluate the performance of the grain cleaning machine. The centrifugal air-flow grain cleaner designed and constructed in this study was carried out to tackle the challenges of chaff removal from grains and adequate cleaning process.

2. MATERIALS AND METHODS

centrifugal air-flow grain cleaner was developed and tested using Swan 2 maize variety at MC levels of 15%, 17%, and 19% (wet basis), and feed rates (FR) of 180, 250, and 320 kg/hr. Repeated trials were conducted which helped to determine that at 25% opening of the aperture, approximately 3000 g of maize will pass through within a minute, equivalent to 180 kg/hr. Using the same process, it was determined that approximately 4166g/min and 5333g/min was equivalent to 250 and 320 kg/hrrespectively, using the same aperture opening. The choice of the FR was to prevent overloading of the hopper and clogging of the machine, while the choice of MC was the range commonly found in the markets. The MC and FR were the independent variables while the cleaning efficiency (EG) (also known as separation efficiency), total efficiency (ET), and product purity (PP) were the dependent variables (performance efficiencies).

2.1 Design Considerations

During the design of the grain cleaning machine, the following factors were considered: strength, rigidity, availability, cost of production of the machine, expected function to perform, ease of use, ease of cleaning, blower air speed, low labor and maintenance cost, variable sieves, durability, safety, and environmental conditions in which it would be used. Due to the presence of broken cobs, stalks, chaff, and other unwanted materials found in uncleaned shelled maize grains, a combination of a blower (pneumatic) and sieves (mechanical) methods to enhance the separation and cleaning were considered.

2.2 Description of the Machine

The centrifugal air-flow grain cleaner consists mainly of the hopper, blower, sieves, and supporting frame. The shape of the hopper is a frustum of a pyramid and made of mild steel sheet. The lower part of the hopper tappers down at an angle of 50º for easy sliding and rolling down of grains (Aremu *et al.*, 2014; Tarighi *et al.,* 2011). A control adjuster was incorporated in the hopper to control grain flow. The blower is locally fabricated and consist of paddles attached to a wheel (centrifugal fan) made of mild steel sheet and can generate high speed. The outlet of the blower is located horizontally to deliver moving air across the materials flowing vertically from the column attached to the sieve housing. The average air speed from the blower exit was recorded as 4.0 m/susing a TPI 565C1 digital hot-wire anemometer. The blower is powered by a single-phase electric motor of 1,450 rpm and 1.5 hp. The sieve housing is connected to the base of the hopper. It comprises two sieves made from stainless steel with diameters of 10 mm and 14 mm to separate impurities with different sizes. The sieves were arranged in layers and were detachable. A connecting rod attached to the sieve housing provides power through the movement of a pulley which is powered by a single-phase electric motor of 1440 rpm and 2 hp. The sieve housing is agitated by an eccentric drive resulting in an oscillatory motion. The two reciprocating sieves were used to aid in the pre-cleaning of the grains. The impurities larger than the grains are separated by the first sieve and the impurities smaller than the grains were separated by the second sieve. The supporting frame of the machine carries the weight of the whole machine and is made of iron. The choice of electric motors as the prime mover was to mitigate air pollution by the release of carbon monoxide which is common among petrol and diesel engines. The prime movers are mounted on the frame to power the blower and the sieve housing using a belt and pulley drive. The specifications of the major components of the machine are shown in Table 1. The schematic layout and exploded view assembly of the grain cleaner is shown in Figures 1 and 2.

Table 1. Specifications of major components of the grain cleaner

Parameters	Units
Pulley diameters	50 mm and 355 mm
Sieve diameters	14 mm and 10 mm
Electric motors (medium speed)	2 hp and 1.5 hP
Shaft diameter	25 mm
Angle iron	5 mm by 4 mm thickness
Pillow bearing	20 mm
Mild steel plate	1.5 mm thickness
Volume of hopper	8.324×10^{-3} m^3
Hopper slope	50°
Degree of sphericity of grain	62.5%
Air speed of blower	4 m/s
Effective length of duct	1.48 m
Effective diameter of grain	9.6 mm
Tension on tight and slack sides of belt	63.4 N and 20.7 N
Resultant angle of belt	60°

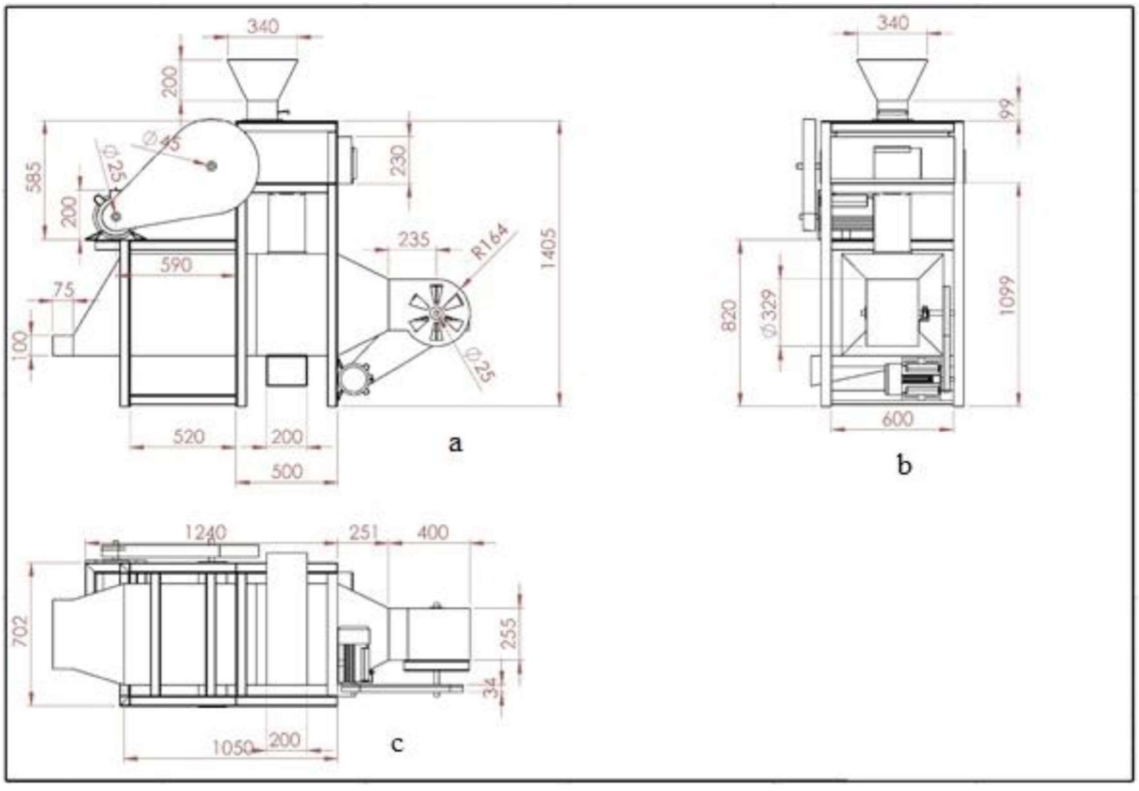
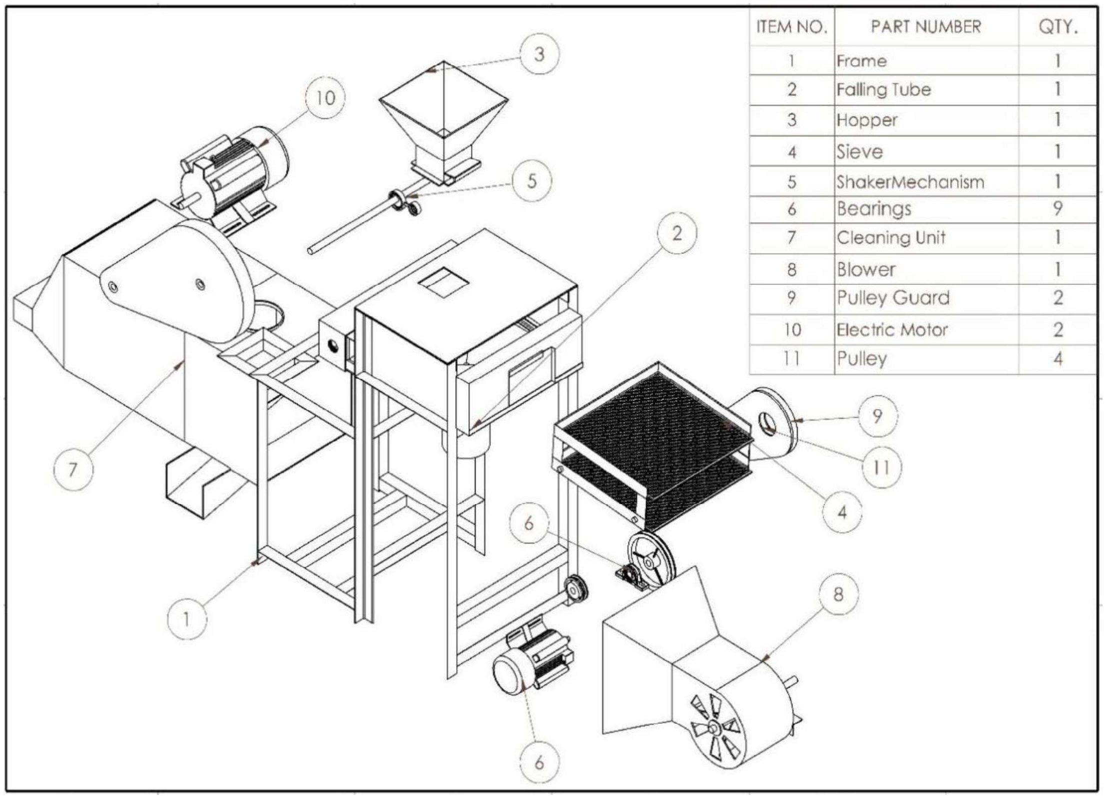


Figure 1. Orthographic views for side elevation (a), front elevation (b), and plan elevation (c)



ITEM NO.	PART NUMBER	QTY.
1	Frame	1
2	Falling Tube	1
3	Hopper	1
4	Sieve	1
5	ShakerMechanism	1
6	Bearings	9
7	Cleaning Unit	1
8	Blower	1
9	Pulley Guard	2
10	Electric Motor	2
11	Pulley	4

Figure 2. The exploded view of the grain cleaner

2.3 Operation of the Machine

The operation of the machine is carried out by switching on the electric motors connected to an electric source which drives the blower and the housing units independently. The grain admixture is fed into the machine via the hopper. The adjuster is opened gently to allow the flow of the admixture through the hopper outlet. The admixture drops on the surface of the sieves and passes through the first and second sieves onto a connecting column (falling tube) to the cleaning unit of the blower housing. The larger sizes of unwanted materials are held back by the sieve and discarded manually on stopping the operation of the machine while the smaller sizes such as grain dust, tiny broken cobs, and stones are pushed by the air current and discharged at the blower outlet. The grains are not carried away as the terminal velocity of the grains is greater than the velocity of the air current from the blower, the grains drop by gravity and are collected at the receptacle for clean grains. The developed grain cleaner is shown in Figure 3.

Figure 3. The fabricated grain cleaner

2.4 Design Calculations

2.4.1 The hopper

The hopper was designed in the shape of a frustum of a pyramid. The material of construction used for the hopper was mild steel sheet metal as it is rigid, readily available in the market, and less expensive. Pythagorean's theorem was used in the design of the hopper and the principle of similar triangles. The dimensions of the top, bottom, and perpendicular height of the hopper were 350, 150, and 169 mm. The volume of the hopper was calculated using the formula as:

$$v = \frac{1}{3} \times h(A + AB + B) \qquad \text{(Suphi, 2015)} \qquad (1)$$

where,

v is the volume of the hopper (m^3), A is the area of the upper base (m^2), B is the area of the lower base in (m^2), and h is the perpendicular height of the hopper (m).

The choice of the hopper slope as 50° was to ensure easy and free sliding down of grains on mild steel surface as the angle of repose of maize grains reported by Aremu *et al.* (2014) was 48° and by Tarighi *et al.* (2011) as 42° to 47° for MC between 5% to 16% respectively.

2.4.2 Terminal velocity of maize

The theoretical determination of the terminal velocities of a particle (grain kernel) was stated by (ASABE, 2006) with the expression for spherical particles calculated as:

$$V_t = \sqrt{\frac{4 \times g \times d_p\,(\rho_p - \rho_f)}{3 \times C_d \times \rho_f}} \qquad (2)$$

where,

V_t is the terminal velocity (m/s); g is the acceleration due to gravity (m/s^2), d_p is the particle diameter (m), ρ_f is the density of fluid (kg/m^3),ρ_p is the density of the particle (kg/m^3), C_d is the drag coefficient which is given as 0.44 (Mohsenin, 1970).

The calculated terminal velocity for the maize kernel was 15.4 m/s. This implies that the maize kernels would remain suspended in a stream of air at 15.4 m/s. Air velocity greater than 15.4 m/s would displace the grain kernels.

2.4.3 Screen characteristics

The effective diameter (De) and degree of sphericity (Φ) of the grains (Sobukola et al., 2012; Mohsenin, 1970) were used to determine the diameter aperture of the sieves in equations 3 and 4. Twenty (20) grain kernels were picked randomly and the average dimensions of the grain kernels were 16, 11, and 5 mm for length, width, and thickness respectively.

$$De = (LWT)^{1/3} \qquad (3)$$

$$\Phi = \frac{(LWT)^{1/3}}{L} \times 100 \qquad (4)$$

where,

L is the length of grain (mm), W is the width of grain (mm), and T is the thickness of grain (mm).

The effective diameter of the averaged grain kernels was calculated as 10 mm. A sieve size of 10 mm and 14 mm was used for the grain cleaner to enable efficient separation. The degree of sphericity was calculated as 62.5%. The degree of sphericity normally lies between 0 and 1, and assuming the grain is spherical, the sphericity of 0.625 was assumed. Hence the choice of a spherical shape aperture sieve. The screen is detachable and can be changed to suit other grains by using the screen characteristics formulae.

2.4.4 Power determination

I. Angular Velocity, Pulley Size and Speed

The angular velocity was determined using the expression according to Khurmi and Gupta (2005) as:

$$\omega = \frac{2\pi N}{60} \tag{5}$$

where,

ω is the angular velocity (m/s), and N is the speed of the shaft (rpm).

The selection of the pulleys was based on strength, durability, availability, and relative low cost compared to other materials. Cast iron pulleys were selected. The determination of the driver pulley and the diameter of the pulley calculations were based on the horsepower rating. The horsepower rating was given at a maximum pitch diameter of the pulleys and corresponding speed. Hence, the horsepower rating therefore determined the diameter of the driver pulley. The driven pulley was calculated based on the relationship between the spindle speed and the speed of the prime mover which was given by the expression below (Abdulkadir*et al.*,2009; Khurmi and Gupta, 2005; Williams, 1953).

$$\frac{N_1}{N_2} = \frac{D_2}{D_1} \tag{6}$$

where,

N_1 is the speed of the driver pulley (rpm), N_2 is the speed of the driven pulley (rpm), D_1 is the diameter of the driver pulley (m), and D_2 is the diameter of the driven pulley (m).

II. Belt Speed and Length of Belt

The speed of the belt was determined as given by Khurmi and Gupta (2005).

$$V = \frac{N_2 \pi D_2}{60} \tag{7}$$

where,

V is the belt speed (m/s), N_2 is the speed of the driven pulley (rpm), and D_2 is the diameter of the driven pulley (m).

The length of the belt was determined based on the diameters of the pulleys and the belt center distance (Khurmi and Gupta, 2005).

$$L_b = 2x + [(\pi/2) \times (D + d)] + \frac{(D-d)^2}{4x} \tag{8}$$

where,

L_b is the length of the belt (m), xis the center distance of the belt (m), D is the diameter of the bigger pulley (m), and d is the diameter of the smaller pulley (m).

A 5% friction loss on the shaft was assumed and considered during the design. Torque exerted on the driver pulley (the effective pull) was calculated as $(T_1 - T_2)r_2$. The slack side tensions of the belt were determined as:

$$2.3\log\left(\frac{T_1}{T_2}\right) = \mu\theta Cosec\,\beta \tag{9}$$

where,

T_1 is the tension on tight side (N), T_2 is the tension on slack side (N); μ is the co-efficient of friction between belt and cast iron or steel pulley given as 0.3 (Abdulkadir *et al.*, 2009), and β is the groove angle given as 38° (Abdulkadir *et al.*, 2009).

III. Shaft Diameter and Belt Width

The determination of the shaft diameter for the connecting rod to be driven by the electric motor as a driver for the cam attached to the sieve housing was calculated to ensure satisfactory strength and rigidity while in operation under various operating and loading conditions. The design of the shaft was based on the maximum shear theory. Shafts are usually subjected to torsion, bending, and axial loads.

A factor of safety three (3) was considered in the design. The diameter of the shaft was designed according to ASME code (ASME, 1995) for a solid shaft having little or no axial loading in the equation below.

$$d^3 = \frac{16}{\pi \tau_{max}} \sqrt{(K_b M_b)^2 + (K_t M_t)^2} \tag{10}$$

where,

d is the diameter of the shaft (m), M_t is the torsional moment (Nm), M_b is the bending moment (Nm), K_b and K_t are the combined shock and fatigue factor applied to bending and torsional moment, and τ_{max} is the allowable stress (Mpa).

The torsional moment (M_t) was calculated from equation 11while equations 12 to 14 were used to determine the tensions on the tight and slack sides, respectively (Khurmi and Gupta, 2005).

$$M_t = \frac{P \times 60}{2\pi N} \tag{11}$$

$$T_i = T_{max} - T_c \tag{12}$$

$$T_{max} = \sigma a \tag{13}$$

$$T_c = mv^2 \tag{14}$$

where,

T_c is the centrifugal tension of the belt (N), T_{max} is the maximum tension of the belt (N), σ is the maximum safe normal stress (N/mm^2), a is the cross-sectional area (mm^2), m is the mass per unit length of the belt(Kg/m), v is the belt speed (m/s), T_i is the tension on tight side of a belt (N), T_j is the tension on slack side of a belt (N), D_2 is the diameter of the driven pulley (mm), P is the power required to drive the machine (watts), and N is the speed of the shaft (rpm).

The maximum bending moment, M_b was determined as:

$$M_b = (M_v^2 + M_h^2)^{1/2} \quad \text{(Khurmi and Gupta, 2005)} \tag{15}$$

where,

M_h is the bending moment on the horizontal plane (Nm), and M_v is the bending moment on the vertical plane (Nm).

The belt width was determined from equation 16.

$$m = A \times L \times \rho = (b \times t) \times L \times \rho \quad \text{(Khurmi and Gupta, 2005)} \tag{16}$$

where,

L is the length of the belt (m), m is the mass of the belt (kg/m), b is the width of the belt required (m), t is the thickness of belt (m), A is the area of belt (m^2), and ρ is the density of rubber belt material taken as 1100 kg/m^3(Austrell and Kari, 2005).

The approximated summation of the power (HP) needed for the movement in the horizontal (Igbeka, 1984) and vertical direction (Ogunlowo and Adesuyi, 1999) of the particles and screen was calculated as the theoretical power requirement for the oscillation.

For the horizontal:

$$HP_1 = \left(\frac{2 \times Ws \times N \times X \times \mu}{4500}\right) \tag{17}$$

For the vertical:

$$HP_2 = \left(\frac{2 \times Ws \times N \times Y}{4500}\right) \tag{18}$$

where,

N is the speed (rpm), Ws is the weight of the sieve assembly and test materials on it (kg), Y is the vertical displacement of the reciprocating assembly (m/stroke), X is the horizontal displacement of reciprocating assembly (m/stroke), and μ is the co-efficient of friction between hinge points taken as 0.4 (Okunola *et al*., 2015).

The total minimum power requirement for the screen movement was calculated by the addition of the horsepower for the vertical and horizontal motions.

2.4.5 Blower section

I. Determination of Air Generated by Paddles

The blower was used to generate the air stream required for adequate separation of the grains and the undesirable materials. The blower was made up of four paddles attached to a 25 mm diameter rod with 430 mm length. The paddles were 215 mm in length, 60 mm in width, and a slant height of 125 mm. Two single-phase direct-speed electric motors of 1,450 rpm and 1,440 rpm with 1.5 hp and 2.0 hp power capacity, respectively were used to drive the moving parts of the machine. The average air speed from the blower exit was recorded using a TPI 565C1 digital hot-wire anemometer (one decimal place) as 4.0 m/s. The volume of the four paddles can be calculated as:

$$v = 4A \times L \tag{19}$$

where,

v is the volume of paddles (m^3), A is the paddle sectional area (m^2), and L is the length of a paddle (m).

II. Hydraulic Diameter and Volumetric Flow Rate

The hydraulic diameter was calculated from the expression according to Rajput (2013).

$$D_h = \frac{4A}{P} \tag{20}$$

where,

A is the area of the duct (m^2), and P is the perimeter of the duct (m).

The volume flow rate was calculated using the expression according to Rajput (2013) as:

$$Q_{max} = v \times A \tag{21}$$

where,

Q_{max} is the maximum volumetric flow rate (m^3/s), v is the conveying air velocity at the exit (m/s), and A is the area of blower size (m^2).

III. Effective Duct Length

The effective duct length for air velocity less than or equal to 13 m/s was calculated using the formula by ASHRAE (2001) as:

$$L_e = \frac{\sqrt{A_o}}{350} \qquad \text{For } v_o \leq 13 \text{ m/s} \tag{22}$$

Where,

L_e is the effective duct length (m), v_o is the duct velocity (m/s), and A_o is the duct area (mm^2).

2.5 Performance Evaluation

Swan 2 maize variety was purchased in May 2017 from Ijaye farm settlement in Akinyele Local Government Area of Ibadan, Oyo State, Nigeria. The maize was shelled using a single-purpose grain sheller without a blower. The MC of the shelled maize was 14% (wet basis) and reconditioned to 15, 17, and 19% (wet basis). The MC of the maize was determined using a John Deere Moisture Meter SW08120. The uncleaned grains were used to test the grain cleaning machine. The EG, ET, and PP were calculated from NIS 320: 1997 Seed/Grain Standard, Igbeka (2013), and Igbeka (1984) indices shown in Equations 23 to 26. These equations were used to determine the performance efficiencies of the grain cleaner. The feed (F) is the uncleaned grains, the products (P) are the grains from the clean outlet, the rejects (R) are the impurities and any grain that might have escaped from the exit duct of the blower, and top of sieves. The good products (GP) refer to the whole grains while the bad products (BP) are the unwanted material that found its way to the clean outlet. The good rejects (GR) are classified as the grains that found its way to the reject outlet, while the bad reject (BR) are the unwanted materials. Samples were collected at each outlet — blower passage for light impurities, materials separated by the sieves, and outlet for clean grains were weighed and recorded. Figure 4 shows the separation and classification of the grains and impurities from the outlets.

$$EG = \frac{GP}{(GP+BP)} \times 100 \tag{23}$$

$$EB = \frac{BR}{(BR+BP)} \times 100 \tag{24}$$

$$ET = \frac{EG \times EB}{100} \tag{25}$$

$$PP = \frac{GP}{(GP+GR)} \times 100 \tag{26}$$

where,

GP is the weight of good products (kg), BP is the weight of the bad products (kg), GR is the weight of the good reject (kg), BR is the weight of the bad reject (kg), EG is the efficiency of separating whole grains (%), EB is the efficiency of separating materials other than grains (%), ET is the total efficiency (%), and PP is the product purity of whole grain in products (%).

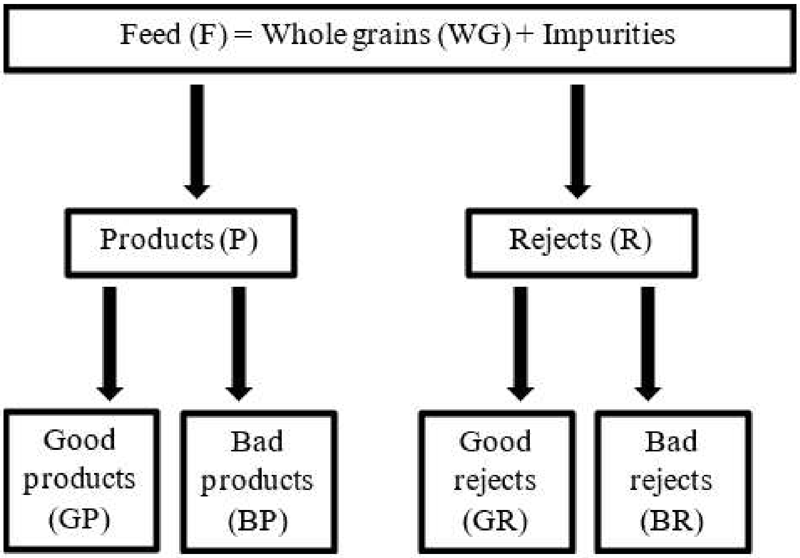


Figure 4. Flow chart showing the classifications of the grains and impurities from the outlets

2.6 Statistical Analysis

Trials were carried out in three replicates. Data were analyzed using Design-Expert® software (Version 6.0.6 StatEase, Inc., Minneapolis, Minn.) for the central composite rotatable design of response surface and analysis of variance (ANOVA) for the effect of FR and MC on EG, ET, and PP at alpha level of 0.05.

3. RESULTS AND DISCUSSION

The results of the average time taken during the performance evaluation of the graincleaner for the three levels of maize MC and FR were 65, 191, and 217 s for 15% MC; 59, 185, and 208 s for 17% MC; and 60, 135, and 172 s for 19% MC. Table 2 shows the results of the parameters that were recorded and determined at the end of the grain cleaner test trials.

3.1 Effect of Feed Rate and Moisture Content on Separation Efficiency of Whole/Cleaned Grains

The maximum average separating efficiency of the grain cleaning machine was 99.0% for operating conditions of 15% MC, and 250 kg/hr FR (Table 2). The separation efficiency results were similar and within the range of Muhammad *et al*. (2013) as they reported a range between 91% and 98% for sorghum, soybean, and millet. Okunola *et al*. (2015) also reported a grain cleaning machine separation efficiency in the range of 73% and 87% for paddy rice. These variations in the separation efficiency were a result of the differences in physical and aerodynamic properties of the grains, the grain type, and machine parameters. The response surface analysis (Fig. 5) showed that a lower maize MC leads to a higher cleaning efficiency, while a lower feed rate leads to a higher cleaning efficiency. This indicates that separation of maize grains was more effective at lower MC and FR. High feeding rates affects separation efficiency as a mat/layer is formed on the sieves due to the thickness and looseness of the grains and impurities (Rothaug *et al*., 2003; Hollatz and Quick, 2003).

ANOVA result shows that the effect of FR and MC were significant on the cleaning efficiency of the coefficient of determination (R^2) value was found to be 0.983, indicating that a strong relationship exists between the feeding rate, moisture content and separation efficiency of cleaned grains.

$$EG = 0.58A^2 + 0.26B^2 + 0.21A - 0.41B + 0.19AB + 97.73 \tag{27}$$

where,

A is the feeding rate (kg/hr), B is the moisture content of the grains (%), and EG is the cleaning efficiency of the cleaned grains (%).

Table 2. Parameters showing the average values of the grain cleaner

Feed Rate (FR) (kg/hr)	Moisture Content (%)	Whole Grain (WG) (kg)	Undersized Grains (UG) (kg)	Good Product (GP) (kg)	Good Reject (GR) (kg)	Bad Product (BP) (kg)	Bad Reject (BR) (kg)	EG (%)[a]	EB (%)[b]	ET (%)[c]	PP (%)[d]
180	15	9.4	0.6	9.3	0.2	0.1	0.4	98.9	86.2	85.5	97.9
	17	9.5	0.5	9.3	0.2	0.1	0.3	99.3	82.4	81.8	98.1
	19	8.9	1.1	8.7	0.2	0.1	0.4	98.3	71.2	69.7	97.9
250	15	14.2	0.8	13.9	0.3	0.1	0.4	99.0	76.9	76.1	98.2
	17	13.8	1.2	13.5	0.3	0.2	0.4	98.6	67.6	66.7	98.1
	19	13.6	1.4	13.4	0.2	0.2	0.5	98.7	73.8	72.8	98.7
320	15	4.7	0.3	4.6	0.1	0.1	0.3	98.6	81.6	80.5	96.9
	17	4.4	0.6	4.3	0.1	0.1	0.3	98.6	82.2	81.0	96.9
	19	4.3	0.7	4.1	0.1	0.1	0.3	98.5	81.9	80.7	96.5

[a] EG is the cleaning efficiency

[b] EB is the efficiency of separating materials other than grains

[c] ET is the total efficiency

[d] PP is the product purity

Table 3. ANOVA of the quadratic regression model for the effect of feed rate and moisture content on the efficiency of separating whole grain

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	2.90	5	0.58	34.37	0.0075	Significant
A[a]	0.35	1	0.35	21.01	0.0195	
B[b]	1.37	1	1.37	80.92	0.0029	
A^2	0.97	1	0.97	57.67	0.0047	
B^2	0.20	1	0.20	11.74	0.0417	
AB	0.15	1	0.15	8.91	0.0584	
Residual	0.051	3	0.017			
Cor total	2.95	8				

[a]A is the feeding rate (kg/hr)

[b]B is the moisture content of the grains (%). Significant level at $p < 0.05$.

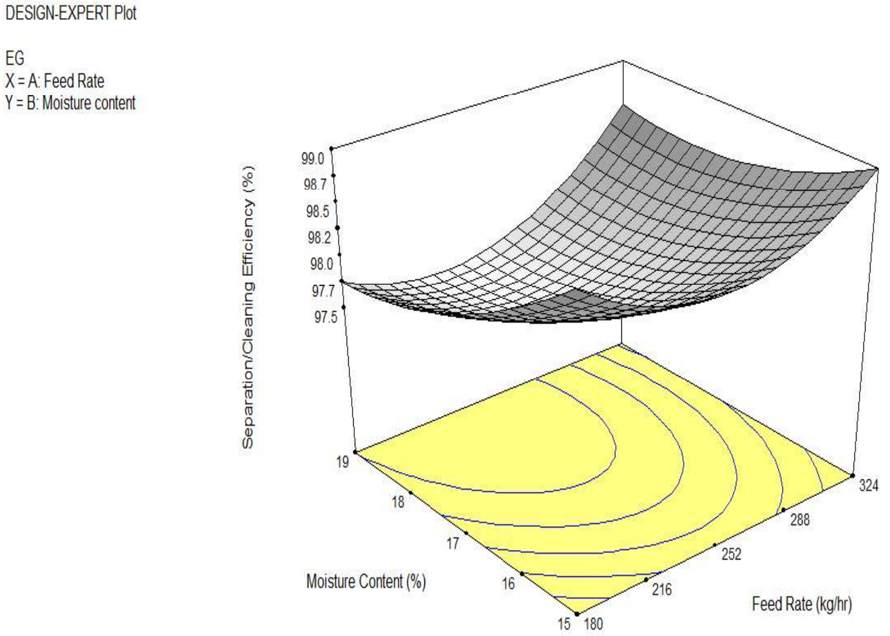


Figure 5. The response surface plot of the separation/cleaning efficiency of whole grains as affected by the moisture content and feed rate

3.2 Effect of Feed Rate and Moisture Content on Total Efficiency

The highest average ET of the grain cleaner machine was 85.5% with operating conditions of 15% MC and 180 kg/hr FR (Table 2). Similar results for ET were reported by Okunola *et al*. (2015) and Tabatabaeefar *et al*. (2003) with values between 69% to 84%, and 84% using paddy rice and chickpea for the evaluation of their grain cleaning machines. The response surface analysis (Fig. 6) showed that a lower maize MC leads to a higher total efficiency, while a lower FR leads to a lower total efficiency. However, a higher MC and FR of uncleaned maize can result to clogging of the sieve thereby prevent the kernels, smaller fines, and chaffs from falling through the sieve as a result of blockage of the sieve holes. Aderinlewo *et al*. (2016) reported that air speed and screen speed were also contributing factors to the total efficiency of a grain cleaning machine. ANOVA results showed that the effects of MC and FR were not significant ($p > 0.05$) on the ET of the machine (Table 4).

Table 4. ANOVA of the quadratic regression model for the effect of feed rate and moisture content on the total efficiency

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	21.17	5	4.23	0.20	0.9403	Not significant
A[a]	2.87	1	2.87	0.14	0.7346	
B[b]	14.98	1	14.98	0.72	0.4581	
A^2	1.84	1	1.84	0.088	0.7857	
B^2	0.11	1	0.11	0.005	0.9465	
AB	1.01	1	1.01	0.049	0.8396	
Residual	62.29	3	20.76			
Cor Total	83.46	8				

[a]A is the feeding rate (kg/hr)

[b]B is the moisture content of the grains (%). Significant level at $p < 0.05$.

The model that gave the best fit was a quadratic relationship (Eq. 28). The R^2 value was found to be 0.254, indicating that there is a weak relationship between the FR, MC and ET considered.

$$ET = 0.79A^2 + 0.19B^2 + 0.50AB + 0.60A - 1.37B + 73.30 \tag{28}$$

where,

A is the feeding rate (kg/s), B is the moisture content of the grains (%), and ET is the total efficiency (%).

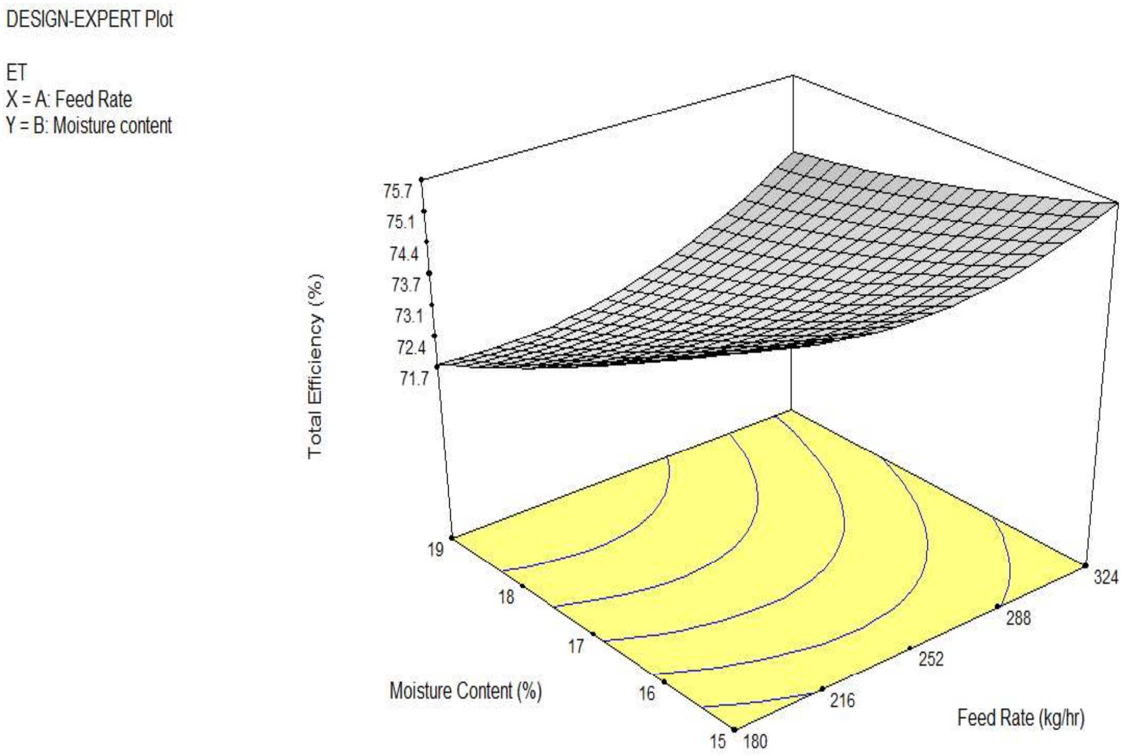


Figure 6. The response surface plot of the total efficiency as affected by the moisture content and feed rate

3.3 Effect of Feed Rate and Moisture Content on the Product Purity of Whole Maize Grains in Product

The lowest mean PP of whole maize grains collected was 96.5% at operating conditions of 19% MC and 320 kg/hr FR (Table 2). These operating conditions can serve as a baseline for determining the PP when evaluating the performance of a grain cleaning machine. Similar results were reported by Aderinlewo *et al*. (2016) for cowpea with PP ranges of 91.3% to 96.2%, and Okunola *et al*. (2015) for paddy rice with PP ranges of 93.0% to 98.0% for the performance evaluation of their grain cleaning machines. ANOVA result showed that the effects of MC and FR were not significant ($p > 0.05$) on the PP of the maize grains (Table 5).

Table 5. ANOVA of the quadratic regression model for the effect of feed rate and moisture content on the product purity of whole grains

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	
Model	0.24	3	0.081	1.39	0.3473	Not significant
A[a]	0.052	1	0.052	0.90	0.3864	
B[b]	0.013	1	0.013	0.22	0.6611	
AB	0.18	1	0.18	3.06	0.1406	
Residual	0.29	5	0.058			
Cor Total	0.54	8				

[a]A is the feeding rate (kg/hr)

[b]B is the moisture content (%). Significant level at $p < 0.05$.

The model that gave the best fit was a 2FI (2-factor interaction) relationship shown in Equation 29. A 2FI implies that the relationship between the dependent variable and the predictors involves interactions between two specific factors or independent variables. This interaction term allows for the possibility that the effect of one variable on the dependent variable is not constant across different levels of the other variable. The response surface analysis (Fig. 7) showed that a lower maize MC leads to a higher product purity, while a higher FR leads to a higher product purity. The R^2 was found to be 0.4552, indicating that there is a weak relationship between MC, FR and product purity.

$$PP = 0.081A + 0.040B + 0.21AB + 97.88 \tag{29}$$

where,

A is the feeding rate (kg/hr), B is the moisture content of the grains (%), and PP is the total efficiency (%).

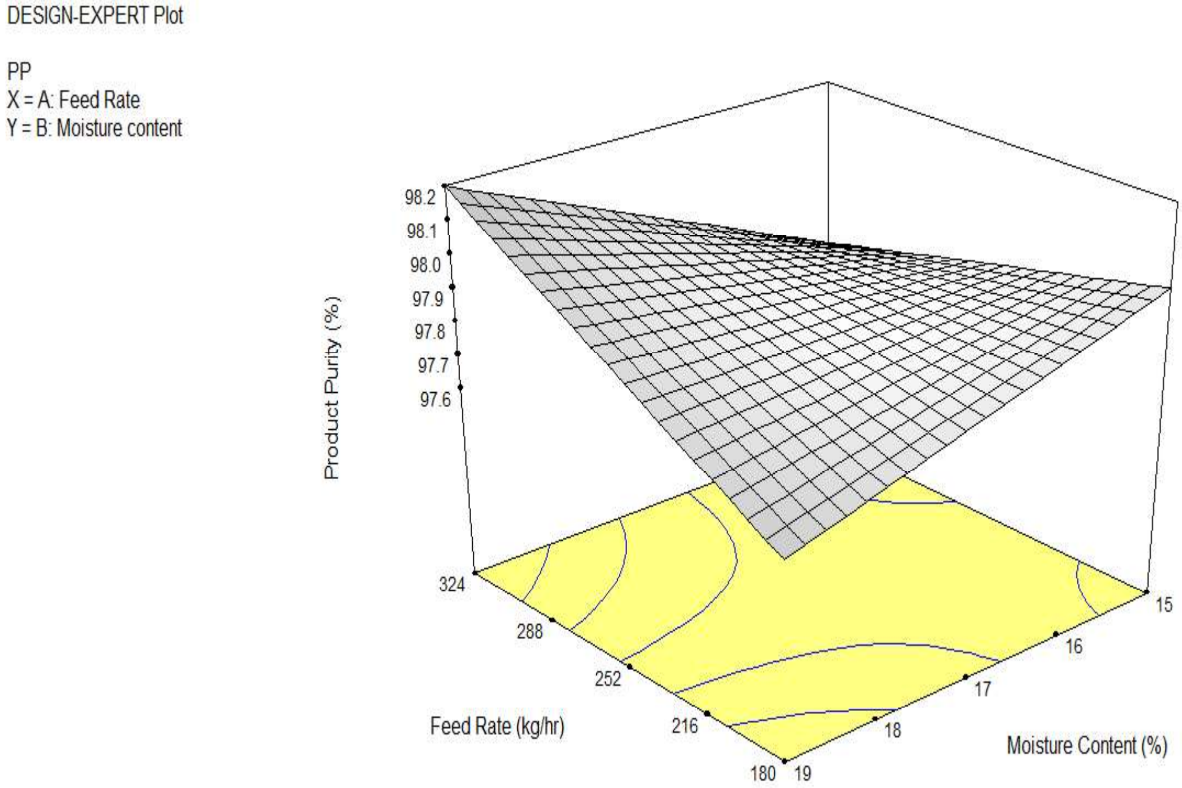


Figure 7. The response surface plot of the product purity as affected by the moisture content and feed rate

4. CONCLUSION

In this study, the grain cleaning machine had the best separation/cleaning efficiencies of 98.9% and 99.3% for uncleaned maize with MC of 15% and 17% (wet basis) at 180 kg/hr FR. The optimum operating parameters were 180 kg/hr FR and 15% MC for a total efficiency of 85.5%. Low FR and MC level of uncleaned grains should be considered during grain cleaning process. The prediction of the cleaning efficiency as affected by the feed rate and moisture content can be determined from the regression model developed. Proper storage of cleaned grains would ensure the mitigation of low-quality grains, reduce susceptibility to insect infestations, and improve the shelf-life. The cost of the grain cleaner was $610 US. Commercial production of this grain cleaner is viable to grain merchants, grain processing industries, and farmers' cooperative society in the country. It was recommended that the use of dampers and other composite materials could be incorporated into the machine to reduce vibrations and noise levels.

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