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Design Improvement and Performance Evaluation of an Air-Screen Rice Cleaning and De-Stoning Machine

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Abstract

This work designed, developed, and evaluated a modified rice cleaning and de-stoning machine based on differential densities and sizes. Unlike traditional horizontal sieves used in most de-stoners, this design adopted the Pedal Operated Seed Cleaner (PoS-Cleaner), which uses rotary sieves with enhancements like a vacuum blower, fractionating unit, and rotary screen with three apertures. Testing focused on Impurity Level (IML), Rice Separation Efficiency (RSE), Stone Separation Efficiency (SSE), Tray Losses (TL), and Chaff Separation Efficiency (CSE). Powered by a 3.5hp motor at 940rpm, it was tested with rice-to-impurity ratios of 25:3, 20:3, and 15:3, and feed gate openings of 5mm, 10mm, and 15mm. Results showed RSE, SSE, and CSE decrease with larger feed gate openings and less rice mass, while IML and TL increase. While the PoS-Cleaner achieved high cleaning efficiencies for maize (95.09%), beans (87.61%), and groundnuts (81.67%), the modified rice cleaner achieved an RSE of 88.35%, SSE of 79.67%, and CSE of 89.55% at a 25:3 ratio and 5mm opening. Future improvements could include variable speed devices for blowers and sieves.

Keywords: Rice cleaning and de-stoning machine, Rotary sieve, Blowers, Fractionating unit, Efficiency, Feed gate opening, Rice-to-impurity ratio.

1 | Introduction

Rice (Oryza spp) is a tropical cereal and the world's single most important staple food which serves as a primary cereal grain for more than a third of the world's population [1]. FAO [2] gave statistics that show that rice is a staple food of well over ninety percent (90%) of the Asian population and postulated that by the year 2025, the world will need about 760 million tonnes of paddy. This was corroborated by [3] that rice has become the second most important grain food in the world after wheat in terms of production due to a decline in maize production. This shows that rice is of great economic importance. Also, it is highly nutritious

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with high-calorie constituents, thus providing more than one-fifth of the calories consumed worldwide by humans [4].

In Nigeria, there has been a significant increase in the local production of rice, owing mainly to the government's policy, which impedes the importation of major agricultural commodities such as rice [5]. For example, rice was cultivated on 221,450 ha with a harvest of about 7.2 million metric tons in the 2020/21 planting season [6].

Despite the increase in local rice production in Nigeria, the local rice still contains MOG [3]. This is because local farmers still use manual cleaning methods, mainly winnowing. Although, cleaning operations could be improved with the use of cleaners and de-stoners. However, there is a high cost of ownership and maintenance of imported mechanized cleaning and de-stoning machines, and the local ones are less efficient.

The locally manufactured rice cleaners and de-stoners mainly use horizontal screens and pressure blowers. The horizontal screens are characterized by higher vibration, higher maintenance requirements, and more clogging compared to rotary screens. Also, the use of pressure blowers causes littering of the workspace. To solve these problems and also increase the efficiency of the local machine, there is a need to design and fabricate a rice cleaner and de-stoner that uses rotary screens, a vacuum blower and a pressure blower.

This work aims to design, improve, and test the performance of a rice cleaning and de-stoning machine that separates rice grains from other impurities based on differential densities and sizes. This paper also presents the results of the testing and performance evaluation of the machine.

2 | Materials and Method

2.1 | Materials

The materials used for the fabrication and testing of the rice cleaning and de-stoning machine are 3.5hp electric motor (power source) with 940rpm, 2mm, and 0.8mm thick mild steel plate, slotted perforated sieves, aluminum composite board, 30mm diameter shaft, 75mm, and 450mm diameter pulleys, three 30mm diameter self-aligning ball bearings, 50mm x 50mm x 5mm angle iron, M12 bolts, and nuts, and milled rice grains.

2.2 | Method

2.2.1 | Experimental site description

This work was carried out at the Innovative, Creativity and Entrepreneurship Technological Hub, opposite Command Engineering Depot, Rigachikun, Kaduna, Nigeria.

2.2.2 | Design considerations

I. The materials used in this research work were sourced locally. This is to reduce the production and maintenance costs of the machine.

II. The properties of the milled rice samples that were taken into cognizance are length, width, and shape, which were considered in choosing the sieves with the required specifications.

III. Clogging or jamming of the device caused by excessive fluxes of materials was reduced by using a uniform, manually operated feeding mechanism.

IV. The machine was designed such that one operator can efficiently operate it.

V. The machine-based factors such as sieve configuration, sieve oscillation, airspeed, and sieve tilt angle were put into consideration.

2.2.3 | Description and working principle of the machine

The air-screen rice cleaning and de-stoning machine under consideration is an improvement of the POS-Cleaner designed by Wilber et al. [7], as shown in Plate 1. Its major components are the hopper, blower, a bicycle-like driving and driven mechanism, frame, pulleys, V-belts, screens and outlets.

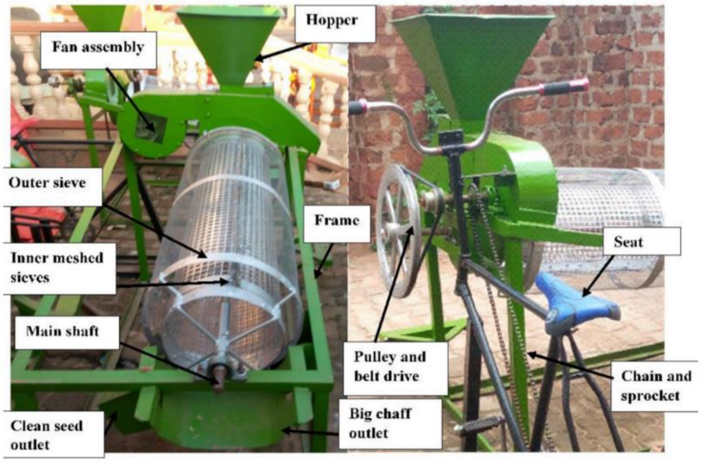

Fig. 1. Assembly of the POS-cleaner [7].

Likewise, the machine under consideration (*Fig. 2*) has almost similar parts but with the introduction of an electric motor, a pressure blower, a vacuum blower, a fractionating unit, and a dust collector (cyclone) without the bicycle-like driving and driven mechanism. The hopper is located at the top of the machine just above the cleaning unit, which comprises two blowers, a hose (a suction hose), a fractionating unit, and a dust collector. The pressure blower generates positive pressure, thereby blowing the MOG lighter than the rice grains, while the vacuum blower sucks the dust/light-weight chaff while heavier rice grains and stones flow to the sieving unit. As the vacuum blower sucks in the light MOG, it passes through the hose and discharges it to the dust collector. This hopper is slightly offset from the de-stoning unit (mainly the screens/sieves); thus, material fed in is carried into the screens under gravity. Controlling the feed rate and allowing uniform distribution of rice grains and the MOG into the cleaning and de-stoning unit. The machine also encompasses three rotary screens, which are made of slotted perforated sieves of various hole sizes and folded into drums of specified diameter. The screens are of equal diameter and are welded to each other horizontally and to a shaft via bracings. The size of the opening of the sieves is determined and chosen such that the fine materials (less than the size of rice) are silted in the first screen, rice grains are silted in the second screen, and the materials bigger than the rice grains (such as bigger chaff and bigger stones) are silted in the third sieve. There are chutes and receptacles for the collection of cleaned products and the MOG. An electric motor was used as the source of power. Also, the drive and driven assembly consists of a shaft, a v-belt, and two pulleys. The supporting frame of the cleaning and de-stoning machine was made from 50mm x 50mm x 5mm angle iron.

Fig. 2. The side view and front view of the machine.

2.2.4 | Description and design calculation of components

The analysis of the design parameters of the various machine parts was carried out in accordance with previous works done by researchers on various similar machines in conjunction with the application of practices, theories, and principles of machine design.

Feed hopper

The hopper is the component through which grain-MOG mixtures are fed into the machine for cleaning and de-stoning. It has four inwardly slanting sides made of a 2mm mild steel plate. Its capacity is based on the volume of a truncated rectangular pyramid. This was calculated as follows:

$$\text{The volume of the truncated rectangular pyramid} = V = \frac{(Ab + aB + 2(ab + AB)).h}{6}, \quad (1)$$

where, A = length of the upper base = 400mm; B = width of the upper base = 296mm;

a = length of the lower section = 175mm; b = width of the lower section = 184mm;

h = height of the truncated rectangular pyramid ends taking along the base centers = 203mm

Substituting each value into *Eq. (1)*, V = 0.0179883m3

Hence, the capacity of the hopper is 0.0179883m3.

Fractionating unit

The grain-admixture is cleaned (winnowed) based on the differential density of the mixture particles. It comprises housing, the pressure blower outlet, and the air/chaff outlet (vacuum blower inlet). The fractionating unit is designed such that the regulated rice admixture falls so that materials lighter than rice are sucked away through the vacuum blower inlet and then ejected via the dust collector. It serves as a link between the hopper and the rotary sieves.

Sieves

The de-stoning unit separates rice from debris based on size differences. A trommel screen with three rotating sieves is employed for this purpose. Rotary screens are preferred due to their simplicity, compactness, and low vibration. Each sieve is cylindrical and welded in series, with progressively larger openings. They're made of slotted perforated stainless and galvanized steel plates, rotating along their axis. Key sieve parameters for efficiency include length, diameter, slot width, and length. Their apertures are 20mm by 1.5mm, 20mm by 3mm, and 20mm by 6mm, with a diameter of 400mm.

Cleaning unit

The cleaning unit consists of a pressure blower, a vacuum blower, a dust collector, and a hose. The orientation of the pressure blower blade is arranged such that the light materials are dispersed directly towards the vacuum blower. The pressure blower is responsible for supplying the air mass needed for the initial sifting of the grain-admixture. The vacuum blower sucks away the lightweight materials (chaff and dust) in the fractionating unit, while the heavier materials (rice grain and stones) are allowed to drop through to the de-stoning unit. The sucked light-weight materials are passed through the hose and ejected to the dust collector, made of 0.8mm thick mild steel plate.

Pulley and belt

The machine required two pulleys: one pulley mounted on the shaft of the electric motor as the main drive and the other on the de-stoning unit shaft. The electric motor pulley has a diameter of 75mm which revolves at 940rpm. In order to avoid slumping, cataracts,s and centrifuging, a speed of about 1:6 was chosen for the shaft. Hence, the main shaft pulley diameter of 450mm was chosen. The speed of the shaft could be derived using *Eq. (2)* below.

$$N_m D_m = \eta\ N_s D_s. \tag{2}$$

Nm = Speed of the electric motor = 940rpm; Dm = Diameter of the electric motor pulley = 75mm;

η = efficiency of transmission of the v-belt drive = 95% = 0.95;

Ns = Speed of the shaft; Ds = Diameter of the driven pulley = 450mm.

From *Eq. (2)*, N_s = 165rpm.

The velocity of the belt drive, v, was calculated using *Eq. (3)* [8].

$$v = \pi \frac{D_s N_s}{60}. \tag{3}$$

The center-to-center distance, C, was determined using the *Eq. (4)* [8].

$$Dm < C < 3(Dm+Ds). \tag{4}$$

Assuming, C = 700mm.

Since the value of C is small, meaning the pulleys are very close to each other, a V-belt is chosen for the machine [8].

The length of the open belt used, L, was calculated using *Eq. (5)* below, as given by [8].

$$L = \frac{\pi}{2}(Dm + Ds) + 2C + \frac{(Dm\ -\ Ds)^2}{4C}. \tag{5}$$

L = 3726mm.

Also, the calculated V-belt length is 3726mm and is to be used on a 2.6kW (3.5hp) electric motor, which is within the B-type power range of 2 to 15kW, hence a B 2202-IS: 2494 V-belt was selected [8].

Shaft

A shaft is a rotating element that is used to transmit power from one place to another [8]. The shaft, which is made of mild steel, was designed based on strength and rigidity. In its design, torque and shaft diameter were the main factors considered.

According to [8], the Torque (T) of a shaft could be determined using *Eq. (6)* below.

$$P = Tw = T\frac{2\pi N_s}{60}, \tag{6}$$

where, P = Power transmitted = 3.5hp = 2.6kW.

T = 150.45Nm.

The minimum diameter of the sieve shaft was determined using *Eq. (7)*, as stated by [8].

$$T = \frac{\pi}{16}\tau_{max} d^3, \tag{7}$$

where = maximum allowable shear stress; d = diameter of the sieve shaft (mm).

180N/mm2 is the yield stress (τ_y) for mild steel rods and considering a factor of safety of 2 [8],

$$\tau_{max} = \frac{\tau_y}{2} = 90N/mm^2. \tag{8}$$

Hence, the minimum diameter of the sieve shaft is 20.41mm.

Electric motor

The electric motor supplied the required energy needed to drive the rotating shaft. Its capacity is 3.5hp and revolves at 940rpm.

Outlets

The machine consists of four outlets or chutes which are the air duct or chaff-dust outlet, the oversized chute, the clean grain chute, and the undersized outlet.

Machine Supporting Frame

This is made of 50mm by 50mm angle iron, which was welded together. It carries all other components of the machine and has a total length, breadth, and height of 1743mm, 600mm, and 880mm, respectively. The detailed dimensions are shown in the appendix. The four legs of the machine frame, which form its stand, have a roller each at its base for easy movement.

2.2.5 | Performance evaluation of the machine

The rice cleaning and de-stoning machine was designed to separate rice grains from other impurities (mainly chaff and stone). Nine different samples of rice-admixture were prepared (see *Tables 1-3*). The machine was switched on and allowed to run at no load to ascertain the smoothness of the rotating parts. Each sample of each grain-admixture ratio was fed into the hopper at 5mm, 10m, and 15mm feed gate openings, respectively-making a total of 9 runs. As the grain-admixture is fed through the hopper, it flows through the fractionating unit under gravity, and light materials such as chaff are dispersed by the pressure blower and sucked away by the vacuum blower; the remains continue to flow to the de-stoning unit/screen. As the electric motor rotates the screen, the materials whose size is less than that of rice are removed first; then the rice is removed at the second sieve and the materials whose size is greater than the rice are removed at the last sieve. The time for each sample to be cleaned and de-stoned was taken using a stopwatch. This is to ascertain the machine's capacity. Also, the cleaned rice, separated chaffs and separated stones were collected at each outlet and weighed using a digital weighing balance and recorded.

The performance indices used in the evaluation of the cleaning and de-stoning machine are similar to those [9]: Impurity Level after separation (IML), Tray Loss (TL), Rice Separation Efficiency (RSE), and Stone Separation Efficiency (RSE). Another index is the Chaff Separation Efficiency (CSE). These are determined as stated below:

I. Impurity Level after Separation (IML): this is the ratio of the mass of impurity in cleaned rice to the total mass of the mixture after separation expressed in percentage.

$$\text{IML} = \frac{\text{M}_{\text{gp}} - \text{M}_{\text{crgp}}}{\text{M}_{\text{gp}}}. \quad \textbf{(9)}$$

II. Tray Loss (TL): This is the percentage of rice that was not recovered in the cleaning and de-stoning process. It is also called cleaning loss.

$$\text{TL} = 1 - \frac{\text{Mcrgp}}{\text{M}_{\text{rm}}}. \quad \textbf{(10)}$$

III. Rice Separation Efficiency (RSE): this is the ratio of the mass of clean rice to the mass of rice in the mixture before separation expressed as a percentage.

$$\text{RSE} = \frac{\text{Mcrgp}}{\text{M}_{\text{rm}}} \text{ X } 100\%. \quad \textbf{(11)}$$

IV. Stone Separation Efficiency (SSE): this is the percentage of the quantity of stone removed during separation to the mass of stone in the mixture before separation.

$$\mathrm{SSE} = 1 - \frac{M_{sgp}}{M_{sm}} \times 100\%. \tag{12}$$

V. Chaff Separation Efficiency (CSE): this is the percentage of the quantity of chaff removed during separation to the mass of chaff in the mixture before separation.

$$\mathrm{CSE} = 1 - \frac{M_{cgp}}{M_{cm}} \times 100\%, \tag{13}$$

where,

M_{rm} = Mass of rice in the mixture (g), M_{sm} = Mass of stone in the mixture (g),

M_{cm} = Mass of chaff in the mixture (g), M_m = Mass of total mixture (g) = Mrm + Msm + Mcm,

M_{cs} = Mass of chaff after separation (g), M_{rp} = Mass of rejected product (g),

M_{gp} = Mass of good product (g), $M_{crgp.}$ = Mass of clean rice in good product (g),

M_{crgp} = Mass of stone in good product (g), M_{crgp} = Mass of chaff in good product (g).

3 | Results and Discussion

The results of the test carried out to evaluate the performance of the developed machine are given in *Tables 1-6*.

Table 1. Performance of the rice cleaning and destoning machine using 25:3 rice grains to MOG mixture.

Feed Gate (mm)	M_{gp} (g)	M_{crgp} (g)	M_{sgp} (g)	M_{cgp} (g)	M_{cs} (g)	M_{rp} (g)	Losses (g)	T_t (s)	IML (%)	TL (%)	RSE (%)	SSE (%)	CSE (%)
5	2290	2263	16	11	144	85	281	82	1.18	9.48	90.52	84.00	96.33
10	2262	2205	21	35	138	102	299	63	2.58	11.80	88.20	79.00	88.33
15	2230	2158	24	48	124	116	328	52	3.32	13.68	86.32	76.00	84.00
Average									2.36	11.65	88.35	79.67	89.55

M_{rm} = 2500g, M_{cm} = 200g, M_{sm} = 100g, M_m = 2800g.

Table 2. Performance of the rice cleaning and destoning machine using 20:3 Rice Grains to MOG mixture.

Feed Gate (mm)	M_{gp} (g)	M_{crgp} (g)	M_{sgp} (g)	M_{cgp} (g)	M_{cs} (g)	M_{rp} (g)	Losses (g)	T_t (s)	IML (%)	TL (%)	RSE (%)	SSE (%)	CSE (%)
5	1874	1803	19	52	136	71	211	76	4.20	9.85	90.15	81.00	82.67
10	1851	1745	38	68	121	99	229	54	4.44	12.75	87.25	72.00	77.33
15	1781	1672	26	83	117	142	261	41	6.90	16.40	83.60	74.00	72.33
Average									5.18	13.00	87.00	75.67	77.44

M_{rm} = 2000g, M_{cm} = 200g, M_{sm} = 100g, M_m = 2300g.

Table 3. Performance of the rice cleaning and destoning machine using 5:1 rice grains to MOG mixture

Feed Gate (mm)	M_{gp} (g)	M_{crgp} (g)	M_{sgp} (g)	M_{cgp} (g)	M_{cs} (g)	M_{rp} (g)	Losses (g)	T_t (s)	IML (%)	TL (%)	RSE (%)	SSE (%)	CSE (%)
5	1404	1304	27	73	114	69	221	63	6.59	13.67	86.93	73.00	75.67
10	1389	1277	33	79	105	88	230	48	7.26	14.87	85.13	67.00	73.67
15	1342	1218	39	85	93	89	291	36	8.08	18.80	81.20	61.00	71.67
Average									7.31	15.78	84.42	67.00	73.67

Mrm = 1500g, Mcm = 200g, Msm = 100g, Mm = 1800g.

Table 4. Values of performance indices of each rice-MOG mixture at 5mm feed gate opening.

Feed Gate Opening = 5mm					
Rice-MOG mixture ratio	**IML (%)**	**TL (%)**	**RSE (%)**	**SSE (%)**	**CSE (%)**
25 : 3	1.18	9.48	90.52	84.00	96.33
20 : 3	4.20	9.85	90.15	81.00	82.67
5 : 1	6.59	13.67	86.93	73.00	75.67
Average	3.99	11.00	89.20	79.33	84.89

Table 5. Values of performance indices of each rice-MOG mixture at 10mm feed gate opening.

Feed Gate Opening = 10mm					
Rice-MOG mixture ratio	**IML (%)**	**TL (%)**	**RSE (%)**	**SSE (%)**	**CSE (%)**
25 : 3	2.58	11.80	88.20	79.00	88.33
20 : 3	4.44	12.75	87.25	72.00	77.33
5 : 1	7.26	14.87	85.13	67.00	73.67
Average	4.76	14.47	86.86	72.67	79.78

Table 6. Values of performance indices of each rice-MOG mixture at 15mm feed gate opening.

Feed Gate Opening = 15mm					
Rice-MOG mixture ratio	**IML (%)**	**TL (%)**	**RSE (%)**	**SSE (%)**	**CSE (%)**
25 : 3	3.32	13.68	86.32	76.00	84.00
20 : 3	6.90	16.40	83.60	74.00	72.33
5 : 1	8.08	18.80	81.20	61.00	71.67
Average	6.10	16.29	83.71	70.33	76.00

While varying the rice grain-admixture ratio, the optimal rice separation, stone separation and CSE of 88.35%, 79.67% and 89.55%, respectively, occurred when the rice grain mass to MOG is high (25:3). Also, varying feed gate opening, the optimal values for performance indices occur at the least opening of 5mm with rice separation efficiency (89.20%), SSE (79.33%) and CSE (84.89%).

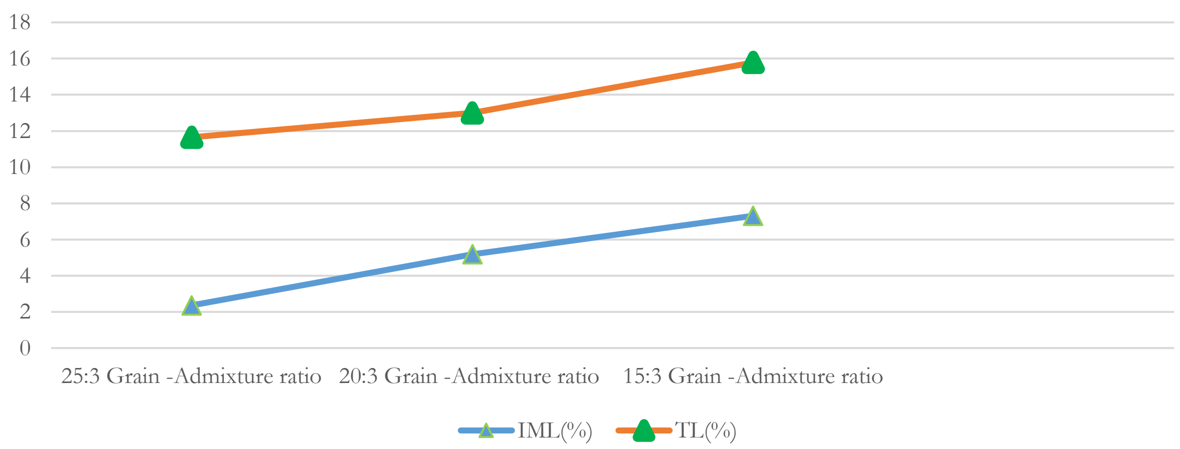

Fig. 1. Effects of varying grain-admixture ratio on IML and TL.

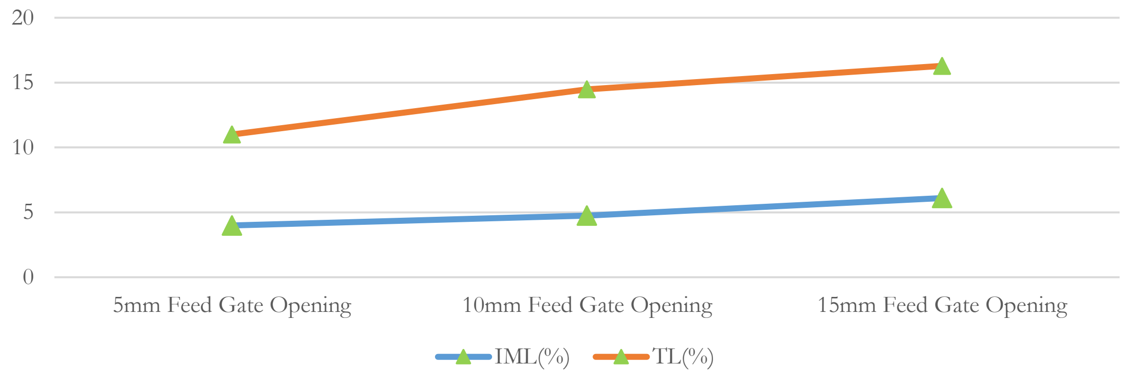

Fig. 2. Effects of varying feed gate opening on IML and TL.

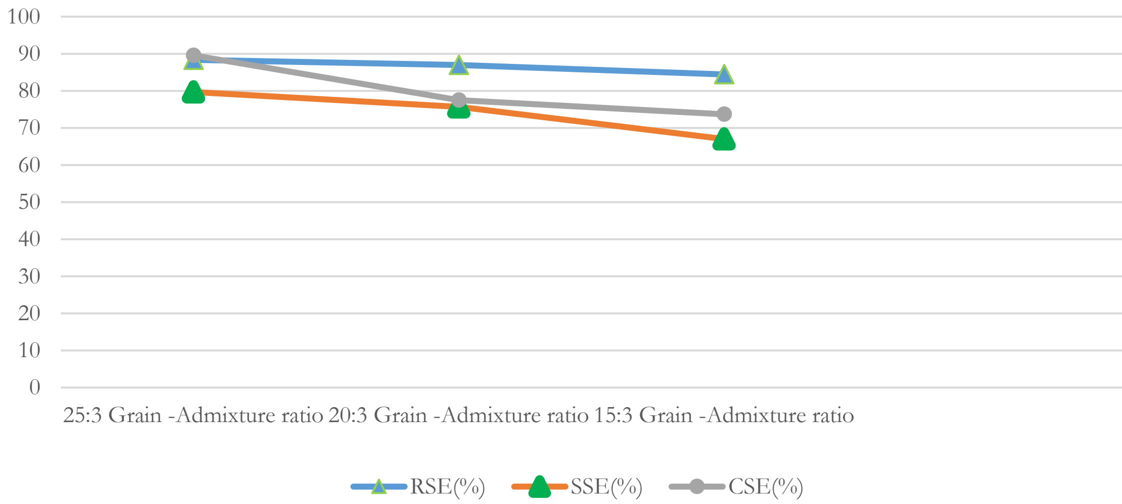

Fig. 3. Effects of varying grain-admixture ratio on RSE, SSE and CSE.

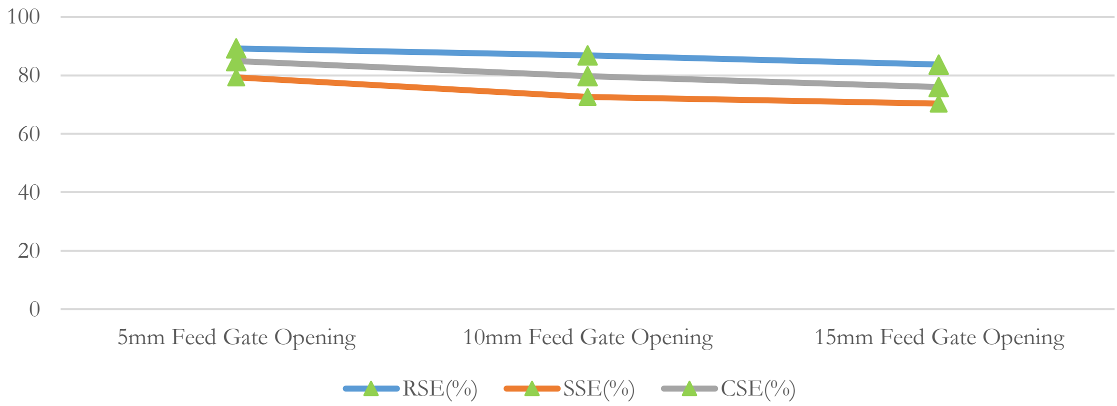

Fig. 4. Effects of varying feed gate opening on RSE, SSE and CSE.

3.1 | Result Validation

The rice cleaning and de-stoning machine and the PoS-Cleaner were validated as follows:

Efficiency comparison

The POS-Cleaner achieved optimal cleaning efficiencies of 95.09% for maize, 87.61% for beans, and 81.67% for groundnuts, respectively. In contrast, the rice cleaning and de-stoning machine exhibited commendable performance with RSE of 88.35%, SSE of 79.67%, and CSE of 89.55%. Despite slight disparities, the modified machine excelled, particularly in rice cleaning, which is more difficult to separate because of its smaller size and lighter weight.

Customization and adaptability

The POS-Cleaner utilized adjustable sieves to accommodate different seed sizes, enhancing its adaptability. Similarly, the modified air-screen machine incorporated rotary screens with three sieves of varying apertures to cater to different sizes and densities of impurities in rice. Both machines showcase a commitment to customization and adaptability, essential factors for addressing the diverse needs of farmers and varying grain conditions.

Performance optimization

The POS-cleaner optimized cleaning efficiencies by adjusting sieve sizes and pedaling speed. The modified air-screen machine, while not directly comparable in terms of operation, offers opportunities for future optimization through the introduction of variable speed devices to the blowers and rotary sieves. This indicates a forward-looking approach towards improving performance and efficiency in both designs.

Overall, the RSE, SSE, and CSE decrease as the feed gate opening increases and the mass of rice in the grain-admixture decreases. This means there are more MOG to be removed within a short period since the processing time also decreases with an increase in feed gate opening. As the feed rate is increased, the material flowing across the air current forms a thicker blanket, making it increasingly more difficult for the air current to penetrate and flush out the unwanted materials. A similar trend of decreasing cleaning efficiency with increasing feed rates was reported by [10] and [11]. Also, the IML and TL increase with the increase in feed gate opening and a decrease in the rice mass in the mixture.

4 | Conclusion

A rice cleaning and de-stoning machine was designed and fabricated, and its performance was evaluated. The test results show that the relationship between separation efficiencies and feed rate is inverse. The inverse relationship was indicated to be due to the increasing load on the sieve that restricted the free movement of grains and undesired materials. Also, a decrease in cleaning efficiencies with an increase in the feed gate opening may be attributed to the reduction in the resident time of flight of materials to be cleaned within the fractionating unit. Furthermore, the decrease in cleaning efficiency with decreasing rice grain-admixture ratio may be due to the less resident time of materials to be separated in the sieving unit. The machine is capable of cleaning and de-stoning rice.

The following recommendations are compiled for the developed machine as a result of observations made during its performance evaluation:

I. During testing, it was noticed that the particles in the grain-admixture were not fully dispersed. Hence, improvement could be made on the feed gate and fractionating unit designs. Also, possible variable speed blowers could be used to control the airflow.

II. To achieve optimal rotational velocity for the sieving unit and to avoid slumping, cataract,s and/or centrifuging effects as noticed during fabrication, a variable speed drive may be introduced to control the sieve oscillation of the machine.

III. The system could be tested using other related grains and possibly change its sieving unit where necessary.

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Data Availability

All data generated or analyzed during this research are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there are no competing interests related to the content or publication of this article.

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