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DESIGN AND ASSESSMENT OF A SMALL-SCALE MACHINE FOR CLEANING WHEAT GRAINS

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A small-scale wheat cleaning machine was designed to winnow and separate grains from materials-other-than-grains (MOG), such as premature grains and chaff, in order to enhance the quality of grains. It was evaluated technically with respect to assessment criteria: cleanliness, grain loss, chaff rejection, and cleaning efficiency. Experiments were carried out at three levels of sieve slopes (5, 10, and 15°), two sieve reciprocating speeds (0.48 and 0.95 m·s^{-1}), two levels of feed rates (1 and 1.5 kg·min^{-1}), and three air velocities (5, 6 and 7 m·s^{-1}). The results showed that, at sieve reciprocating speed of 0.95 m·s^{-1}, the maximum cleanliness value was – 96.25% – observed at 1.5 kg·min^{-1} feed rate, 5 m·s^{-1} air velocity and 5° sieve slope. The minimum cleanliness value – 76.82% – was observed at a feed rate of 1 kg·min^{-1}, 15° sieve slope, 7 m·s^{-1} air velocity, and 0.48 m·s^{-1} sieve reciprocating speed. The results showed that the use of either a very low, or a very high sieve slope angle and sieve reciprocating speed while using different air velocities and feed rates is not recommended.

Keywords: grains; separation; cleaning; feed rate; performance; loss

Wheat is the leading cereal grain produced, consumed, and traded in the world today (Bian et al., 2015). It provides nearly 55% of carbohydrates and 20% of the food calories. It contains 78.10% of carbohydrates, 14.70% of protein, 2.10% of fat, 2.10% of minerals (zinc, iron), and considerable proportions of vitamins (thiamine and vitamin B) (Kumar et al., 2011; Akatuhurira et al., 2021). Wheat is one of the oldest and most important grain crops relied upon by the Egyptian people in terms of their food. It represents almost 10% of the total value of agricultural production (Rai and El-Ghobashy, 2014). The planted area has expanded from an average of 559000 to 1.36 million hectares during 2010–2017. As a result, total production has quadrupled from 2.20 million tonnes during 1980–1989 to 8.75 million tonnes during 2010–2017 (Abdelaal and Thilmany, 2019). The average flow of wheat in Egypt from 2010 to 2013 was approx. 8.7 million tonnes of domestic production. Out of the 8.7 million tonnes, on-farm consumption accounts for 5.5 million tonnes, 1.7 million tonnes are used as feed wheat, 280000 tonnes are used for seed, and 3.6 million tonnes are milled and consumed by farmers. Wheat consumed on-farm is stored at the farm level and milled in small-scale village mills – the final product of this process is a very coarse 100% extraction flour for a fee (McGill et al., 2015). Wheat grains undergo certain post-harvest processes before milling; the most important of them is cleaning (Dudarev et al., 2020), which must be performed prior to milling for the separation of impurities from the wheat. Such impurities cause poor quality of flour output (Astanakulov et al., 2011; Bian et al., 2015). Exposure of grains and impurities to a current of air – the speed and momentum of air are determined by the properties of grains and impurities (Panasiewicz et al., 2012; Kuzminskyi et al., 2018) – allows separation of light impurities, which depends on weight, dimensions, state of its surface, and material (Zewdu, 2007; Choszcz et al., 2020). The most popular machines are separating machines with the oscillatory movement of flat separating sieves (Aipov et al., 2020). To clean an elongated grain, slotted top and bottom sieves are essential. Furthermore, this process may also require the elongated grain to pass through a round-hole top sieve or entirely different kind of sieve (Awgichew and Fanta, 2015).

The minimum power requirement of a developed cleaning unit of a combined harvester is 3.35 kW at 5.9 m·s^{-1} aerodynamic suction velocity, 5° sieve slope, 3 kg·min^{-1} feed rate, 245 rpm rotational speed, and the circular shape of suction tube. The maximum average value of cleanliness was 99.41% at an aerodynamic suction velocity of 14.9 m·s^{-1}, sieve slope of 15°, feed rate of 3 kg·min^{-1}, the rotational speed of 245 rpm, and with rectangular shape of the suction tube. In their experiments, Sehsah et al. (2018) observed the maximum average value of the grain loss of 4.04% at 14.9 m·s^{-1} aerodynamic suction velocity, 15° sieve slope, feed rate of 7 kg·min^{-1}, 350 rpm rotational speed, and rectangular shape of suction tube. On the other hand, wheat immersing and dipping in the canal's water is the most frequent cleaning method utilized in the Egyptian countryside for the purposes of separation of foreign bodies and impurities from wheat – farmers put the wheat in a sack and submerge it in the canal water for a certain time, then take it out and put the wet grains on a tarpaulin surface susceptible to air and sun to dry. However, this is very dangerous method, as

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it leaves the wheat grains susceptible to infections, germs, etc. It is employed due to the rareness of cleaning machines in the rural villages and high price points of such devices. Therefore, this research aims to design and evaluate a small-scale wheat cleaning machine suitable for rural villages for the purposes of performing the required operations with minimum loss at the lowest cost possible and ensuring the availability of materials locally in order to reduce the cost of production, maintenance and operation. It was achieved by:

1. designing and manufacturing of a wheat cleaning machine based on its physical and mechanical properties;
2. testing the designed machine under actual operational conditions to investigate its performance.

Material and methods

Design of wheat grain cleaner

Frame

It was made of steel L profile equal angle section of 30 × 4 mm and 20 × 2 mm. It was 81 cm high, 47 cm wide, and 93 cm long to support the feeding hopper, the sieve unit, the blower, and the power source.

Power source

A single-phase electric motor (0.25 kW) with a maximum rotating speed of 1480 rpm was installed on the frame of an adjustable motor base to easily align the pulleys with each other and set the proper belt tension. The pulleys were mounted on a 25 mm steel shaft, as shown in Fig.1. Furthermore, Table 1 shows the dimensions of the pulleys used in the assembly.

Table 1 Dimensions of pulleys in the driven assembly

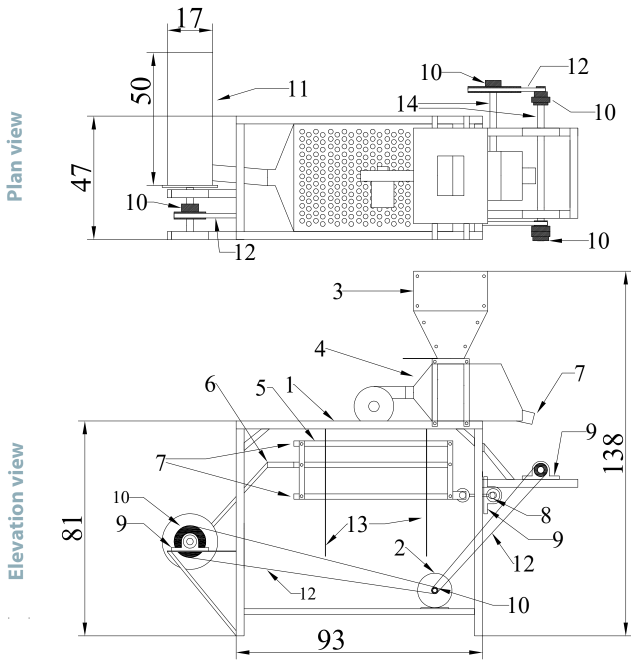
Component	Dimensions
Aluminium double grooves V Belt Pulley for motor	5 cm
Aluminium single groove V Belt Pulley (motor to the shaft)	5 cm
Aluminium double grooves V Belt Pulley (shaft to eccentric)	5 and 3.5 cm
Aluminium single groove V Belt Pulley for eccentric	20 cm
Aluminium single groove V Belt Pulley for polishing unit	11.7 cm

Hopper

It allows continuous feeding of grains while being controlled by an adjustable gate; the upper opening was 36 cm wide and 28 cm long. The bottom end was 15 cm wide and 10 cm long, with an overall height of 32 cm and a total capacity of 23.9 kg.

Blower and sieve unit

A 600 W blower with a speed controller (FIT model EB 6003) was used as the air source. The sieve unit consists of the upper and lower sieves and a steel plate, which was 40 cm



NO	Description	NO	Description	NO	Description
1	Frame	6	Grain outlet	11	Polishing unit
2	Motor	7	MOG outlet	12	V-Belt
3	Hopper	8	Eccentric arm	13	Rocker arm
4	Blower	9	UC 205 bearing housing	14	Shaft
5	Sieve unit	10	Pully		

Fig. 1 Schematic diagram for the prototype of a cleaning unit (all dimensions are in cm)

wide, 60 cm long and 22 cm high. The upper sieve was made of a steel plate of 0.12 cm thickness and with round holes with diameter of 6 mm to separate the larger MOG. The lower sieve had round holes with diameter of 3 mm to separate the smaller MOG. Additionally, there was installed a steel plate at the bottom for the purposes of collecting the smaller MOG and its disposal. The frame for supporting the sieve unit was made of a 20 × 2 mm L profile steel equal angle section with four oscillating (or rocking) arms made of sheet metal with 0.2 cm thickness, 2 cm width and 49 cm height. The distance between them was 38.2 cm and these were connected to both the frame and sieve unit by bolts.

Arrangement of sieves and slope adjustment

The bottom side of sieve unit was connected to a wrist pin eccentric on two bearings, which produced the reciprocating motion of the sieving unit. Three different sieve slopes (5°, 10°, and 15°) were tested; to adjust the inclination to the required slope, three holes were made on the front rocker arms, as shown in Fig. 2. These holes were made by taking the length between the arms as hypotenuse as follows:

$$\sin \theta = x/38.2 \quad (1)$$

Driving shafts

The machine has two shafts with pulleys to control the speed transferred from the motor to the eccentric. Figure 3 shows forces acting on those shafts, where: W_{AP} – weight of pulley at A; T_{AH} –total belt tension at A (T_i + T_j); R_{BH} –

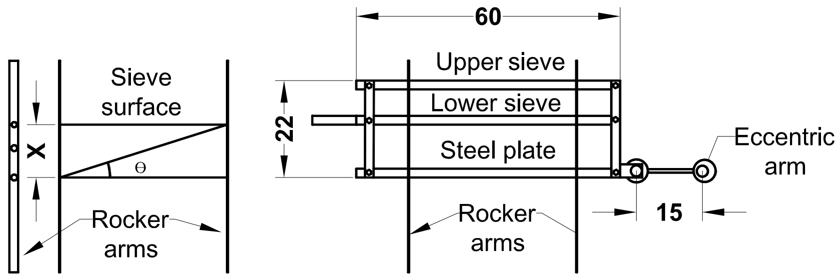


Fig. 2 Sieve arrangement and sieve slope adjustment mechanism (all dimensions are in cm

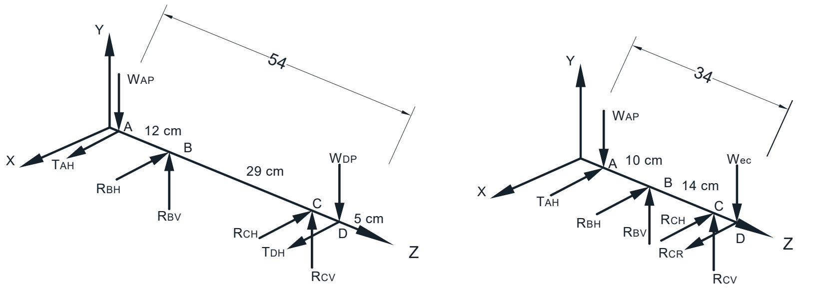


Fig. 3 Forces acting on driving shafts and their locations (all dimensions are in cm)

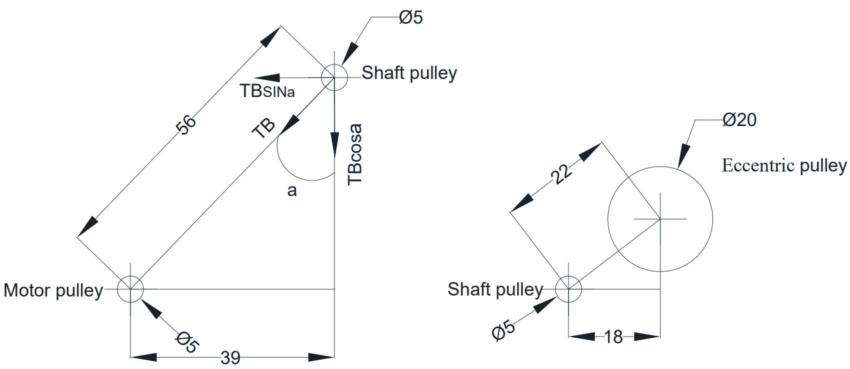


Fig. 4 Direction of belt pull in terms of the shaft and eccentric pulleys (all dimensions are in cm)

horizontal bearing reaction force at B; R_{BV} – vertical bearing reaction force at B; R_{CH} – horizontal bearing reaction force at C; R_{CV} – vertical bearing reaction force at C; WDP – weight of pulley at D; T_{DH} – total belt tension at D ($T_i + T_j$); W_{EC} – weight of eccentricity at D; R_{CR} – horizontal force due to connecting rod at D; T_i – tension on the tight side of a belt (N); T_j – tension on the slack side of a belt (N).

Tensions on the tight and slack belt sides can be determined utilizing dimensions shown in Fig. 4 as follows (Awgichew and Fanta, 2015):

$$T_j = T_{max} - T_c \quad (2)$$

$$\frac{T_i - T_c}{T_j - T_c} = e^{\mu\theta cosec\frac{\alpha}{2}}$$

or

$$2.3\log\left(\frac{T_i}{T_j}\right) = \mu\theta cosec\frac{\alpha}{2} \quad (3)$$

$$T_{max} = \sigma a \quad (4)$$

$$T_c = mv^2 \quad (5)$$

$$v = \frac{N_2 \pi D_2}{60000} \quad (6)$$

$$\theta = 180 - 2\left[\sin^{-1}\left(\frac{D_2 - D_1}{2C}\right)\right] \quad (7)$$

$$M_t = (T_i - T_j)\frac{D_2}{2} \quad (8)$$

where:
T_c and T_{max} – centrifugal and maximum tension of a belt, respectively (N); T_i – tension on a tight side of a belt (N); T_j – tension on a slack side of a belt (N); σ – maximum safe normal stress (2.1 $N \cdot mm^{-2}$); a – cross sectional area (81 mm^2); μ – coefficient of friction between belt and pulley (0.3); α – groove angle (40°); θ – wrap angle; m – mass per length unit of belt (0.108 $kg \cdot m^{-1}$); v – belt speed ($m \cdot s^{-1}$); D_1 and D_2 – diameters of driving and driven pulleys, respectively (mm); N_1 and N_2 – rpm of driving and driven pulleys; C – centre distance between two adjacent pulleys (mm); L – belt length (mm); M_t – torsional moments (N·mm). The values of σ, a, μ, α, and m are from standard tables (Awgichew and Fanta, 2015). Subsequently, based on Eqs 2 to 8, the values of v, T_i, T_j, T_c, T_{max}, θ, and M_t were calculated: 0.696 $m \cdot s^{-1}$, 170.03 N, 10.85 N, 0.075 N, 170.1 N, 3.14 rad, and 3979.5 N·mm, respectively

Measuring devices

An electric balance (AMIR/ US-KA6) with an accuracy of 0.01 g and ±0.3 g error range was used in calculating the initial and final weights of wheat and MOG in samples. A digital hot wire anemometer TECPEL (AVM-714) was used for measuring air velocity ($m \cdot s^{-1}$) and a digital photo/contact tachometer LUTRON DT-2236 was used for measuring the rotational speeds of the pulleys. Device specifications are shown in Table 2. A digital caliper (INSIZE 1112-150) was used for measuring dimensions with an accuracy of 0.01 mm and a range of 0.01–150 mm.

Samples

This research was carried out on season 2019. The wheat variety used was Gemmiza 11. Threshed components included grains, chaff, and dust at 12% moisture content. The samples used had 29.64% MOG in every kg, which was determined by using an electric balance. Table 3 presents the average values of physical, mechanical, and aerodynamic properties for Gemmiza 11 at ten replicates (Sehsah et al., 2018).

Experimental parameters

These included two feed rates (1 and 1.5 $kg \cdot min^{-1}$); three air velocities (5, 6, and 7 m·s^{-1}); two sieve reciprocating speeds (0.48 and 0.95 m·s^{-1}); three sieve slopes (5°, 10°, and 15°); making it a total of 36 sets – each set result was weighed several times to ensure accuracy.

Machine evaluation criteria

For the purposes of evaluating the cleaning unit performance, parameters such as cleanliness, grain loss, chaff rejection and cleaning efficiency (Afolabi et al., 2019) were taken into account (Hanna et al., 2010):

$$\eta_{imp} = \left[\frac{(IMP\ in)}{(IMP\ out)}\right] \times 100\% \quad (9)$$

where:
η_{imp} – overall cleaning efficiency (%); *IMP in* – total mass of impurities in test samples before separation (kg); *IMP out* – total mass of impurities removed from test samples (kg)

$$cleanliness = \left[\frac{a}{(a+b)}\right] \times 100\% \quad (10)$$

$$chaff\ rejection = \left[\frac{d}{(b+d)}\right] \times 100\% \quad (11)$$

where:
a – grain recovery in the product; *b* –straw and immature in the product; *c* – grain in the reject; *d* – straw and immature in the reject (Hanna et al., 2010)

$$grain\ loss = \left[\frac{a}{(a+b)}\right] \times 100\% \quad (12)$$

where:
a – grains in the reject; *b* – clean grains in the product (Sehsah et al., 2018)

Results and discussion

Cleanliness in the cleaning unit

The results indicate that the increase in both air velocity and slope angle negatively affected the cleanliness (%). The maximum cleanliness (96.25%) was achieved at 5 m·s^{-1} air velocity, 5° sieve slope, 1 kg·min^{-1} feed rate, 0.95 m·s^{-1} sieve reciprocating speed, and with 2.3% grain loss, as illustrated in Fig. 5.

The minimum cleanliness (76.82%) was observed at 7 m·s^{-1} air velocity, 15° sieve slope, 1 kg·min^{-1} feed rate, 0.48 m·s^{-1} sieve reciprocating speed, and with 4.85% grain loss, as shown in Fig. 6. Figures 5 and 6 suggest that, at different feed rates and sieve reciprocating speeds, the increase in sieve slope to 15° and air velocity to 7 m·s^{-1} resulted in cleanliness decrease by 19.43%.

Grain loss in the cleaning unit

As a result of grains changing the direction of movement during the transition from one sieve to another, a small amount of grains flew out from the sieving unit during the separation, which can be avoided by covering the sides of sieving unit as described by Dudarev et al. (2020). Moreover,

Table 2 TECPEL anemometer and LUTRON tachometer specification

Anemometer	Air velocity range	Air velocity resolution	Air velocity accuracy
Specification	0.2–20 m·s^{-1}	0.1 m·s^{-1}	±(5% + 1 d)
Tachometer	speed range (rpm)	resolution (rpm)	accuracy
Specification	photo: 5 to 100000 contact: 0.5 to 19999	0.1 : 1	±0.05%

Table 3 Physical and mechanical properties for wheat grains and chaff samples

Property	Grain	Chaff
Length (mm)	7.53 ±0.3	13.2 ±0.8
Width (mm)	3.23 ±0.42	1.8 ±0.2
Thickness (mm)	3.04 ±0.26	–
Sphericity (%)	55.64 ±1.03	–
Volume (mm^3)	38.71 ±0.12	–
Mass of thousand seed (g)	51.3 ±1.66	–
Bulk density (kg·m^{-3})	856 ±7.4	77.3 ±0.78
True density (kg·m^{-3})	1314.2 ±8.45	–
Surface area (mm^2)	55.43 ±0.53	–
Angle of repose, degree	25 ±1.4	42 ±0.7
Angle of static friction, degree	17.7 ±1.88	–
Coefficient of static friction	0.32	–
Terminal velocity (m·s^{-1})	8.5 ±0.23	2.8 ±0.13
Drag coefficient	0.65 ±0.03	–

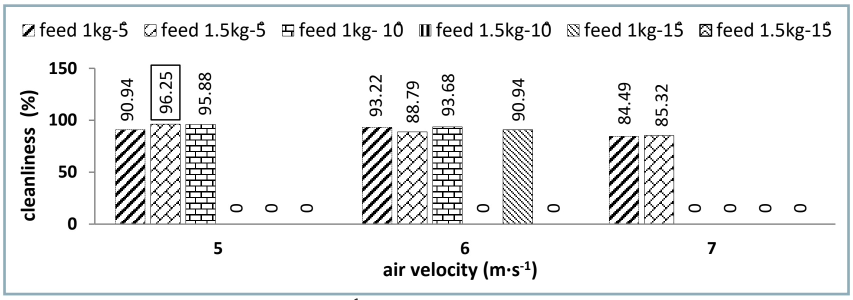


Fig. 5 Cleanliness (%) at 0.95 m·s^{-1} sieve reciprocating speed

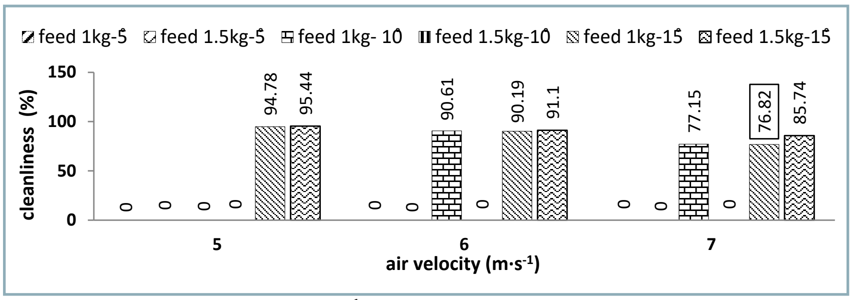


Fig. 6 Cleanliness (%) at 0.48 m·s^{-1} sieve reciprocating speed

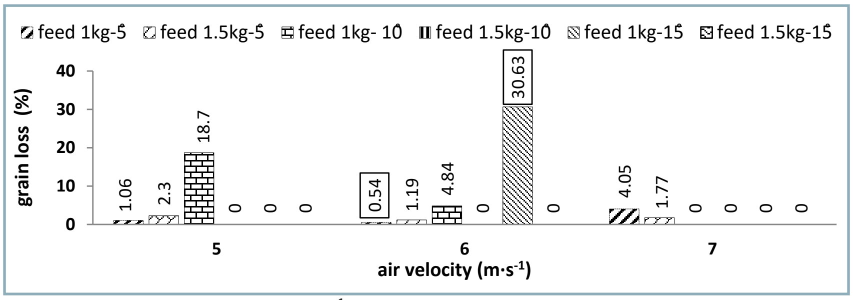


Fig. 7 Grain loss (%) at 0.95 m·s^{-1} sieve reciprocating speed

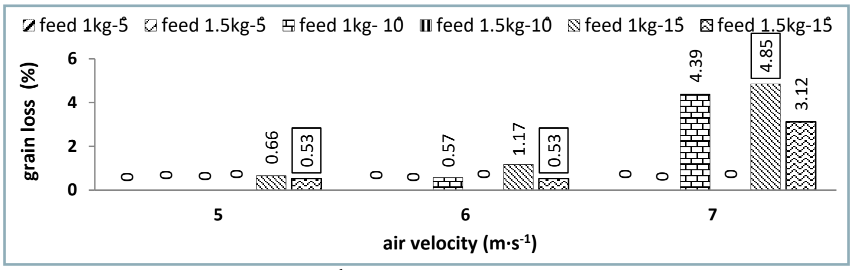


Fig. 8 Grain loss (%) at 0.48 m·s^{-1} sieve reciprocating speed

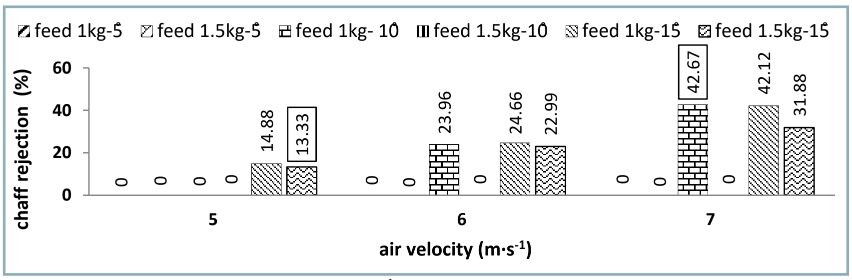


Fig. 9 Chaff rejection (%) at 0.48 m·s^{-1} sieve reciprocating speed

an increase in both sieve slope angle and sieve reciprocating speed tends to increase the value of grain loss.

As illustrated in Fig. 7, for 0.95 m·s^{-1} sieve reciprocating speed, the minimum value of grain loss (0.54%) was observed at 6 m·s^{-1} air velocity, 5° sieve slope, and 1 kg·min^{-1} feed rate, while the maximum value (30.63%) was achieved at 6 m·s^{-1} air velocity, 15° sieve slope, and 1 kg·min^{-1} feed rate.

For 0.48 m·s^{-1} sieve reciprocating speed, the maximum grain loss (4.85%) was obtained at 7 m·s^{-1} air velocity, 15° sieve slope, 1 kg·min^{-1} feed rate, while the minimum value (0.53%) was obtained at 5 and 6 m·s^{-1} air velocity, 15° sieve slope, and 1.5 kg·min^{-1} feed rate.

Chaff rejection in the cleaning unit

Increasing the air velocity while using a low feed rate, screen slope, and sieve reciprocating speed tends to increase the ratio of chaff rejection as illustrated in Figs 9 and 10; this is due to the increase in the proportion of the chaff rejection in the blower unit and the increase in time that the gains and remaining MOG are in the sieving unit before exiting it. As shown in Fig. 9, the maximum chaff rejection value (42.67%) was observed at 7 m·s^{-1} air velocity, 10° sieve slope, 1 kg·min^{-1} feed rate, and 0.48 m·s^{-1} sieve reciprocating speed, while the minimum chaff rejection (13.33%) was achieved at 5 m·s^{-1} air velocity, 15° sieve slope, and 1 kg·min^{-1} feed rate at the same sieve reciprocating speed.

Based on Fig. 10, the maximum chaff rejection at 0.95 m·s^{-1} (33.56%) sieve reciprocating speed was obtained at 7 m·s^{-1} air velocity, 5° sieve slope, and 1 kg·min^{-1} feed rate, while the minimum value (10.21%) at 5 m·s^{-1} air velocity, 10° sieve slope, 1 kg·min^{-1} feed rate.

Cleaning efficiency of cleaning unit

Regardless of the screen slope angle used, increasing the air velocity while using a low feed rate and sieve reciprocating speed tends to increase the cleaning efficiency (%), as shown in Figs 11 and 12. For 0.48 m·s^{-1} sieve reciprocating speed, the maximum cleaning efficiency (75.23%) was

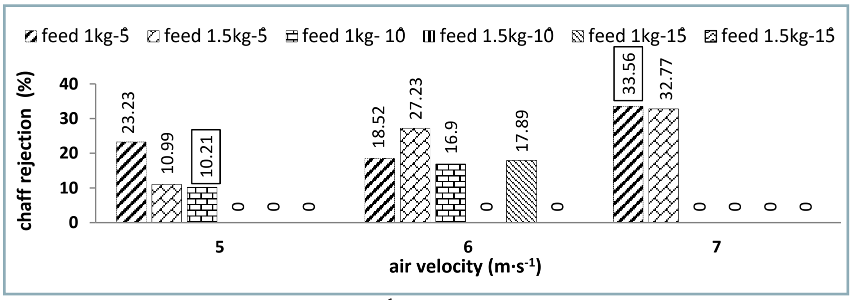


Fig. 10 Chaff rejection (%) at 0.95 m·s^{-1} sieve reciprocating speed

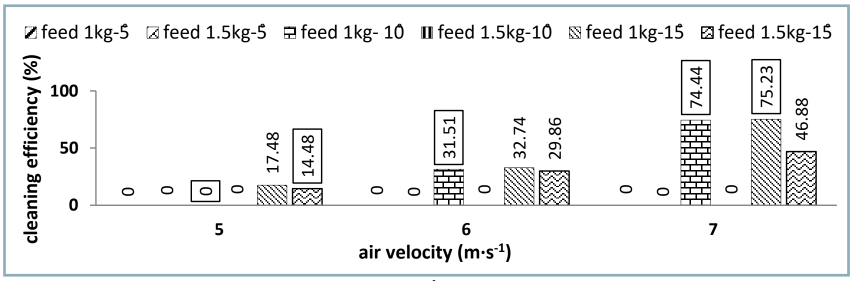


Fig. 11 Cleaning efficiency (%) at 0.48 m·s^{-1} sieve reciprocating speed

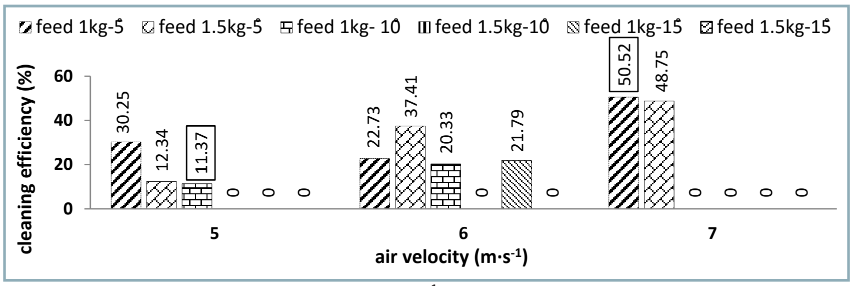


Fig. 12 Cleaning efficiency (%) at 0.95 m·s^{-1} sieve reciprocating speed

observed at 7 m·s^{-1} air velocity, 15° sieve slope, 1 kg·min^{-1} feed rate, while the minimum value (14.48%) at 5 m·s^{-1} air velocity, 15° sieve slope, and a feed rate of 1.5 kg·min^{-1}. The results allow conclusion that it is not advisable to increase sieve reciprocating speed to higher than 0.95 m·s^{-1} while using a high screen slope angle, as it will result in the highest grain loss in the first screen MOG outlet.

Figure 12 illustrates that the maximum cleaning efficiency at 0.95 m·s^{-1} (50.52%) sieve reciprocating speed was achieved at 7 m·s^{-1} air velocity, 5° sieve slope, and 1 kg·min^{-1} feed rate, while the minimum value (11.37%) at 5 m·s^{-1} air velocity, 10° sieve slope, and 1 kg·min^{-1} feed rate. Furthermore, using 10° sieve slope angle and 0.48 m·s^{-1} sieve reciprocating speed while employing air velocity of 5 m·s^{-1} and a feed rate of 1 kg·min^{-1}, as well as utilization of sieve slope angle of 10° and sieve reciprocating speed of 0.48 m·s^{-1} while using air velocity of 5, 6, and 7 m·s^{-1} and a feed rate of 1.5 kg·min^{-1}, resulted in certain issues. Application of 10° sieve slope angle and high sieve reciprocating speed (0.95 m·s^{-1}) while using air velocity of 5, and 7 m·s^{-1} and feed rate of 1 kg·min^{-1}, and utilization of air velocity of 5, 6, and 7 m·s^{-1} and a feed rate of 1.5 kg·min^{-1}, resulted in high grain loss in the first sieve and MOG outlet and high grain loss in the blower casing outlet. This also occurred with usage of 15° sieve slope and 0.95 m·s^{-1} sieve reciprocating speed under all treatment conditions.

Statistical analysis

Several statistical values were calculated – mean, variance, standard deviation, and P-value – for the evaluation of results obtained from experiments using EXCEL 2010. Table 4 shows the statistical values of mean, variance and standard deviation for the evaluation parameters concerning the experimental parameters.

Table 5 shows that certain experimental parameters have a high statistical significance in affecting the values of evaluated parameters and several of them have no significance,

Table 4 Means, variance, and standard deviation for evaluated parameters

Parameters	Cleaning efficiency	Cleanliness	Grain loss	Chaff rejection
Mean	16.06	42.26	2.25	11.33
Variance (s^2)	471.90	2068.89	34.64	193.05
Standard deviation	21.72	45.48	5.88	13.89

Table 5 *P*-value for the evaluated parameters

P-value	Feed rate	Sieve slope	Air velocity	Sieve speed
Cleaning efficiency	0.000249226*	0.105524019$^{N.s}$	0.008013362*	0.000157985*
Cleanliness	4.7561×10^{-06}*	0.000144964*	3.132×10-05*	3.7212×10-06*
Grain loss	0.322768863$^{N.s}$	0.000598766*	6.566×10-05	0.124061372$^{N.s}$
Chaff rejection	0.000118829*	0.580682762$^{N.s}$	0.025413817*	5.6961×10-05*

N.s = not significant; * = significant at level 5%

indicating that the P-value is the most significant from the statistical viewpoint (Sehsah et al., 2018; Nugus, 2009).

Conclusion

The electric motor and blower used were sufficient in terms of the sources of power and air for the cleaning unit. As shown, the maximum cleanliness in designed machine – 96.25% – was achieved at 5 $m \cdot s^{-1}$ air velocity, 5° sieve slope, 1 $kg \cdot min^{-1}$ feed rate, and 0.95 $m \cdot s^{-1}$ sieve reciprocating speed, with 2.3% of grain loss. The maximum cleaning efficiency – 75.23% – was obtained at 7 $m \cdot s^{-1}$ air velocity, 15° sieve slope, 1 $kg \cdot min^{-1}$ feed rate, and 0.48 $m \cdot s^{-1}$ sieve reciprocating speed. All things considered, it can be inferred that the sieve unit slope and reciprocating speed had the most significant effect on the results. The results also showed that the use of low screen slope angle and sieve reciprocating speed while using different air velocities and feed rates is not recommended. This is also valid for the application of high screen slope angle and sieve reciprocating speed while using different air velocities and feed rates. In the light of these results, it is advisable to increase the number of sieves used to 3 or 4 sieves and to increase their length in order to prolong the time the grains spend on the sieves. Furthermore, it is also recommended to use a brushing mechanism under each sieve to clean the sieve slots and avoid their clogging in order to enhance the machine performance.

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