Design of a Motorised Maize Sheller and Optimisation of its Operating Parameters

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ABSTRACT

Maize shelling is an important post-harvest operation to separate the grains from its cob. Traditional methods involve rubbing maize cobs against each other, rubbing on stones, or hand method. These methods are labour-intensive, time-consuming, and drudgery-prone. Migration from rural population to cities for better livelihoods has created labour shortage in rural areas during the peak period of maize shelling. A study was undertaken to design, develop, and evaluate the performance of an electric motor powered maize sheller. It consisted of a frame, feeding chute, cylinder, outer cover, rotor shaft, electric motor, belt, and outlet. The developed maize sheller was operated at three cylinder speeds (150, 200, 300 rpm) and three cob moisture contents [12, 14, 16% (w. b.)]. Highest and lowest shelling rates were 96.9 kg.h⁻¹ and 90.92 kg.h⁻¹ at cylinder speed and moisture content of 300 rpm, 12% (w. b.) and 150 rpm, 16% (w. b.). Shelling efficiency was 98.60% at 300 rpm, 12% (w. b.) and 89.00% at 150 rpm, 16% (w. b.). Grain damage was 8.37% at 300 rpm, 16% (w. b.) and 3.1% at 150 rpm, 12% (w. b.). Shelling rate and shelling efficiency decreased with increase in moisture content, but grain damage increased. Shelling rate, shelling efficiency, and grain damage also increased with increase in cylinder speed from 150 rpm to 300 rpm. Sheller cylinder speed of 150 rpm and grain moisture content of 12% (w. b.) gave the best shelling rate, shelling efficiency, and minimum grain damage of 92.07 kg.h⁻¹, 91.40%, and 3.10 per cent. The payback period of the maize sheller was 1.13 year, while the benefit-cost ratio was 1.01.

Maize (Zea mays L.) is a popular cereal grain grown around the world, and in India. It is a member of the Gramineae family, and is native to Mexico and South America. Maize, also known as corn, is thought to have originated from a wild grass 7,000 years ago in central Mexico (Dula, 2019). Following paddy and wheat, maize is the third important cereal grain in the world (Hulmani et al., 2022). India is one of the world's top four producers of maize, accounting for 2% of global production and ranking seventh in terms of area. Maize production in India during 2022–2023 was 346.13 lakh tonne, and is 8.83 lakh tonne higher than the production of 337.30 lakh tonne during previous year (Anon., 2023). With different variabilities among the soils, climate, biodiversity, and method of management, the area, production, and productivity in the world the maize crop were 201 Mha, 1,162 Mt, and 5,754.7 kg.ha⁻¹, respectively (FAOSTAT, 2020).

Due to its importance in human and animal diets, it is referred to as the "queen of cereals" and "the king of fodder". However, it serves as a fundamental raw material for manufacturing of starch, oil, and protein, as well as alcoholic drinks, food sweeteners; and, more recently, food for nutrition for both humans and animals. Maize accounts for between 15% and 20% of daily caloric intake in more than 20 developing countries (Nalado, 2015). In terms of its composition,
maize has an energy density of 365 kcal.100 g⁻¹, and comprises roughly 72% starch, 10% protein, and 4% fat (Dula, 2019).

Shelling is a key post-harvest technological operations that separates the grain from its cob for use as seeds, fodder, for oil extraction, to prepare the value-added product, and to maintain product quality (Kumar and Begum, 2014). Various traditional methods are used to separate the grains from its cob, such as pressing with fingers or rubbing on stones; but these are time-consuming, labour-intensive, and drudgery prone. Hand shelling is the most accurate method, and produces unbroken kernels. However, the process is very tedious (Nsubuga et al., 2021).

Various pedal- and hand-operated maize shellers were designed to separate the grains from its cob, but they require more energy (Nsubuga et al., 2021). Kumar and Begum (2014) designed and evaluated performance of hand-operated maize sheller at different grain moisture contents [10, 12, 14, 16, 18, 20% (w.b.)] and feed rates (120, 130, 140 kg.h⁻¹) corresponding to cylinder speeds of 300, 330, 350 rpm, respectively. The shelling efficiency, unshelled percentage, and visible grain damage were 99.56%, 0.44%, and 1.07%, respectively, for grain moisture content of 12.5% (w.b.) and feed rate of 130 kg.h⁻¹. Chitoda et al. (2017) designed a pedal-operated maize sheller which gave average throughput rate of 150 kg.h⁻¹ per person, and was 5.5 time higher compared to locally available hand-operated maize sheller. The average collection efficiency, shelling efficiency, and kernel shelling rate were 94%, 98.5%, 110 kg.h⁻¹, respectively. Chilur and Kumar (2018) designed a maize dehusker-cum-sheller with overall dimension of [1,200 × (500 × 610) × 810] (Length × (top × bottom) × Height), cylinder length and diameter of 1,000 × 250 mm, 44 number of lugs arranged in staggered form in first 4 row × 6 lugs and second 4 row × 5 lugs, row centre-to- centre distance of 190 mm along axis, lug overall dimension of 6 × 25 × 42 mm (Thick × Width × Height), 95 mm spacing between two lugs for zig-zag arrangement leading to impact with abrasion to maize cobs. The maize sheller was operated at cylinder peripheral speed and concave clearance of 7.1 m.s⁻¹ and 25 mm, respectively. The shelling capacity, shelling efficiency, total grain loss, cleaning efficiency, dehusking efficiency, germination, and seed coat damage were 600 kg.h⁻¹, 98.01%, 3.63%, 99.11%, 99.56%, 98.93%, and 3.03%, respectively. Sahu et al. (2020) designed a hand-operated small-scale maize sheller consisting of a main frame (300 × 600 × 1050 mm), feeding chute size of 250 × 150 × 250 mm, rotating wheel diameter and width of 570 mm and 180 mm, concave length and diameter of 660 mm and 20 mm, concave clearance of 30 - 60 mm, and outer cover of 1200 mm. Operating at moisture contents of 10, 12, 14, 16, 18, 20% (w.b.) and cylinder speed of 90, 100, 120 rpm, shelling efficiency, unshelled grains, and grain damage of the sheller were 99.43%, 0.49%, and 0.97% at grain moisture content of 10% (w.b.) and cylinder speed of 120 rpm. Dixit and Bashir (2020) studied the effect of moisture content on the shelling performance of a lever-operated maize cob sheller with overall dimension of 850 × 450 × 900 mm, rectangular pedal (508 × 406.4 mm) as power source, connecting rod length of 406 mm and diameter of 10 mm, and shelling unit of 31.75 × 31.75 mm. The maize sheller operated at three moisture contents (20 - 22, 18 - 20, 16 - 18%) gave shelling capacity, shelling efficiency, and grain damage of 30.50 kg.h⁻¹, 91.37%, and 5.86%, respectively, at 12–16% (w. b.) grain moisture content. Dange et al. (2021) designed a small portable maize cob de-husker and maize sheller. The developed maize sheller consisted of a main frame 610 × 390 × 650 mm (Length × Width × Height), roller length of 750 mm, concave assembly of MS flat (25 × 5 mm) for support, square rod (8 × 8 mm), and two MS flats (25 × 5 mm) on both top surfaces to reinforce the frame, bottom of concave fitted with 600 mm length and 20 mm diameter sieve for easy grain discharge, and power source of single phase 2.24 kW electric motor. The developed maize sheller was operated at three roller speed (1.7, 1.91, 2.08 m.s⁻¹) and feed rate (600, 800, 1000 kg.h⁻¹). The maximum shelling efficiency was 98.86% at cylinder speed of 7.35 m.s⁻¹, feed rate of 800 kg.h⁻¹, and grain moisture content of 14.12% (d.b.). The minimum unshelled grain percentage was 1.04% at cylinder speed of 6.35 m.s⁻¹ and moisture content of 12.14% (d.b.). The minimum blower loss was 1.37% at 1.7 m.s⁻¹ roller speed and 600 kg.h⁻¹ feed rate. Olaya et al. (2021) developed a motorised thresher for shelling maize.

Various losses occur during gathering, threshing, separating, and cleaning operations. Kernel loss and damage losses depend on crop morphology, physical characteristics, and mechanical properties as well as machine design and adjustment, and operation (Nsubuga et al., 2021). Moreover, cylinder speed, moisture content, cylinder concave clearance, and maize varieties have impacts on cob breakup during maize shelling (Tunhaw et al., 2019).
In view of the above, a maize sheller with enhanced capacity of 90 - 110 kg.h$^{-1}$, low grain damage, reduced labour cost and drudgery is required for small and marginal farmers. The present study was undertaken with the objective to design an improved motor-operated maize sheller and optimise its operating parameters.

**MATERIALS AND METHODS**

**Location of Study**

The maize sheller was designed and developed during the year 2020 at the Department of Farm Machinery and Power Engineering, Aditya College of Agricultural Engineering and Technology, Beed, Maharashtra. Performance evaluation of the prototype was carried out in the experimental farm of the College of Agricultural Engineering and Technology, Beed, Maharashtra.

**Design Considerations**

Before design of the motorised maize sheller, features of some recent maize shellers were taken into consideration. The specification of some existing maize shellers are shown in Table 1.

Kumar and Begum (2014) reported a hand-operated maize sheller consisting of a main frame [925 × 850 × 1365 mm (Length × Width × Height)], feeding chute (280 × 180 × 390 mm), shelling cylinder of 860 mm length and 210 mm diameter, cylinder concave clearance of 20 - 50 mm, flywheel diameter of 405 mm, outer cover of 274 mm. The length of opening was 910 mm with slotted opening size of 303 × 25 mm.

Aremu et al. (2015) designed a motorised maize sheller consisting of an angle iron (45 × 45 × 6.25 mm) frame with overall dimension of 830 × 605 × 950 mm; shelling cylinder length and diameter of 450 mm; number of pegs: 16 (4 rows, each containing 4 pegs), peg size: 25 × 25 mm, cross-section of peg: 25 mm, power source: single phase 2.24 kW, 220 V, 1430 rpm electric motor. The maize sheller was operated by a single-phase 2.23 kW electric motor with speed of 950 rpm. The initial cost of the maize dehusker-cum-sheller was ₹ 34,500/-.

Singh et al. (2022) reported a solar energy-operated maize sheller consisting of a feeding chute (top 400 × 400 mm, bottom 220 × 220, height above cylinder cover 280 mm), shelling cylinder [diameter: 170 mm with pegs, without pegs: 120 mm; length: 450 mm; number of pegs: 16 (4 rows, each containing 4 pegs), peg size: 25 × 25 mm, cross-section of peg: 25 mm, height: 95 mm, peg spacing in row: 25 mm, diameter and length of cylinder shaft: 470 mm and 250 mm, concave: 450 mm, peripheral width and diameter of concave: 180 mm and 170 mm. The initial cost of the maize sheller was more than 600 W.m$^{-2}$ solar intensity without battery backup.

Design features of the above maize shellers and their critical components as shelling mechanisms for low grain damage requiring accurate design of cylinder diameter, length, number of pegs were studied. The electric motor-operated maize sheller was thus provided with transportation wheels for easy movement with less human drudgery, low power electric motor for less power consumption and dead weight, and use of locally available raw materials for low initial cost.

The major design considerations for a motorised maize sheller were

(a) Simple in design, portable and affordable for small and marginal farmers,
(b) Easily operatable by farm workers.
(c) High shelling efficiency with low grain damage,
(d) Easy availability of spare parts.

**Principles of Shelling**

Shelling cylinder with mounted spikes was used to produce impact and shearing forces, which carried out the shelling process for removal of maize grains from a cob. Cylinder speed is required to be controlled along with proper feeding rate of maize cobs, as different
### Table 1. Technical specifications of some existing maize shellers

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Existing maize sheller</th>
<th>Specifications</th>
<th>Power source</th>
<th>Cost of machine, ₹</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Solar energy-operated maize sheller</td>
<td>Feeding chute: Top: 400 x 400 mm, Bottom: 220 x 220 mm, Height: 280 mm. Cylinder: Diameter: 170 mm, Length: 450 mm, Number of pegs: 16, Length, diameter of cylinder shaft: 250, 450 mm</td>
<td>Solar panel size: 1960 x 992 x 40 mm, Max. power: 325 W voltage and current: 37 V, 8.78 A, DC motor rated power: 450 W Motor speed, torque: 480 rpm, 76 kg cm</td>
<td>-</td>
<td>Singh et al. (2022)</td>
</tr>
<tr>
<td>2.</td>
<td>Motorised maize sheller</td>
<td>Overall dimension (Length x Width x Height): 830 x 605 x 950, Angle iron: 45 x 45 x 6.25 mm, Iron rod: 14 mm, Shaft: 22 mm, Shelling cylinder length, diameter: 645, 92 mm, Total no. of spikes on shelling cylinder: 47</td>
<td>Electric motor, Single phase 1.10 kW Electric motor speed: 1440 rpm</td>
<td>46750/-</td>
<td>Aremu et al. (2015)</td>
</tr>
<tr>
<td>3.</td>
<td>Electric motor-operated maize sheller</td>
<td>Feeding chute dimension: 420 x 327 x 100 mm (L x W x T), Threshing shaft length, diameter: 500 x 25 mm</td>
<td>Single phase 2.24 kW electric motor, speed of 1430 rpm and torque of 14.92 Nm.</td>
<td>-</td>
<td>Azeez et al. (2017)</td>
</tr>
<tr>
<td>4.</td>
<td>Maize dehusker-cum-sheller</td>
<td>Overall dimension: [1200 x (500 and 610) x 810] mm [Length x Width (top and bottom) x Height], Cylinder length and diameter: 1000 x 250 mm, Number of lugs: 44, Lugs overall dimension: 6 x 45 x 42 mm (Thickness x Width x Height), Concave clearance: 25 mm</td>
<td>Single phase 2.23 kW electric motor, speed of 950 rpm.</td>
<td>34,500/-</td>
<td>Chilur and Kumar (2018)</td>
</tr>
<tr>
<td>5.</td>
<td>Hand-operated maize sheller</td>
<td>Frame: 925 x 850 x 1365 mm, Feeding chute: 280 x 180 x 390 mm, Cylinder (L x D): 860 x 210 mm, Cylinder concave clearance: 20 - 50 mm, Flywheel diameter: 405 mm, Outer cover: 274 mm</td>
<td>Manual hand-operated</td>
<td>-</td>
<td>Kumar and Begum (2014)</td>
</tr>
</tbody>
</table>
Design of machine components

Power requirement
Torque was calculated using the following equation (Azeez et al., 2017):

\[ T = m \times g \times r \]  ...(1)

Where,
- \( T \) = Torque, Nm,
- \( m \) = Mass of shelling cylinder, (23.4 kg),
- \( g \) = Acceleration due to gravity, (9.81 m. s\(^{-2}\)), and
- \( r \) = Radial distance of shelling cylinder shaft, (0.12 m).

\[ T = 23.4 \times 9.81 \times 0.12 \]
\[ T = 27.55 \text{ Nm} \]

Power requirement was calculated using the following equation (Khurmi, 2005):

\[ P = \frac{2\pi NT}{60} \]  ...(2)

Where,
- \( N \) = Speed of shaft (750 rpm),
- \( T \) = Torque (27.55 kg. m), and
- \( P \) = Power, kW.

Thus, power requirement was:

\[ P = \frac{2\pi \times 750 \times 27.55}{60} \]
\[ P = 2164 \text{ W} \]
\[ P = 2.164 \text{ kW} \]

Feeding chute volume
The volume of feeding chute was calculated using the following equation (Mogaji, 2016):

\[ V_h = \frac{V_{ct}-V_{cb}}{2} + V_{cb} \]  ...(3)

Where,
- \( V_h \) = Volume of feeding chute, m\(^3\),
- \( V_{ct} \) = Volume of feeding chute top and its length and breadth, m\(^3\), and
- \( V_{cb} \) = Volume of feeding chute bottom and its length and breadth, m\(^3\).

\[ V_{ct} = 360 \times 200 \times 100 = 0.0072 \text{ m}^3 \]
\[ V_{cb} = 320 \times 150 \times 100 = 0.048 \text{ m}^3 \]

\[ V_h = \frac{0.0072 - 0.0048}{2} + 0.0048V_h = 0.006 \text{ m}^3 \]

Design of cylinder
The diameter of shelling cylinder was calculated using the following variables (Mogaji, 2016):

Diameter of shelling cylinder is a function of the following variable,

Shelling cylinder speed, \( n = 300 \text{ rpm} \),
Length of shelling cylinder, \( L_c = 580 \text{ mm} \),
Average weight of maize cob with grain, \( W_e = 331 \text{ mm} \),
Maximum length of maize cob with grain, \( L_m = 211 \text{ mm} \),
Maximum width of maize cob with grain, \( W_m = 45 \text{ mm} \),

Shelling case
The diameter of shelling case was calculated using the following equation (Mogaji, 2016):

\[ d_c = d + 2H_s + 2W_m + 2C \]  ...(4)

Where,
- \( d \) = Diameter of shelling cylinder, 98 mm,
- \( H_s \) = Height of spikes, 45 mm,
- \( W_m \) = Maximum width of maize cob with grain, 45 mm, and
- \( C \) = Smallest diameter of grain, 3.5 mm

\[ d_c = 0.098 + 2 \times 45 + 2 \times 45 + 2 \times 3.5 \]
\[ d_c = 285 \text{ mm} \]

Therefore, diameter of shelling cage as 285 mm m was selected.

Number of shelling cylinder spikes
The number of spikes on the shelling cylinder was calculated using the following equation (Aremu et al., 2015):

\[ N_p = \frac{L_c \times \pi d}{S_r \times S_c} \]  ...(5)

Where,
- \( N_p \) = Number of spikes on shelling cylinder,
- \( L_c \) = Length of shelling cylinder, 580 mm,
- \( S_r \) = Spike spacing on row, 53 mm,
- \( S_c \) = Spike spacing on circle, 50 mm, and
- \( d \) = Diameter of shelling cylinder, 98 mm.

For \( L_c = 580 \text{ mm} \), \( S_r = 53 \text{ mm} \), \( S_c = 50 \text{ mm} \), and \( d = 98 \text{ mm} \), 66 number of spikes were required on the shelling cylinder.
Mass of shelling cylinder

The mass of shelling cylinder was calculated using the following equation (Mogaji, 2016):

\[ M_{cs} = \rho \times V_{cs} \]  

...(6)

Where,

\[ \rho = \text{Density of high carbon steel grade, 7.8} \times 10^6 \text{ kg/m}^3, \] and

\[ V_{cs} = \text{Volume of cylinder shaft, mm}^3. \]

The volume of cylinder was calculated by using following equation (Mogaji, 2016)

\[ V_{cs} = \pi R^2 L - \pi r^2 L = (r + t)^2 - \pi r^2 \]  

...(7)

Where,

\[ L = \text{Length of cylinder shaft, 580 mm}, \]
\[ T = \text{Thickness of cylinder, 10 mm}, \]
\[ R = \text{Outer radius of shelling cylinder, 98 mm}, \] and
\[ r = \text{Inner radius of shelling cylinder, 95 mm}. \]

Therefore, mass of shelling cylinder was 23.4 kg.

Diameter of pulley shaft

The diameter of pulley shaft was calculated using the following relationship (Ezurike et al., 2020):

\[ N_1 D_1 = N_2 D_2 \]  

...(8)

Where,

\[ N_1 = \text{Speed of motor pulley, 750 rpm (measured value)}, \]
\[ N_2 = \text{Speed of rotor shaft, 300 rpm}, \]
\[ D_1 = \text{Diameter of motor pulley, 40 mm}, \] and
\[ D_2 = \text{Diameter of rotor pulley, mm}. \]

For motor pulley speed of 750 rpm, shaft diameter of 40 mm, and rotor shaft speed of 300 rpm, the calculated value of the diameter of pulley shaft was 100 mm. Accordingly a value of 100 mm was considered.

Power transmission system

Length of belt

For the present design, an open drive was considered as the two parallel shafts were required to rotate in the same direction.

The length of belt was calculated using the following equation (Ezurike et al., 2020):

\[ L = 2C + \frac{\pi (D+d)^2}{2} + \frac{(D-d)^2}{4C} \]

\[ L = 2 \times 250 + \frac{\pi (100+40)^2}{2} + \frac{(100-40)^2}{4C} \]

...(9)

A standard belt of length 720 mm was selected for power transmission from to motor to shelling cylinder

Where,

\[ L = \text{Length of belt, mm}, \]
\[ C = \text{Centre-to-centre distance between two pulleys, mm}, \]
\[ D = \text{Diameter of bigger pulley, mm}, \] and
\[ d = \text{Diameter of smaller pulley, mm}. \]

For a centre-to-centre distance of 250 mm, bigger pulley diameter of 100 mm, and smaller pulley diameter of 40 mm, the calculated value of the length of belt was 723.54 mm. Accordingly, the length of the belt was considered as 720 mm.

Working Principle

An electric motor (2.16 kW) provided rotational energy to the cylinder on which spikes were fitted. The cobs rotated in the shelling unit, and the grains were separated from the cobs. The kernels were collected at the bottom end of the outlet, and clean grains were collected at the bottom of the threshing unit. One person was required for the operation of the maize sheller for feeding maize cobs at the feeding chute and collecting clean grain at the outlet. Conceptual 3-D design and layout of the maize sheller is shown in Figs. 1, 2. Technical specifications of the maize sheller are reported in Table 2, and specification of the electric motor in Table 3.

Testing Methodology

A standard test procedure (IS 7050, 1973) for power maize sheller was used to test the developed maize sheller at three different moisture contents and cylinder speeds of 12, 14, 16 per cent (w. b.) and 150, 200, 300 rpm with three replications, respectively, at constant feed rates of 20 kg/batch\(^\dagger\). Each trial was conducted with 120 kg of maize cob fed continuously (Feeding chute capacity: 20 kg) for 10 minutes. Before test run, the direction of rotation of the pulleys, belt tension, and motor electric power supply were checked. The speed of the cylinder was checked with a tachometer [model SE188, overall dimension of (1.30 \times 0.70 \times 0.29 m), range 2.5 to 10,000 rpm, accuracy \pm (0.05%\% 1 Digit)].

Physical Properties of Maize

Physical characteristics of maize cobs have direct
Influence on the performance of maize shellers. Moisture content influences the various other biological properties of grain (Nandede et al., 2021).

Physical characteristics of maize cob (moisture content, smallest and largest diameter, weight, length) of Suvarna NMH 589 variety were measured for design of the maize sheller. These physical characteristics of maize cob were measured using the following methods.

**Moisture content**

Maize grains were dried at 103°C for 48 h in an oven to determine their moisture content. The moisture content on wet basis was determined by the following formula (Nandede et al., 2021):

\[
M_w = \frac{W - W_d}{W}
\]

Moisture content of grain should be reduced to 16% or less to minimise grain damage during shelling. Grain moisture content of 13% is reported to achieve better shelling of maize grains (ASHRAE, 1998). Madanhire et al. (2019) reported that best shelling of maize grains was achieved at 13 – 14% (w.b.) moisture content. It is, therefore, important to measure moisture content of maize grains before shelling operation.

Moisture content of maize grain before shelling was determined at 12%–16% by carefully monitoring grains in an oven at a temperature of 43°C. The moisture content of maize grains was measured after every
hour till it reached in the range of 12% - 16% (w.b.) (Alsharifi et al., 2019).

**Cob and grain major dimensions**

External diameter of maize cob generally decreases along its longitudinal axis. Thirty maize cob samples were randomly selected to determine the dimensional properties. The largest and smallest diameter were obtained at the base and apex of a maize cob, excluding the portion without kernels. A vernier calliper (Model: DIGE150, 1 LR44 battery powered, depth and steps measuring range: 0 - 1.50 m, least count: 0.0000 m) was used to determine the largest and smallest diameter, cob width, longitudinal length of maize cob, and grain diameter (Fig. 3).

The largest and smallest diameters of maize cobs were used to determine the cob guiding cylinder, and fix the shelling spike diameter, respectively.

**Weight**

A sample of 30 cobs was chosen at random, and their individual weights were measured. The weight of the cobs without grains were also measured using a digital weighing balance (Make: Venus, ABS plastic, range: 0-10 kg), and the average weights determined (Fig. 4).
Shelling efficiency

Shelling efficiency of the maize sheller was calculated using the following equation (Bello et al., 2019):

\[
\text{Shelling efficiency, } \% = \frac{\text{Mass of shelled grain, kg}}{\text{Total mass of grain, kg (Shelled + Unshelled)}}
\]  

...(12)

Grain damage

After shelling operation, grains were randomly selected from each treatment. Using suitable sieves, damaged grains were first separated from whole grains (Gomaa et al., 2022). Subsequent to separation of damaged grains, a sample of 200 g of grains were randomly selected for visual observations for cracks in the grains (Sharifi et al., 2019).

Grain damage caused by the maize sheller was calculated using the following equation (Bello et al., 2019):

\[
\text{Grain damage, } \% = \frac{\text{Mass of damage grain, kg}}{\text{Mass of shelled grain, kg}}
\]  

...(13)

Statistical Analysis

Design Expert software (version 7.0) was used for experimental design and statistical analysis. In this study, a two-factorial design with nine treatment combinations (with 3 replications) was used. To optimise the independent operating parameters of the developed maize sheller, a multi-level categoric factorial was used, which is suitable for categoric factors with different levels. A significant level for each response was determined through analysis of variance (ANOVA). The statistical significance was tested using the F-statistic calculated from the data. Model adequacies were verified by R², adj- R², and pre- R², standard deviations (SD), and coefficients of variance (CV).

Using the software, the numerical multi-response optimisation method was utilised to determine the optimal conditions for developing maize shellers. The maximum shelling rate, maximum shelling efficiency, and minimum grain damage were considered when determining the effect of cylinder speed and moisture content (w.b.).

RESULTS AND DISCUSSION

Components of developed Motor-operated Maize Sheller

The developed motor-operated maize sheller (Fig. 6) consisted of the main components listed below. Technical specifications of the machine components are reported in Table 2.

Main frame

It was made of mild steel with overall dimension of 580 × 550 × 410 mm (Length × Width × Height). The main frame supported the feeding chute, electric motor, power transmission system, cylinder, and cylinder shaft.

Feeding chute

The feeding chute was constructed using 18-gauge thick mild steel sheet, with overall dimension of 360 × 200 × 100 mm (top) and 320 × 150 × 100 mm (bottom) (Length × Width × Height), respectively.

Shelling cylinder

The shelling cylinder of 98 mm diameter and 580 mm length was made with I.S. steel. A total of 66 spikes (6 × 12 × 20 mm) were placed on the cylinder about 53 mm in equally spaced six rows (50 mm row-to-row distance), Fig. 5. The cylinder rotated along its longitudinal axis to separate the grains from the cobs. Cylinder with spikes is inexpensive, and simple to fabricate.
Rotor shaft
The rotor shaft was made of high carbon steel (grade 40C8) with a yield strength of 320 MPa and ultimate tensile strength of 560-670 MPa. The overall dimension of the rotor shaft was 12 × 580 mm.

Shelling unit cover
It was constructed with metal sheet, and bent into a semi-circular shape with diameter of 580 mm. It was tightly fixed to provide protection for the cylinder, and prevent grains from pouring out. The feeding chute was attached to the outer cover. Brush was placed inside the outer cover for easier cleaning of the inner cylinder.

Power transmission system
Electric motor power was transmitted from the motor pulley (100 mm diameter) to the rotor shaft (40 mm diameter) through V-belt and pulley.

Grain outlet
On one end of the shelling unit, an outlet made of metal sheet was provided for collection of clean grains.

Transportation wheel
A front transportation wheel (65 × 26 mm) and a rear wheel (40 × 15 mm) were provided for transportation of the motor-operated maize sheller.

Electric motor
A single-phase 2.164 kW electric motor was used to operate the threshing mechanism of the maize sheller. Detailed specification of the electric motor is given in Table 3.

The prototype of the maize sheller is shown in Fig. 6.

Physical Characteristics of Maize Cob
The physical characteristics of maize cobs are reported in Table 4.

The maximum and minimum lengths of maize (variety: Suvarna NMH 589) cob ranged from 227.0 mm to 189.4 mm, respectively. The average length of a maize cob was 211.11 mm. The average diameter of maize cob at major, intermediate, and minor were 45.2, 34.85, and 26.50 mm, respectively. The average values for the core (cob after shelling) were 43.45, 32.97, and 27.55 mm, respectively. The weights of cob with husk, husk, dehusked cob, core, shelled kernel, and unshelled kernel were 331.27, 52.36, 280.21, 107.23, 159.25, and 21.36 g, respectively.
Nandede et al. (2016) had reported maximum and minimum diameters of maize cob were [50 mm, 33 mm (largest diameter); 35 mm, 25 mm (smallest diameter)], length of cob (210 mm and 105 mm), and weight of cob as 246.05 g. The diameter of maize cob (variety: Ganga 101) was 51.4, 48.15, 24.5 mm (top, middle, tip), with length of 187.9 mm (Singh et al., 2022). Das et al. (2023) had reported length, width (top and bottom), thickness and weight of maize cob as 145 mm, 35 mm and 37 mm, 140 mm, and 130.62 g, respectively.

### Impact of Machine and Crop Variables on Performance

Performance results of some recent maize shellers reported by various authors are presented in Table 5.

Singh et al. (2022) reported performance evaluated at feed rates of 102, 103.5, 105.2, and 107.67 kg.h⁻¹ shelling efficiency, cleaning efficiency, broken grain, blown grain, and average power requirement was 99.6%, 97.8%, 3.9%, 3.6%, 356 W at feed rate of 102 kg.h⁻¹; and 98.9%, 97.0%, 3.85%, 4.2%, 387 W of a solar power-operated maize sheller at feed rate of 107.67 kg.h⁻¹. The result showed that with increase of feed rate, shelling efficiency and cleaning efficiency decreases while broken grain, blown grain, and power requirement increases. The moisture content of maize grains was 14.3% (d.b.). The capacity of the maize sheller was lower as compared to engine- and electrically-operated maize sheller.

Aremu et al. (2015) reported maximum and minimum shelling efficiency, cleaning efficiency, grain recovery efficiency, sheller performance index, total grain losses, and output capacity of a motorised maize sheller to be 87.07%, 95.48%, 95.48%, 95.11%, 2.96%, 623.99 kg.h⁻¹ for cylinder speed and moisture content of 886 rpm, 13% (d.b.); and 54.84%, 93.29%, 95.89%, 89.45%, 2.23%, 393.60 kg.h⁻¹ at cylinder speed of 623 rpm, and grain moisture content of 17% (d.b.), respectively. With increase of cylinder speed from 623 rpm to 886 rpm, shelling efficiency increased from 62.85% to 87.07%, cleaning efficiency from 94.56% to 95.48%, sheller performance index from 91.08 to 95.48, grain losses from 2.84% to 2.96%, output capacity from 450.65 kg.h⁻¹ to 623.99 kg.h⁻¹; but decreased grain recovery efficiency from 96.12% to 95.48 per cent. Increase in moisture content from 13% to 17% (d.b.) decreased the shelling efficiency (62.85 to 54.84 %), cleaning efficiency (94.56 to 93.29%), grain recovery efficiency (96.32 to 95.89%), sheller performance index (91.08 to 89.45), output capacity (450.65 to 393.60 kg.h⁻¹) and grain losses (2.84 to 2.23%). The optimised operating parameters for the motorised maize sheller were 13% (d.b.) grain moisture content and 886 rpm cylinder speed.

Azeez et al. (2017) reported performance of an electric motor-operated maize sheller to be 55 kg.h⁻¹ shelling rate, 91.29% shelling efficiency, and 0.12% grain damage.

Chilur and Kumar (2018) reported performance of a maize dehusker-cum-sheller at cylinder peripheral speed and concave clearance of 7.1 m. s⁻¹ and 25 mm,
respectively. The shelling capacity, shelling efficiency, total losses of grain, cleaning efficiency, dehusking efficiency, germination and seed coat damage were 600 kg.h\(^{-1}\), 98.01%, 3.63%, 99.11%, 99.56%, 98.93%, and 3.03%, respectively.

Kumar and Begum (2014) reported performance of a hand-operated maize sheller operated at different moisture contents [10, 12, 14, 16, 18, 20% (w.b.)] and feed rates (120, 130, 140 kg.h\(^{-1}\)). Feed rates of 120, 130, and 140 kg.h\(^{-1}\) corresponded to cylinder speed of 300, 330, and 350 rpm, respectively. The shelling efficiency, unshelled percentage, and visible grain damage were 99.56%, 0.44%, and 1.07%, respectively, at moisture content of 12.5 (w.b.) and feed rate of 130 kg.h\(^{-1}\). Shelling efficiency decreased with increase of moisture content due to difficulties in separation of grain at higher moisture content. Unshelled grain increased with increase of grain moisture content because of higher elastic condition of grains due to decrease in grain cohesive force with decreasing moisture content. Visible damage percentage of grain increased with increase of grain moisture content due to softness of grain at higher moisture content and brittle at lower moisture content.

### Effect of cylinder speed and moisture content on shelling rate of maize cob

An analysis of variance (ANOVA) for the percentage shelling rate is given in Table 6. The effects of the independent variables of developed maize sheller such as cylinder speed and moisture content were significant, but their interaction was non-significant with SD and CV values of 0.334 and 0.357, respectively. Regression analysis indicated that the R\(^2\) was 0.971 and the adjusted R\(^2\) was 0.95. The highest and lowest shelling rate were 96.9 kg.h\(^{-1}\) and 90.92 kg.h\(^{-1}\) at cylinder speeds and moisture contents of 300 rpm (12% w. b.) and 150 rpm (16 per cent w. b.), respectively.

Figure 7 shows that with increase in moisture content (12% to 16%, w.b.), the shelling rate decreased from 96.6 kg.h\(^{-1}\) to 90.92 kg.h\(^{-1}\) because at high moisture content, the shelling unit tends to get blocked. By increasing cylinder speed, the shelling rate increased because the cobs were engaged by the cylinder spikes.
Table 6. ANOVA on effect of cylinder speed and moisture content on shelling rate of maize cob

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of squares</th>
<th>df</th>
<th>Mean square</th>
<th>F-value</th>
<th>p-value</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>26.67</td>
<td>5</td>
<td>5.33</td>
<td>47.76</td>
<td>&lt; 0.0001</td>
<td>S</td>
</tr>
<tr>
<td>A-Cylinder speed</td>
<td>7.46</td>
<td>1</td>
<td>7.46</td>
<td>66.79</td>
<td>&lt; 0.0001</td>
<td>S</td>
</tr>
<tr>
<td>B-Moisture content</td>
<td>18.62</td>
<td>1</td>
<td>18.62</td>
<td>166.72</td>
<td>&lt; 0.0001</td>
<td>S</td>
</tr>
<tr>
<td>AB</td>
<td>0.0576</td>
<td>1</td>
<td>0.0576</td>
<td>0.5157</td>
<td>0.4959</td>
<td>NS</td>
</tr>
<tr>
<td>A²</td>
<td>0.3467</td>
<td>1</td>
<td>0.3467</td>
<td>3.10</td>
<td>0.1215</td>
<td>NS</td>
</tr>
<tr>
<td>B²</td>
<td>0.0301</td>
<td>1</td>
<td>0.0301</td>
<td>0.2691</td>
<td>0.6200</td>
<td>NS</td>
</tr>
<tr>
<td>Residual</td>
<td>0.7818</td>
<td>7</td>
<td>0.1117</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lack of Fit</td>
<td>0.0904</td>
<td>3</td>
<td>0.0301</td>
<td>0.1742</td>
<td>0.9086</td>
<td>NS</td>
</tr>
</tbody>
</table>

Note: SS: Sum of Square; df: degree of freedom; C.V: Coefficient of Variance; R²: Coefficient of determination; *p<0.05: significant at 5% level of significance, **p<0.01 significant at 1% level of significance, ***p<0.001: significant at 0.1% level of significance

Fig. 7: Effects of cylinder speed and moisture content on shelling rate of maize cob

greater number of times within a specified time period, resulting an increase in the shelling rate. Figure 8 shows maize cob samples before shelling by the machine and after shelling operation.

Abagisaa et al. (2015) had reported that with increase in drum speed, the threshing capacity increased due to increased impact force for crop threshing. Dixit and Bashir (2020) had reported that at low moisture contents of 12–14% (w. b.), the shelling rate increased because of the weak bond between maize grains and shell. Shelling rate increased (252.7 kg.h⁻¹ to 291.3 kg.h⁻¹) with increase of cylinder speed from 200 rpm to 300 rpm (Gomaa et al., 2022). With increase of moisture content from 15% to 19% (w.b.), the shelling capacity decreased from 135 kg.h⁻¹ to 1117 kg.h⁻¹ (Alsharifi, 2018).

With increase of grain moisture content [13% to 17% (w.b.)], the output capacity decreased from 450.65 kg.h⁻¹ to 393.60 kg.h⁻¹; and with increase of cylinder speed from 623 rpm to 886 rpm, the output capacity increased from 623.99 kg.h⁻¹ to 478.00 kg.h⁻¹ (Aremu et al., 2015). Higher shelling efficiencies were thus observed at 350 rpm rotor speed, but grain damage was slightly higher (Kumar and Rajshekarappa, 2012). Nsubuga et al. (2020) observed that the shelling rate was highest at grain moisture content of 10% (w.b.) and lowest at 17% (w.b.).

Effect of cylinder speed and moisture content on shelling efficiency of maize cob

An analysis of variance (ANOVA) for the percentage of shelling efficiency is given in Table 7. It was observed that the effects of the independent parameters (cylinder
speed, moisture content) and their interactions were significant, with SD and CV values of 0.55 and 0.59, respectively. Regression analysis indicated that $R^2$ was 0.97 and adjusted $R^2$ was 0.96. Shelling efficiencies were 91.40%, 90.80%, 89.00% at cylinder speed of 150 rpm and grain moisture content of 12%, 14%, 16% (w.b.). Shelling efficiency increased to 94.33%, 93.78%, 92.67% at cylinder speed of 200 rpm and grain moisture content of 12%, 14%, 16% (w.b.), respectively; and 98.60%, 97.52%, 95.26% at cylinder speed of 300 rpm and grain moisture content of 12%, 14%, 16% (w.b.), respectively.

Highest and lowest shelling efficiencies were 98.60% and 89.00% at cylinder speeds and moisture contents of 300 rpm (12% w.b.) and 150 rpm (16% w.b.), respectively. From Fig. 9, it could be seen that with increase in moisture content, shelling efficiency decreased (98.60% to 89.00%) because the shelling unit tended to choke with maize at higher moisture

### Table 7. ANOVA on effect of cylinder speed and moisture content on shelling efficiency of maize cob

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F-value</th>
<th>p-value</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>96.83</td>
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<td>19.37</td>
<td>62.54</td>
<td>&lt; 0.0001</td>
<td>S</td>
</tr>
<tr>
<td>A-cylinder speed</td>
<td>31.37</td>
<td>1</td>
<td>31.37</td>
<td>101.31</td>
<td>&lt; 0.0001</td>
<td>S</td>
</tr>
<tr>
<td>B-Moisture content</td>
<td>46.65</td>
<td>1</td>
<td>46.65</td>
<td>150.64</td>
<td>&lt; 0.0001</td>
<td>S</td>
</tr>
<tr>
<td>AB</td>
<td>5.29</td>
<td>1</td>
<td>5.29</td>
<td>17.08</td>
<td>0.0044</td>
<td>S</td>
</tr>
<tr>
<td>$A^2$</td>
<td>2.73</td>
<td>1</td>
<td>2.73</td>
<td>8.81</td>
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</tr>
<tr>
<td>$B^2$</td>
<td>5.80</td>
<td>1</td>
<td>5.80</td>
<td>18.72</td>
<td>0.0035</td>
<td>S</td>
</tr>
<tr>
<td>Residual</td>
<td>2.17</td>
<td>7</td>
<td>0.3097</td>
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</tr>
<tr>
<td>Lack of Fit</td>
<td>1.13</td>
<td>3</td>
<td>0.3761</td>
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<td>0.3543</td>
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</tr>
<tr>
<td>Pure Error</td>
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<tr>
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<td></td>
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<tr>
<td>Std Dev</td>
<td>0.5565</td>
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<td></td>
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<tr>
<td>Mean</td>
<td>93.79</td>
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<tr>
<td>C.V. %</td>
<td>0.5933</td>
<td></td>
<td></td>
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<tr>
<td>$R^2$</td>
<td>0.9781</td>
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<td></td>
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</tr>
<tr>
<td>Adjusted $R^2$</td>
<td>0.9625</td>
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<tr>
<td>Predicted $R^2$</td>
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<tr>
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</tbody>
</table>

Note: SS: Sum of Square; df: degree of freedom; C.V: Coefficient of Variance; $R^2$: Coefficient of determination; *p<0.05: significant at 5% level of significance, **p<0.01 significant at 1% level of significance, ***p<0.001: significant at 0.1% level of significance.
content (16 per cent). By increasing cylinder speed, the shelling efficiency also increased because of higher frequency of contacts of maize cobs with the cylinder pegs within short period and caused increased shelling of grains. Alsharifi et al. (2019) had reported increasing shelling efficiency with increase in the drum rotational speed due to a blockage cavity in machine at low speed. Kumar and Begum (2014) had observed that the shelling efficiency decreases with increase in moisture content. Parihar et al. (2022) had reported that with increase of cylinder speed, the threshing efficiency also increased. Kumar and Rajeshkarappa (2012) had observed that the shelling efficiency of maize was 98.51% was significantly higher when the moisture content of maize was 13 per cent. Nsubuga et al. (2020) reported that the optimum moisture content for shelling of maize crop was 13 per cent. Aremu et al. (2015) had observed that with increasing moisture content, shelling efficiency declined from 62.85% to 54.84 per cent.

Effect of cylinder speed and moisture content on grain damage of maize cob

An analysis of variance (ANOVA) for the percentage of grain damage is given in Table 8. The effects of all independent parameters (cylinder speed, moisture content) were significant, but their interaction was non-significant with SD and CV values of 0.34% and 5.98 per cent, respectively. Regression analysis indicated that R² was 0.97 and the adjusted R² was 0.95. Grain damages were 3.10%, 3.82%, 4.27% at cylinder speed of 150 rpm and grain moisture content of 12%, 14%, 16% (w.b.), respectively. Grain damage increased to 4.72%, 5.41%, 6.02% at cylinder speed of 200 rpm and grain moisture content of 12%, 14%, 16% (w.b.); and

Table 8. ANOVA on effect of cylinder speed and moisture content on grain damage of maize cob

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F-value</th>
<th>p-value</th>
<th>Sig.</th>
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<tbody>
<tr>
<td>Model</td>
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<td>4.19</td>
<td>35.39</td>
<td>&lt; 0.0001</td>
<td>S</td>
</tr>
<tr>
<td>A-cylinder speed</td>
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<td>1</td>
<td>6.30</td>
<td>53.29</td>
<td>0.0002</td>
<td>S</td>
</tr>
<tr>
<td>B-Moisture content</td>
<td>14.26</td>
<td>1</td>
<td>14.26</td>
<td>120.54</td>
<td>&lt; 0.0001</td>
<td>S</td>
</tr>
<tr>
<td>AB</td>
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<td>0.0441</td>
<td>0.3728</td>
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</tr>
<tr>
<td>A²</td>
<td>0.2320</td>
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<td>0.2320</td>
<td>1.96</td>
<td>0.2041</td>
<td>NS</td>
</tr>
<tr>
<td>B²</td>
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<td>1</td>
<td>0.2168</td>
<td>1.83</td>
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<td>Lack of Fit</td>
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<td>0.3881</td>
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<td>Std. Dev.</td>
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<tr>
<td>Mean</td>
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<tr>
<td>C.V. %</td>
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<tr>
<td>R²</td>
<td>0.9619</td>
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<tr>
<td>Adjusted R²</td>
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<td>Predicted R²</td>
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</table>

Note: SS: Sum of Square; df: degree of freedom; C.V: Coefficient of Variance; R²: Coefficient of determination; *p<0.05: significant at 5% level of significance, **p<0.01 significant at 1% level of significance, ***p<0.001: significant at 0.1% level of significance
further increased to 6.12%, 7.22%, 8.37% at cylinder speed of 300 rpm and grain moisture content of 12%, 14%, 16%, (w.b.), respectively.

The lowest and highest grain damage were 3.1% and 8.37% at cylinder speeds of 150 rpm and 300 rpm and moisture contents of 12% and 16% (w. b.), respectively. Grain damage increased (3.1% to 8.37%) with increases of cylinder speed (150 rpm to 300 rpm) and moisture content [12% to 16 per cent (w.b.)] (Fig. 10). Grain damage increased with increase in cylinder speed, as at higher cylinder speed the cylinder came into direct contact with maize cobs causing higher damage of grains.

Nsubuga et al. (2020) had reported that the percentage of damaged grain was 8.4 per cent. Increase in moisture content also increased the grain damage as maize cobs got stuck in the cylinder due to greater number of cylinder revolution. Alsharifi et al. (2019) had also reported that grain damage decreased with decrease in rotational speed.

Thus, considering the shelling rate, shelling efficiency, and minimum grain damage of maize cob reported above for the designed maize sheller, the best operating conditions were found to be cob moisture content of 12% (w. b.) and cylinder speed of 150 rpm that gave grain damage of 3.1 per cent.

CONCLUSIONS

An electric motor-operated maize sheller was designed and evaluated at cylinder speeds of 150, 200, and 300 rpm and grain moisture contents of 12%, 14%, and 16% (w. b.). Highest and lowest shelling rate were 96.9 kh.h⁻¹ and 90.92 kh.h⁻¹ at cylinder speed and moisture content of 300 rpm, 12% (w. b.) and 150 rpm, 16% (w. b.). Shelling efficiencies were 98.60% and 89.00% at 300 rpm, 12% (w. b.) and 150 rpm, 16% (w. b.). Grain damage was 8.37% and 3.1% at 300 rpm cylinder speed, 16% (w. b.) grain moisture content and 150 rpm, 12% (w. b.), respectively. With increase in grain moisture content, shelling rate and shelling efficiency decreased, and grain damage increased. With increase in cylinder speed, the shelling rate, shelling efficiency, and grain damage increased. At cylinder speed of 150 rpm and moisture content of 12% (w. b.), the machine operated with minimum grain damage of 3.10%, maximum shelling rate of 92.07 kg.h⁻¹, and shelling efficiency of 91.40 per cent. The payback period was 1.13 years, while the benefit-cost ratio was 1.01. The total manufacturing cost of the maize sheller was ₹ 10,235/-.

AUTHORS CONTRIBUTION

Gatkal Narayan Raosaheb: Conceptualisation, conduct of experiment, data analysis, writing- original draft.

Nalawade Sachin Madhukar: Supervision, editing–original draft

Pawase Pranav Pramod: Reviews, supervision

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest in any form that could have influenced the research work reported in this paper. Competing interest in disclosure of the research work has been considered by the authors.

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