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Development of a Mini-tractor Operated Onion De-topper cum Digger

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Harvesting of onion include multiple tasks such as de-topping, digging, soil separation and windrowing. Traditional methods of harvesting are labour demanding, tedious and time-consuming leading to increased labour cost and time. Labour shortages during peak seasons further delay harvesting, which affects product quality and profitability. To address these challenges, a mini-tractor operated onion de-topper cum digger was developed at GBPUA&T, Pantnagar. This intervention combines de-topping, digging, soil separation and windrowing in a single operation suitable for market needs, leading to reduced cost of cultivation and increased profitability among onion growers. The developed machine consists of a de-topping unit that removes onion leaves up to the neck, a digging unit that uproots the de-topped bulbs, a soil separation unit to separate soil adhering to the onions, a power transmission unit to drive de-topping and soil separation unit and a frame for attaching it to the tractor. A Finite Element Analysis (FEA) was also carried out to evaluate structural performance (maximum stress, strain and deflection) acting on the digging blade. Further, the influence of crop and operational parameters (moisture content of onion leaves, cutter bar speed and machine forward speed) on de-topping efficiency was also evaluated. Statistical analysis of the data obtained revealed that de-topping efficiency increases initially with an increase in independent parameters (moisture content of onion leaves, cutter bar speed and machine forward speed) but further increase in independent parameters decreases the de-topping efficiency. The developed machine demonstrated a theoretical field capacity of 0.20 ha/h, an actual field capacity of 0.17 ha/h and a field efficiency of 85%. The developed machine requires 5.88 h/ha costing Rs. 2145 which is 65.6% less than the manual method of harvesting (Rs. 6250/- per ha). The input energy requirement for both manual and machine-assisted (developed machine) were also analyzed, as they are crucial for reducing operational costs and improving the overall sustainability of onion harvesting. The analysis showed that the total input energy needed in manual and with the developed machine were 1381 and 1022 MJ/ha respectively.

Keywords: De-topping, FEA analysis, Mini-tractor, Onion harvester, Onion

Introduction

India is the world's second largest onion producer after China, with an annual production of 26.73 million tonnes cultivated over an area of 1.43 million ha.[1] In India onion alone contributes to 7.4% of total vegetable production among all vegetable crops.[2] However, the productivity of onion is 18.1 MT/ha, which is less than many developed and developing countries. This is because of several factors including a lack of modern crop production practices, low levels of mechanization and limited adoption of hybrid varieties from other regions. In addition to these factors, the use of traditional harvesting methods also significantly affects the productivity of onions.[3,4]

Therefore, the adoption of mechanized cultivation methods can address the issue of traditional harvesting and also enhance the crop yield both quantitatively and qualitatively.[5] Over the years, there have been developments in the mechanization of onion harvesting.[6] Although there have been several efforts made to mechanize onion harvesting, de-topping and digging are still labour-intensive operations that have received scant attention in the past.[4,7] In India, the traditional manual harvesting is done by pulling out plants with hands or digging with locally available tool (*khrupa*) requiring about 200–280 man-h/ha[8,9] performing the activity in an odd stooped posture. It consumes about 21.4% of the total production cost.[10,11] After harvesting the crop is field-cured. After field curing, a de-topping operation has to be performed in which onion leaves are manually wrenched up to their neck using hand shears. It demands substantial labour amounting to 12.5 man-h/ton, which accounts for approximately 40% of the total labour needed for the entire cultivation of the crop. Besides the de-topping operation needs to be performed within a short period.[4] Otherwise, if this

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period is prolonged it decreases the storage life of the onion significantly and also results in the formation of roots and sprouting of bulbs.[6,12]

Therefore, many mechanical solutions were considered for harvesting onions, the main one is the use of sophisticated onion combines.[13] But most of the Indian farmers cannot afford it and their farms are usually small and scattered**.** Some of the researchers worked on the removal of onion leaves during harvesting before digging.[12–16] However, these require two passes, which again incurs additional cost. But these machines are also not suitable for direct adoption under Indian conditions. Therefore many researchers worked on onion diggers suitable for Indian conditions[11,13,17,18,20] but confined to digging operation only and some are addressed soil separation operations too. None of the researchers addressed the de-topping, digging, soil separation and windrowing operation in a single pass.[21] Considering the above facts, an onion de-topper cum digger was developed and evaluated.

Materials and Methods

The study was conducted at G.B. Pant University of Agriculture & Technology (GBPUA&T) in the Department of Farm Machinery and Power Engineering, Pantnagar, during 2019–20. The developed machine comprised a de-topping unit, digging unit, soil separation unit, power transmission unit and a frame.

Functional considerations considered for the design of the developed machine are given below:

- The machine should de-top the standing onion leaves ahead of the digging unit to suit market standards (cleaned onion bulb)
- The de-topped onions should be dug by the digging unit and moved to the soil separation unit
- The onion damage (cut, sliced and bruised) during de-topping, digging and soil separation should be minimum
- It can be operated by a mini-tractor size of 15–20 hp range a most common mini-tractors owned by Indian farms

Design of the Functional Units

De-topping Unit

A standard cutter bar having a stroke length of 76.2 mm was used as a de-topping unit. This width of the de-topping unit was selected based on the track width of the mini-tractor. The cutter bar assembly was made up of serrated trapezoidal blades riveted on 25 × 5 mm MS flat, these blades will reciprocate between ledger plates fixed on a 40 × 40 × 10 mm angle iron to cut and divide onion leaves from bulbs. An extension was provided at one end of the cutter bar to attach a connecting rod to drive it from the gearbox through belts and pulley arrangement. This whole arrangement gives a single knife standard cutter bar and will be beneficial as it is less weight and requires less power than a double knife cutter bar. The reciprocating cutter bar was selected over an impact cutting because it provides controlled, gradual cutting and ensures clean removal of leaves without harming the bulbs. The entire assembly was positioned 150 mm ahead of the digging unit to de-top onion leaves before uprooting the bulbs. This arrangement ensure the de-topping was completed before the digging operation.[4,6,7,14] The assembly also had a provision to adjust the height of the cut (1–5 cm) of onion leaves as needed through different slots provided and lock with nuts and bolts where needed. The crop biological parameters like moisture content of leaves, number of tillers per plant, bulb crown diameter and cutting force required to cut the onion leaves were considered for development of the de-topping unit.[22]

Digging Unit

The digging unit featured a blade specifically designed to uproot de-topped onion bulbs along with the surrounding soil. The blade width was selected according to the track width of the mini-tractor. The draft acting on the digging blade was calculated based on the passive resistance acting upon it as suggested[23], and it was found 145 kg. The blade thickness was also determined based on the load acting on it [24] and it was found 8 mm. These values were used to develop the digging unit according to the power requirements.

Determination of Draft Acting on the Digging Blade

The passive resistance (Pp) acting on a digging blade which deforms the soil in two dimensions was initially calculated using the equation as suggested [23]

$$Pp = \gamma {Z_1}^2 N_r + C Z_1 N_c$$

where, γ is the bulk density of soil (1600 kg/m^3); Z_1 is the operating depth (0.10 m); C is the soil cohesion (1200 kg/m^2); N_γ is 1.49 and N_c is 1.66 (N- factors for the angle of soil metal friction ($\delta = 20°$) and internal friction ($\alpha = 25°$)

Substituting these values, the value of P_P is 120.94 kg/m

$$Pp = 1600 \times (0.10)^2 \times 1.49 + 1200 \times 0.07 \times 1.66$$
$$= 223.04\ kg/m$$

For a share width (b) of 0.65 m is P_P = 223.04 × 0.65 = 144.976 ≈145 kg

Then, the horizontal draft is given by $D_h = P_p \sin(\alpha + \delta) = 145\ sin\ (25 + 20)$ = 102.5 kg

The force acting parallel to blade face is $P_{p1} = p_P \cos\ (90 - \delta) = 145 \times \cos 70 = 49.59\ kg$

The force acting perpendicular to the blade face is $P_{P2} = P_P \cos\ \delta = 145 \times \cos 20 = 134.85\ kg$

Determination of Thickness of Digging Blade

The blade thickness was determined based on the load exerted on it. According to (Bernacki *et al*. 1972)[24], the mean soil resistance acting on the blade is applied at a distance of 0.2 Z_1 from the cutting edge. This places the center of resistance 14 mm from the cutting edge, with the blade fixing point at 100 mm. Consequently, the effective lever arm was calculated.

L= 100−14 = 86 mm

Then, bending moment due to P_{p2} is $B.M = P_{P2} \times L = 134.85 \times 86 \times 9.8 = 113651\ \text{N} - \text{mm}$

Then bending stress (σ_b) acting on the blade is

$$\sigma_b = \frac{B.M}{\left(\frac{1}{6}\right) b \times t^2} = \frac{113651}{\left(\frac{1}{6}\right) 150 \times t^2} = \frac{113651}{25t^2}$$

where, b is width of blade (150 mm) and t is the thickness of blade (mm)

The direct stress (σ_d) is $\sigma_d = \frac{P_{P1}}{bt} = \frac{49.51}{150 \times t}$

Then, total stress is σ = (σ_b+ σ_d) × factor of safety (1)

Then, equating total stress with safe stress of MS (70 MPa)

$$70 = \left[\frac{113651}{25t^2} + \frac{49.51}{150 \times t}\right] \times 1$$

Solving the above expression, we will get t= 8 mm

Based on the above recommendations, a 'V-shaped' blade made of mild steel (MS) flat was selected for uprooting onion bulbs. The V-shaped blade was selected due to it requires less draft compared to other blade geometries.[11] The mild steel material was selected for blade design because of its cost-effectiveness and ease of fabrication. The rear end of the blade was firmly fixed to a base plate using nuts and bolts. Two flat plates were welded perpendicular to both sides of the base plate, having slots to enable adjustment of the digging blade's rake angle between 10–20°. A 2 mm thick MS sheet was also welded on each side of the blade to direct the excavated material toward the soil separation unit.

Calculation of Power Requirement for Developed Machine

The power requirement for the developed machine was calculated by considering the draft acting on the digging blade was 145 kg. Since the blade is a major soil working component and is likely to encounter unpredictable soil conditions, a factor of safety of 3 was taken. This resulted in a total draft of 435 kg acting on the digging blade. The maximum operating speed of the machine was 3 km/h (0.83 m/s) then the power requirement for operating the machine was calculated using the following formula.[27]

$$\text{Power required (hp)} = \frac{\text{Draft (kg)} \times \text{Speed } \left(\frac{\text{m}}{\text{s}}\right)}{75}$$

$$= \frac{435 \times 0.83}{75} = 4.81\ \text{hp}$$

Considering a tractive efficiency of 80%, the required power (481/0.80) is 6 hp. Based on the calculated power requirement and market availability, a mini tractor with a 15–20 hp power range is considered the most suitable option for operating the developed loped machine.

Finite Element Analysis (FEA) *of Digging Blade*

To study the behavior of a digging blade under external forces, Finite Element Analysis (FEA) was carried out in SolidWorks software (Version, 2018). The digging blade experiences fluctuating digging resistance during actual field conditions due to variations in soil conditions. However, this simulation analysis was done by assuming constant load acting throughout the operation. The material properties of the mild steel used for the fabrication of the blade in this simulation study includes a yield strength of 6.20×10^8 N/m², tensile strength of 7.23×10^8 N/m², elastic modulus of 2.1×10^8 N/m², Poisson's ratio of 0.28, mass density of 7700 kg/m³ and shear modulus of 7.9×10^{10} N/m². These properties are essential in accurately predicting the blade's response to external forces.

Soil Separation Unit

The main function of the soil separation unit is to separate soil and other adhered impurities from the onions. As the machine moves forward, the de-topped onions along with the soil dug by the digging unit are conveyed onto the soil separation unit where soil adhered to the onion bulb will separate. A rectangular sieve having a size of 700×550 mm was used as the soil separation unit. This sieve was placed at an inclination of 15° from the blade to avoid contact with the ground. It consisted of two passive rollers on which a 50 mm thick rayon endless belt continuously rotates in the opposite direction to the machine's forward direction. The belt ply was chosen based on the volume of material excavated by the blade and transferred to the soil separation unit.[17] The mild steel flats of 20×550 mm were fixed perpendicular to the rayon endless belt with a 250 mm gap between them, allowing soil to pass through them while retaining the onions. The spacing of the gaps was decided based on the equatorial and polar diameters of the onions. Two sprockets with 15 teeth were provided with a 25.4 mm chain to drive the rollers and prevent slippage. The length (70–75 cm) and slope (10–20°) of the soil separation unit can be adjusted as needed. The angle of repose of the onion was considered to determine the slope of the soil separation unit. The width of the soil separation unit was decided based on the width of the digging blade.

Determination of Length of Soil Separation Unit

The length of the soil separation unit was decided based on the total volume of material dug, taking into account the width of the digging blade (650 mm), depth of operation (100 mm) and maximum forward speed (3 km/h). Then,

$$\text{Volume of soil dug } (\text{m}^3/s) = \text{Width of share (m)} \times \text{Depth of operation (m)} \times \text{Forward speed } (m/s)$$

$$= 0.65 \text{ m} \times 0.10 \text{ m} \times 0.83\ m/s = 0.053 \text{ m}^3/s$$

The weight of soil excavated was calculated assuming, soil bulk density as 1600 kg/m^3

Weight of soil excavated (kg/s) = Volume of soil dug out (m^3/s) × soil bulk density (kg/m^3)
= 0.053 × 1600 = 84.8 kg/s.

Considering the inter and intra-row spacing of the crop (150 mm and 100 mm respectively and the average weight of the onion was 70g, the onion dug over a second was calculated as

$$\text{Number of plants dug out} = \frac{650}{100} \times \frac{0.55}{150} = 5.14$$

Weight of onions = 5.14 × 0.07 kg = 0.36 kg/s
Thus, total weight of material (Q_{out})= weight of soil dugout (84.8 kg/s) + weight of onions (0.36 kg/s)
= 85.16 kg/s

For determining length of soil separation unit, it was assumed that material spread over a 6 cm thick uniform layer. Then, soil separation unit length (L) was determined using the equation.

$$Q_{out} = \text{Soil density} \times \text{L} \times \text{thickness of material} \times \text{conveyor speed}$$

$$85.16\ kg = 1600\ \left(\frac{kg}{m}\right) \times L\ (m) \times 0.05\ m \times 1.2\ m/s$$

$$L = \frac{85.16}{1600 \times 0.06 \times 1.2} = 0.73 \approx 70\ m$$

Based on these soil separation unit was taken as 70 cm to accommodate the material flow efficiency.

Design of Power Transmission Unit

The primary purpose of the power transmission unit is to transfer power from the tractor's PTO to the de-topping and soil separation units at the desired speeds. It consisted of a gearbox, flat and cross belts and pulleys as shown in Fig. 1. A gearbox with a 1:1 speed ratio was employed to transfer power from the tractor's PTO shaft to the output shaft. The output shaft extended sideways and was equipped with a pulley for power transmission.

Drive for Soil Separation Unit

Speed at pulley 1 (N_1) = 540 RPM (Rpm at PTO), Diameter of pulley 1 (D_1) = 76.2 mm

Speed at pulley 2 (N_2) = 180 RPM, Diameter of pulley 2 (D_2) = 228.6 mm

Speed ratio at soil separation unit = $\text{S.R}_c = \frac{N_1}{N_2} = \frac{540}{180} = 3:1$

The power from the gearbox shaft pulley to the soil separation unit shaft pulley was transmitted through 'B' type V-cross belt and pulley mechanism having a speed ratio of 3:1. The soil separation unit belt rotates rollers in opposite directions. Hence, the material will be conveyed to the rear end for windrowing.

Drive to the De-topping Unit

Speed at pulley 3 (N_3) = 180 RPM, Diameter of pulley 3 (D_3) = 254 mm

Speed at pulley 4 (N_4) = 450 RPM, Diameter of pulley 4 (D_4) = 101.6 mm

Speed at pulley 5 (N_5) = 225 RPM, Diameter of pulley 5 (D_5) = 203.2 mm

Speed ratio at de-toppingunit pulley $S.R_t =$

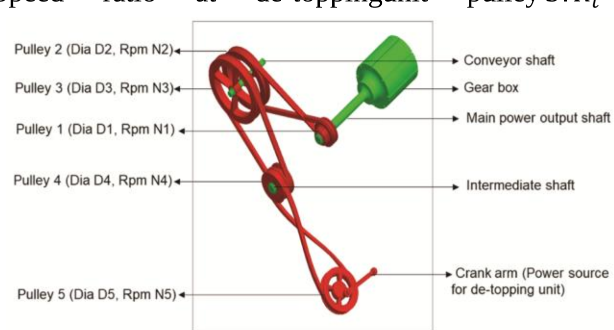

Fig. 1 — Power transmission view of developed machine

$$\frac{N_1 \times N_2 \times N_3 \times N_4}{N_2 \times N_3 \times N_4 \times N_5}$$
$$\frac{540}{225} = 2.4:1.$$

From the soil separation unit shaft pulley, the power was transmitted to the intermediate shaft pulley. This intermediate pulley has a driver pulley, from this pulley power was transmitted to the de-topping unit sieve pulley having a speed ratio of 2.4:1 and the cross belt having belt size B 55 was used for this purpose.

Main Frame

The main frame carries all the components (de-topping, digging, soil separation, power transmission and windrowing unit). The frame was fabricated with angle iron and a three-point hitch was made with 40×10 mm flats for attaching the machine to the tractor. The rear end of the frame was provided with wheels (25.4 cm dia) for transportation purposes. The overall dimensions of the developed machine were 1200 ×1050 × 800 mm.

Developed Machine and Its Working Principle

The schematic views of the designed machine are shown in Fig. 2 and the detailed specifications of the developed machine are presented in Table 1. When

Table 1 — Detailed specifications of developed onion de-topper cum digger

Components	Specifications
De-topping unit	
Type of de-topping	Reciprocating cutter bar
Working width, mm	750
Speed ratio	2.4:1
Shape of cutting blade and type	Trapezoidal and serrated
Diameter and speed of crank pulley (mm, rpm)	203 and 225
Digging unit	
Length × Width × Thickness, mm	650 × 150 × 80
Shape of digging blade and material	V-shaped and mild steel
Rake angle of blade, degree	15
Soil separation unit	
Length × Width, mm	700 × 550
Slope of soil separation unit, degree	15
Width × length × thickness of M.S. flat, mm	20 × 550 × 10
Spacing between flats, mm	25
Windrower, Length × Width, mm	800 × 550
Gearbox speed ratio	1:1
Overall dimensions of the machine, mm	1200 ×1050 × 800
Total weight of machine, kg	135

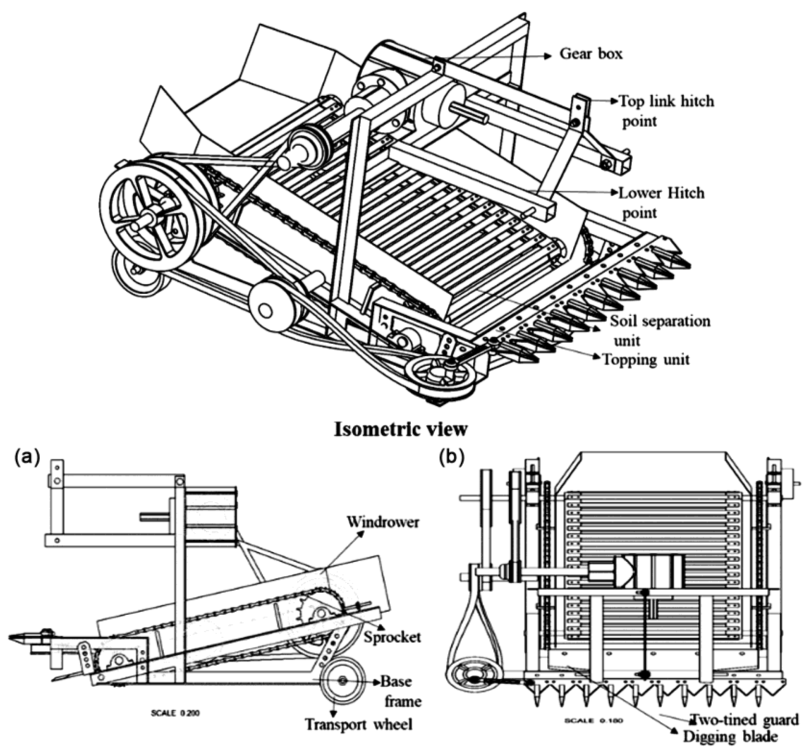

Fig. 2 — Different views of designed machine

operated in the onion field, the machine initially removes the onion leaves up to the bulb's crown area (de-topping) with a de-topping unit. This unit was provided in such a way that when a digging unit penetrates a 100 mm depth, the de-topping unit will exactly touch the upper surface of the ground. It aligns exactly with the stem of the plant at the crown area of the bulb. The de-topping unit is mounted 150 mm ahead of the digging unit, allowing it to remove the onion tops (leaves) initially. After de-topping, the bulbs are dug up by the digging unit. The dug bulbs along with the soil move to the soil separation unit. In this, the soil adhered to the onions are separated. Finally, the cleaned onion bulbs are discharged by the windrowing unit at the rear end of the machine. The flow chart of the working of the developed machine is shown in Fig. 3.

Field Evaluation of the Developed Onion De-topper cum Digger

The actual performance of the onion de-topper cum digger was field evaluated at the Vegetable Research Center (V.R.C.), GBPUA&T, Pantnagar, India, during 2019–20. Field evaluation was conducted under three different independent parameters, moisture content of onion leaves (10, 12 and 14% (db)), cutter bar speed (1, 1.5 and 2 m/s) and forward speed of the machine (1.5, 2.0, and 2.5 km/h). The de-topping efficiency was evaluated using a full factorial design with 27 experimental runs, each replicated three times and analyzed using SPSS software (Version 29.0.1.0; IBM Corp., Armonk, NY). An Analysis of Variance (ANOVA) was conducted to determine the significance of the independent variables on the response variables at 5 and 1% levels of significance. Further Dunccan's test was used to compare the means of multiple groups. The different levels of independent parameter values such as the moisture content of onion leaves were maintained in the range of 10–14% (db) through natural drying and controlled irrigation practices. The selected range is consistent with previously reported values for post-harvest curing and mechanized handling of onions.[25] Different cutter bar speed was achieved by changing different speed ratios with varying pulley sizes (0.16, 0.12 and 0.08 m), this range was recommended in other crops[26] and different forward speeds of the machine were achieved by operating it at different tractor gears. The response (de-topping efficiency) was measured by demarcating one square meter area at three randomly selected places in each treatment after an experimental test run. Then the responses were analyzed by using the following procedures.

De-topping Efficiency (η_{DT}): It is the ratio of the number of onion bulbs topped to the total number of onion bulbs performed for de-topping, it is expressed as a percentage and determined using the following equation.[16]

$$De-topping\ efficiency\ (\%) = \left(\frac{N_{To}}{N_T}\right) \times 100$$

where, N_{To} is number of topped onion bulbs; N_T is total number of onions performed for de-topping

Determination of Machine Performance Parameters

Theoretical Field Capacity

Theoretical field capacity was calculated based on the width of the digging blade and travel speed using the following equation.[27]

$$\text{Theoretical field capacity (ha/h)} = \frac{\text{Width of operation (m)} \times \text{Travel speed (km/h)}}{10}$$

Effective Field Capacity

It is the actual time required by the machine to perform a specified operation. Effective field capacity was calculated using the following equation.

$$\text{Effective field capacity (ha/h)} = \frac{\text{Actual area covered (ha)}}{\text{Total time taken to cover the area (h)}}$$

Field Efficiency

The field efficiency of the developed machine was calculated by using the following equation.

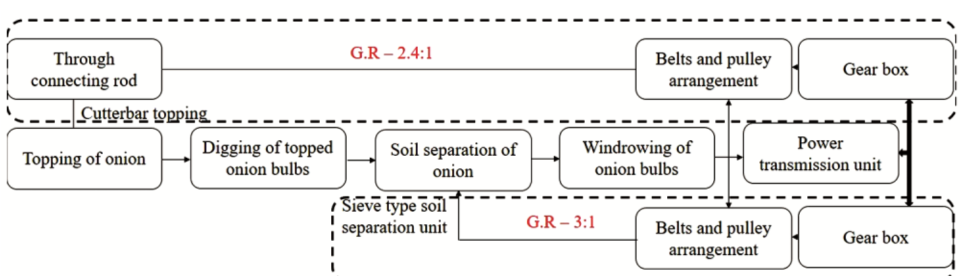

Fig. 3 — Working of the developed Onion Digger integrated with De-topping Unit

$$\text{Field efficiency (\%)} = \frac{\text{Effective field capacity (ha/h)}}{\text{Theoretical field capacity (ha/h)}}$$

Cost Economics of Developed Machine

The resilience of a machine depends mainly on its performance, cost of operation and percent saving in cost over the existing method. In this context, the cost of operation of a mini-tractor operated onion de-topper cum digger was calculated based on the Indian standards guide for estimating the cost of farm machinery[28] and this cost was compared with the manual harvesting. For manual harvesting, the number of labour hours required per hectare was determined and used as a basis for the cost estimation calculations.

Energy Expenditure in Manual and Mechanical Methods of Onion Harvesting

In any farm operation, it is essential to understand the energy consumption pathways and the amounts of energy used in both manual and mechanical methods. This helps to identify ways to reduce energy input for specific tasks, thereby improving energy production efficiency. Reducing energy consumption in crop production can increase crop productivity per unit area by optimizing input use. Therefore, in this study the input energy requirements for harvesting onions using both manual and mechanical methods were computed to understand the pathways and explore opportunities for reducing energy consumption.

Manual Harvesting Method

In this method, the onion plants were plucked and gathered in the middle of the bed manually for windrowing the crop for field curing. After field drying, the onion plants are de-topped. During the experiment, the time required per unit area was calculated and the time required per hectare was determined. Then, the energy expenditure in the manual method was computed using the following formula[29]

$$E_m = 1.96\, N_m T_m$$

where, E_m is manual energy expended (MJ/ha), N_m is the number of labour required for activity, T_m is effective time spent by labour on an activity (h/ha).

Mechanical Harvesting Method

In the mechanical method of harvesting onion, the developed onion de-topper cum digger was used, it can efficiently de-top onion leaves and dugs up de-topped onion bulbs, separate them from the soil and windrow on the field. In this study, the mechanical energy utilized in the mechanical harvesting of onions was computed by the following formulas.[30,31]

The assumptions considered for calculation were prime mower used was a 20 (14.92 kW) hp tractor having 1200 kg weight with 10 years of lifetime and 1000 hr annual use with fuel consumption 3 l/h. The implement is an onion de-topper cum digger weight 150 kg with life and annual uses are 6 years 250 h with a speed of operation of 3.5 km/h.

$$\text{Prime mower energy}, (MJ/ha) = \frac{W_P \times 68.4 \times H_P}{L_P \times AU_P}$$

$$\text{Machine energy}, (MJ/ha) = \frac{W_m \times 62.7 \times H_m}{L_m \times AU_m}$$

where, W_P and W_m are prime mower and machinery mass to be contributed towards the activity (kg), H_P and H_m are hours of usage of prime mower and machine for a particular activity (h/ha), L_P and L_m are life of prime mower and machine (years), AU_p and AU_m are annual use of prime mower and machine (h), L_p and L_m are life of prime mover and machine (years).

$$Fuel\ (diesel) energy\ (MJ/ha) = 56.31\, D$$

where, D is the amount of fuel (diesel) consumed (l/ha).

Results and Discussion

The field operation of the developed mini-tractor operated onion de-topper cum digger was shown in Fig 4. During the evaluation average crop parameters at the time of harvest were measured and recorded. These included the shape index found to be 1.01, which is the ratio of the polar to the equatorial diameter and is an important parameter consideration for designing the soil separation unit. Other parameters measured were bulk density (561 kg/m³), plant height (28.76 mm), the number of tillers per plant (5), onion bulb depth (6.54 cm) and the weight

Fig. 4 — Field performance evaluation of onion de-topper cum digger

of bulbs with leaves (60.03 g) and without leaves (45.64 g).

Structural Analysis Verification using Finite Element Analysis on Digging Blade

The stress, displacement and strain experienced by the digging blade in FEA are depicted in Fig 5. The maximum and minimum stress values acting on the digging blade were 4.89×104 N/m^2 and 2.97×106 N/m^2 respectively. These values fall below the yield stress (6.204 ×108 N/m^2) of the mild steel utilized for the fabrication of the blade in the developed machine. Moreover, the maximum and minimum resultant displacement and strain values recorded on the digging blade were 2.73×10^{-7} and 0 and 9.729×10^{-6} and 7.309×10^{-5} N/m^2 respectively. These results suggest that the blade is capable of withstanding the expected load without any significant deformations or material failure.

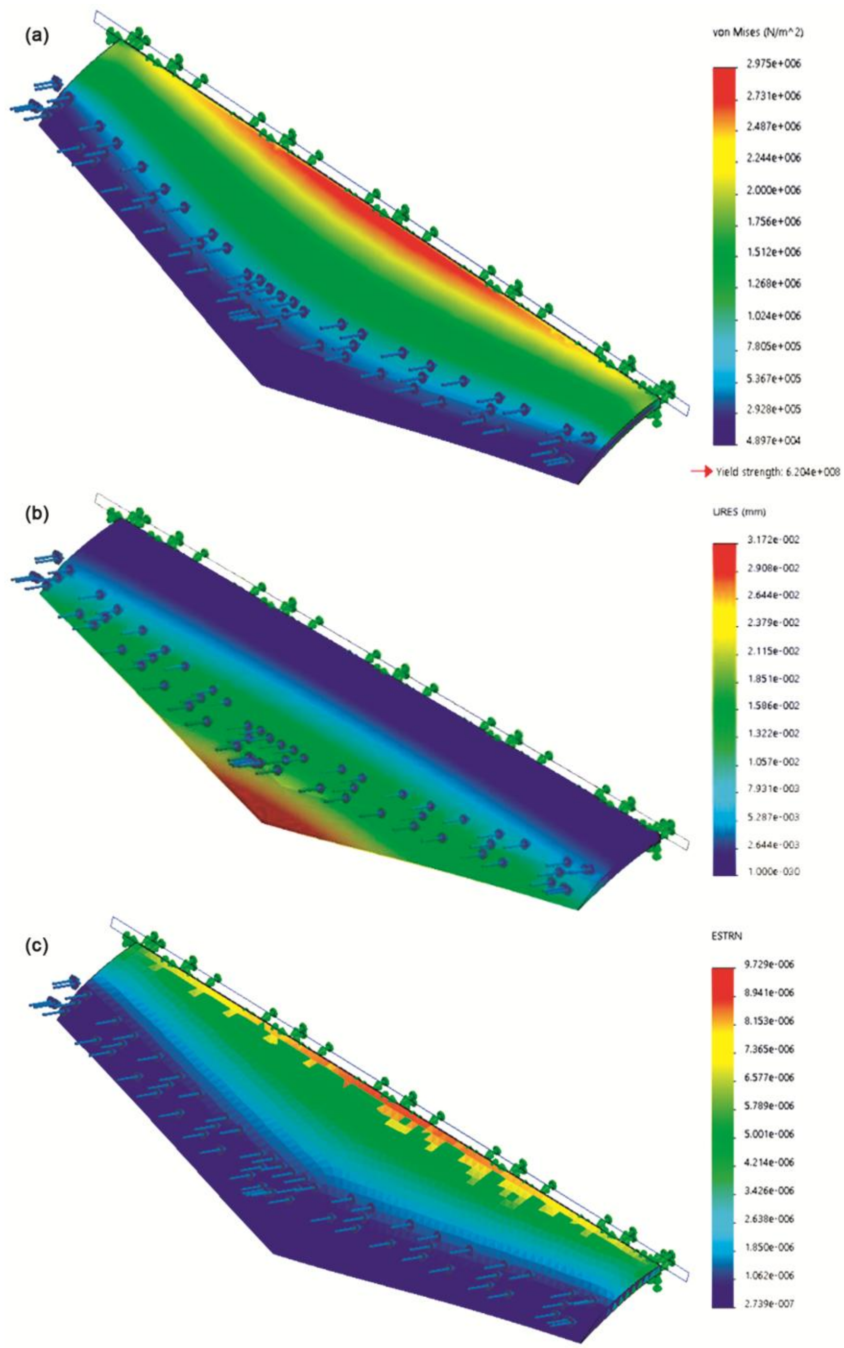

Fig. 5 — (a) Distribution of stress (b) distribution of displacement (c) distribution of strain over the digging blade

Table 2 — Results of ANOVA analysis for de-topping efficiency

Source	SS	Df	MSS	F-Value
Model	3534.06	26	135.93	43.91**
Moisture content of onion leaves (A)	2419.42	2	1209.71	390.77**
Cutter bar speed (B)	656.87	2	328.43	106.09**
Forward Speed of Machine (C)	330.77	2	165.38	53.42**
AB	40.81	4	10.20	3.30*
BC	17.52	4	4.38	1.41
CA	33.73	4	8.43	2.72*
ABC	34.94	8	4.37	1.41
Error	160.98	52	3.10	
Total	3695.96	80	46.20	
Corrected total	2.358			

*, ** indicates significant at 5 and 1% respectively

Effect of De-topping Efficiency with Different Independent Parameters

The analysis of variance (ANOVA) for the different independent parameters and their interactions on de-topping efficiency were studied and the results are presented in Table 2. The table indicates the individual effects of moisture content of onion leaves (A), cutter bar speed (B) and forward speed (C) are highly significant at a 99% confidence interval ($P \leq 0.01$). Additionally, the interaction between the moisture content of onion leaves and cutter bar speed (AC), as well as the interaction between the moisture content of onion leaves and forward speed (AB), were found significant at a 95% confidence interval ($P \leq 0.05$). Other interactions were found to be non-significant.

The effects of moisture content of onion leaves, cutter bar speed and forward speed of the machine on de-topping efficiency shown in Fig. 6. The Duncan's test results indicate the significant differences in the mean values of de-topping efficiency across different independent variables at both the 1 and 5% significance levels. From, Fig. 6 it can be observed that the de-topping efficiency of onions initially increased with an increase in moisture content of onion leaves, cutter bar speed and forward speed of the machine. However, beyond certain values, further increases in these independent parameters led to a decrease in de-topping efficiency. The variations in de-topping efficiency with various independent parameters (moisture content of onion leaves, cutter bar speed and forward speed of the machine) are presented in Table 3.

At a forward speed of machine 2 km/h, the de-topping efficiency was found as 79.27 – 81.87%, 77.60 – 83.95% and 68.73 – 73.15% respectively at respective moisture contents of onion leaves (10, 12 and 14% db). The higher de-topping efficiency at 12 (% db) moisture content of onion leaves and lower de-topping efficiency in cases of 10 (% db) and 14 (% db) were observed. This can be attributed to variations in plant strength due to different moisture contents. Lower moisture content increases plant

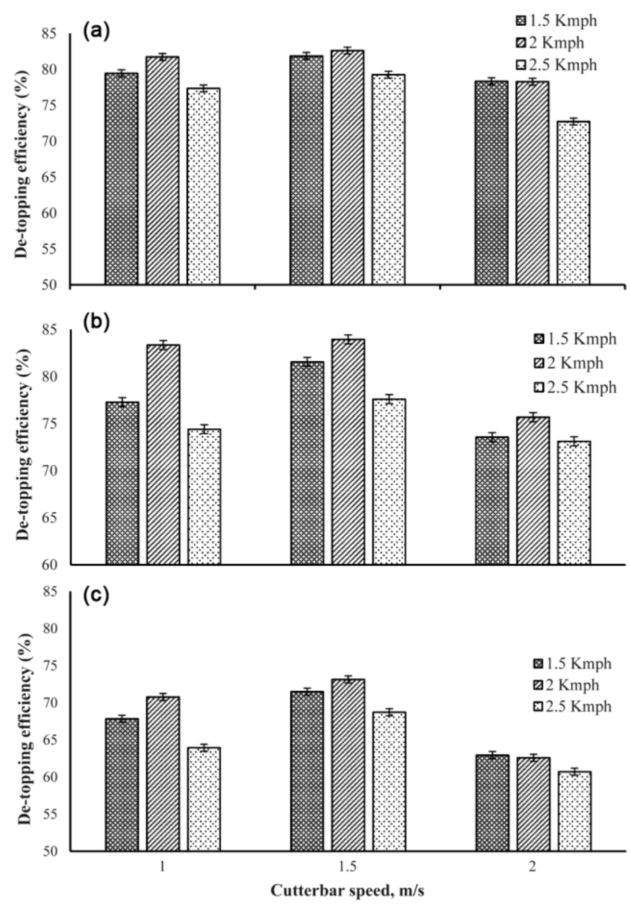

Fig. 6 — Effect of cutter bar speed, forward speed and (a) moisture content of levees at (10 % db), (b)12 (% db) and (c) (14% db) on de-topping efficiency

Table 3 — Variation of de-topping efficiency on different independent parameters

Independent parameters			Response
Moisture content (% db)	Forward speed (km/h)	Cutterbar speed (m/s)	De-topping efficiency
10 (% db)	1.5	1	79.46
	1.5	1.5	81.73
	1.5	2	77.35
	2	1	81.87
	2	1.5	82.61
	2	2	79.27
	2.5	1	78.35
	2.5	1.5	78.28
	2.5	2	72.74
12 (% db)	1.5	1	77.28
	1.5	1.5	83.36
	1.5	2	74.40
	2	1	81.56
	2	1.5	83.95
	2	2	77.60
	2.5	1	73.56
	2.5	1.5	75.68
	2.5	2	73.12
14 (% db)	1.5	1	67.84
	1.5	1.5	70.79
	1.5	2	63.94
	2	1	71.49
	2	1.5	73.15
	2	2	68.73
	2.5	1	62.94
	2.5	1.5	62.59
	2.5	2	60.72

strength due to higher internal turgor pressure, thus reducing de-topping efficiency. Conversely, excessive moisture content causes the onion tops to slip in the cutter bar, leading to decreased efficiency. A similar trend was observed in the Bengal gram harvester[32] and the maize harvester.[33]

As depicted in Fig. 6, de-topping efficiency increases with an increase in forward speed, but further increments in forward speed decrease the de-topping efficiency. For example, at a 12 (% db) moisture content of onion leaves the de-topping efficiency was found to be 74.40–83.36%, 77.60–83.95%, and 73.12–75.68% at forward speeds of 1.5, 2 and 2.5 km/h respectively. This can be attributed to the fact that a lower forward speed of the machine results in a lower cutter bar speed, causing it to miss the onion tops. Conversely, at very high forward speeds, the crowded plants (number of plants handled per unit time) may experience high dynamic cutting forces, which lowers de-topping efficiency. Additionally, higher forward speeds may result in

Table 4 — Cost economics of the developed machine and manual harvesting

Costs	Amount
Developed machine	
Total fixed cost of tractor (depreciation, intrest, insurance and housing)	Rs. 87.62/h
Total fixed cost of onion de-topper cum digger (depreciation, intrest, insurance and housing)	Rs. 28.25/h
Variable cost of tractor (repair and maintenance)	Rs. 8.8/h
Variable cost of developed machine (repair and maintenance)	Rs. 4.50/h
Variable cost (tractor + onion de-topper cum digger) (fuel consumption, lubrication and operator wages)	Rs. 235.5/h
Total cost of operation with the developed machine	Rs. 364.67/h
Total cost of operation (including field capacity of machine)	Rs. 2145/ha
Manual harvesting	
Total cost involved in harvesting	Rs. 6250/ha

some onion tops being missed leading to uneven de-topping. These results are in line with a study by Wingate-Hill.[16]

It was observed that the de-topping efficiency increased initially with an increment of cutter bar speed further increment of cutter bar speed, the de-topping efficiency was decreased. At 12% (db) moisture content of leaves and 2 km/h, the de-topping efficiency values are 81.56, 83.95 and 77.60% respectively at respective cutter bar speeds of 1, 1.5 and 2 m/s. This is due to a lower cutter bar speed increasing the cutting resistance of plant attributes to decreased de-topping efficiency also, at a lower cutter bar speed, the onion leaves flatter and crush, which requires higher resistance towards cutting of onion leaves. A similar trend was observed by Sahoo & Raheman[26] in the paddy crop.

Cost Economics of Developed Machine

The total cost economics of the developed machine is presented in Table 4. The cost of operation for the tractor was calculated assuming an initial purchase price of Rs. 500000 a salvage value of 10% of the initial cost and a lifespan of 10 years (10000 hours). The fixed costs for the tractor included depreciation (Rs. 45/h), interest (Rs. 33/h), insurance and taxes (Rs. 5.5/h), and housing (Rs. 4.1/h) resulting in a total fixed cost of Rs. 87.62 per hour. Additionally, the variable cost for repair and maintenance was calculated as Rs. 8.80 per hour. For the onion de-topper cum digger, the initial investment was Rs.

Table 5 — Input energy requirement in harvesting of onions

Particulars	Developed machine	Manual harvesting method (Including all operations) (A)	Increase (+) or decrease (−) over manual harvesting method (%) {(A-B)/(B)}* 100
Total time required, man-h/ha	37	704.79	−94.75 %
Total energy (human as well as mechanical consumption, MJ/ha)	1022.07	1381.37	−26.01 %

31500 with a salvage value of 10% of the initial cost and a lifespan of 6 years (1500 hours). The fixed costs included depreciation (Rs. 18.9/h), interest (Rs. 8.31/h), and housing (Rs. 1.03/h) amounting to a total of Rs. 28.25 per hour. The variable cost for repair and maintenance of the developed machine was calculated as Rs. 4.50 per hour. The combined variable costs for the tractor and implement included fuel consumption (Rs. 180/h), oil consumption (Rs. 18/h), and operator wages (Rs. 37.5/h). The total operational cost for the tractor and implement was calculated as Rs. 364.67 per hour. With an effective field capacity of 0.17 ha/h, the cost of operation was Rs. 2145 per hectare, which is significantly lower than the cost of manual harvesting, estimated at Rs. 6250 per hectare.

The developed mini-tractor-operated onion de-topper cum digger requires 5.88 hours per hectare. The cost associated with operating the onion de-topper cum digger was Rs. 2145 per hectare, whereas the cost of manual digging and collection was Rs. 6250 per hectare (Table 4). This shows a cost saving of Rs. 4105 per hectare, corresponding to a 65.68% reduction in cost using the developed mini-tractor-operated onion de-topper cum digger compared to the conventional manual method.

Input Energy Requirement in Manual and Mechanical Methods of Onion Harvesting

The result of the study showed that the total input energy requirement in manual and mechanical method onion harvesting was 1381.37 and 1022.07 MJ/ha. In the mechanical method of onion harvesting, the greatest input energy was diesel, followed by humans, prime mover and machinery. The input energy requirement in manual and mechanical methods of onion harvesting is presented in Table 5.

Conclusions

The moisture content of onion leaves mostly affects the de-topping efficiency of crop followed by forward speed and cutter bar speed. The theoretical field, actual field capacity and field efficiency of the machine were calculated and found to be 0.20 ha/h, 0.17 ha/h and 85%, respectively. The developed machine requires 5.88 h/ha costing Rs. 2,145 per ha which is 65.6% less than the manual method of harvesting (Rs. 6250/- per ha). The developed machine can be adapted for other root crops (potato, garlic, carrot) with minimal adjustments. It is a dependable solution, as cost and input requirement savings are 65.68 and 26% respectively over the conventional manual method of onion harvesting. In the future, a root crop combine for Indian scenario can be developed to suit various root crops and deliver the harvested product in accordance with market requirements.

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