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Development and performance evaluation of a tractor operated Chinese potato harvester

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Abstract

Manual harvesting of Chinese potato tubers is labour intensive, time consuming and tedious. An average of 100 female labourers and 20 male labourers are needed to harvest one acre of Chinese potato tubers. To mitigate labour shortages and to reduce harvesting costs, a tractor operated prototype Chinese potato harvester has been designed and developed to harvest the tubers grown in ridge and furrow system. The harvester comprises of a main frame, digging system, discharge system, power transmission system and transport system. It can cover three ridges with a spacing of 30 cm and a depth of operation of 15 cm. The performance evaluation of the developed unit was conducted, and the operational parameters were standardized. The digging unit of the harvester was tested with different treatment combinations of blade geometries *viz*., inverted V shape, crescent shape and straight type blade at different rake angles of 15, 20 and 25° and at different forward operating speeds of 1.5, 2.0 and 2.5 km h^{-1}. The effects due to these parameters were optimized based on performances parameters *viz*., digging efficiency, per cent damage and fuel consumption by numerical optimization technique. The maximum digging efficiency of 97.28 per cent was noticed for inverted V type digging blade, whereas the lowest of 82.37 per cent was obtained for straight shaped blade. The least percent damage of 3.42 per cent was for the inverted V shape blade and the highest of 9.91 per cent was recorded for straight blade. Among the different types of blade geometry, the maximum (6.24 l h^{-1}) and minimum (4.75 l h^{-1}) fuel consumptions were obtained for straight blade and inverted V shape blade, respectively. The cost per hectare of harvesting using the developed harvester was determined to be ₹ 18,400/- per hectare compared to ₹ 1,12,500/- for harvesting manually, with a cost savings ₹ 94,100/- per hectare.

Keywords: Chinese potato, Harvester, Manual harvesting, Labour shortage, Mechanical harvesting

Introduction

Chinese potato (*Plectranthus rotundifolius*) is one among the minor tuber crops that is under-exploited and believed to be originated in Africa. Its cultivation is now spread to Sri Lanka and Southeast Asia (Harlan et al., 1976; Agyeno et al., 2014). It is one of the important minor tropical tuber crops cultivated in India for edible purpose. In India, it is mainly cultivated in Kerala (Thrissur, Palakkad, Kasaragod and Kannur districts) and Tamil Nadu (Tirunelveli, Tenkasi, Tuticorin, Virudhunagar and Kanyakumari districts. It is an aromatic tuber crop with approximately

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18-20% starch by fresh weight. The tubers have medicinal properties due to their high flavonoid content. Terpenoids contribute to the characteristic flavour of Chinese potato. The crop is propagated by stem cuttings. Stem cuttings are raised from nursery beds using healthy seed tubers of Chinese potato.

Harvesting is the most labour-intensive process in the agricultural sector. Time and availability of labour determines the price of the harvest. Harvesting of Chinese potato tubers usually takes places when the vines dry up at 4 to 5 months after planting. At present, Chinese potato tubers are harvested manually using spade. The average yield of tubers per acre is 10 tonne. For harvesting one acre of land, it requires around 100 female labourers and 20 male labourers. This has been found to be a tedious, laborious, and time-consuming process with high cost of production. The increasing non-availability of skilled labour for this work and the prevailing higher harvesting charges demanded a need to develop mechanical means of harvesting Chinese potato tubers. The size of the tubers varies from 1 cm to 6 cm, depending on soil conditions. The existing potato harvester might not be appropriate for harvesting Chinese potato tubers because of the large variation in the size of these tubers. The Chinese potato tubers are very small compared to potatoes, and the depth of tuber formation is lower (about 15 cm below the soil surface) than that of potato tubers. In this background, an attempt was made to develop a tractor operated Chinese potato harvester suitable for ridge and furrow planting system with low power requirements, minimal harm to tuber roots, and efficient harvesting at a reasonable operating cost.

Materials and Methods

The design considerations for the development of tractor operated Chinese potato harvester require a planting system with ridges and furrows that are 30 cm and 15 cm apart, respectively, as well as a free spacing of 30 cm between three ridge and furrow for the machine to function.

Design of Chinese potato harvester

A mechanical harvesting unit for Chinese potato tubers was designed using the P.T.O. power of the tractor, considering the parameters of the soil, crop, and machine. When harvesting tubers mechanically, the entire tuber must be extracted from the ground with as little damage or bruising as possible. Using a digging blade, the dirt adhering to the tuber was released, and the conveying unit was then required to remove the collected soil clump. Next, the chain conveyor holding the tubers were passed into rear side of the discharge system. The digging unit and the conveying unit were the two main operational parts. The machine parameters affecting the performance of tractor operated Chinese potato harvester were rake angle and digging blade geometry. The geometry of the digging blade is governed by rake angle of the blade and frictional properties of the soil (Agbetoye, 1998). The Rake angle of the blade is defined as the angle between the digging direction and a line normal to the edge of blade. The width of the digging blade was decided based on the width of the ridge on which Chinese potato tubers were grown. The blade was designed for its thickness based on load acting on it. These parameters needed to be optimized for better digging and conveying efficiency of Chinese potato tubers from ridge and furrow planting system.

Functional requirements

The following functional requirements were considered for the design of different components of the harvester.

1. The prime mover should be able to operate the harvester at the required speed under full load.
2. The digging blade of harvester should penetrate to the required depth of around 150 mm into the soil to dig out the whole tuber soil clump.
3. The digging unit should loosen the soil adhered to the tuber without damaging the tubers.
4. The conveying unit of the harvester should convey and discharge the tubers at the rear of the harvester at one side, which could be collected manually with minimum drudgery in minimum time.
5. Damage to the tubers during harvest operation i.e., cut, crush and bruise should be minimum as possible.
6. The machine should be operated by a tractor in the power range of 35 to 60 hp range, being the common size of tractor available in Indian conditions,
7. The harvester should be simple in design and fabrication, and efficient in its performance.

Selection of prime mover

Choosing an appropriate prime mover requires knowledge of the overall power needed to operate the harvester. Combining the power needed to draw the machine and the power needed to excavate and transport the tuber after it has been separated from the soil results in the overall power demand. The prime mover was chosen in this manner aiming to maximise farmer benefits from the use of the designed harvester. Chinese potato harvesters are designed to run on tractors because the ideal power requirement for them is quite high.

Power required for digging unit

The total width of the ridge and furrow was 1200 mm, *i.e.*, covering three ridges and three furrows at a time. The maximum depth of tuber penetration into the soil was observed as 150 mm. Hence, the width of the blade was selected as 1200 mm and the maximum depth of operation was considered as 200 mm.

Area of cross section of soil dugout by blade = Working depth × Blade width … Eqn. (1)

$= 0.20 \text{ m} \times 1.2 \text{ m}$

$= 0.24 \text{ m}^2$

Maximum unit draft of sandy loam soil is 0.103×10^6 N m^{-2} (Smith, 1968). Since the tuber harvester was operated in the soil which was relatively loose compared to the unploughed land, the unit draft of the soil was considered at 80 per cent of the assumed value.

Therefore,

Unit draft $= 0.103 \times 10^6 \times 0.80$ … Eqn. (2)

$= 82400 \text{ N m}^{-2}$

Soil resistance for cutting = Unit draft × Cross section area of soil cut … Eqn. (3)

$= 82400 \times 0.24$

$= 19776$ N

Maximum forward speed of tractor is considered as 0.833 m s^{-1} (Khurana et al., 2012). Therefore,

Power required for digging unit = Draft × Speed … Eqn. (4)

$= 19776 \times 0.83$

$= 16.41$ kW

Power required for pulling harvester

Total weight of Chinese potato harvester with hitch point was 5424 N.

Force required to pull the harvester, $F = \mu \times R$ … Eqn. (5)

Where, μ is the coefficient of friction and R is total weight of the harvester, N

Coefficient of friction of sandy loam soil is 0.80 (Kepner et al., 2005).

Total force required to pull the harvester, $F = 0.80 \times 5424$ … Eqn. (6)

$= 4339$ N

Power required for pulling the harvester = Force × Speed … Eqn. (7)

$= 4339 \times 0.83$

$= 3.60$ kW

Power required for conveying unit

The weight of the soil clump to be conveyed per second on conveyor was 180 kg. Assuming 50 per cent of the soil mass would fall down at the time of conveying, the net mass to be conveyed is 90 kg. The maximum speed of the conveyor should be considered as 0.97 m s^{-1}.

Power required for conveying unit = Force × Speed … Eqn. (8)

$= (90 \times 9.8) \times 0.97$

$= 0.85$ kW

Let us consider the slip factor as 25 per cent.

Power required for conveying unit $= 0.85 \times 1.25$ … Eqn. (9)

$= 1.06$ kW

Total power requirement of the unit = Power required for digging unit + Power required for pulling harvester + Power required for conveying unit … Eqn. (10)

$= 16.41 + 3.60 + 1.06$

$= 21.07$ kW

The total power required for the harvester was 21.07 kW, but the power exerted by commercially available tractors was above 28 kW. Therefore, the power required to operate the machine will be adequately provided from the PTO of a 28 kW tractor. As the most used tractor segment is 35-60 HP on Indian farms, a 55 HP tractor was selected as the prime mover to operate the Chinese potato harvester.

Development of the prototype Chinese potato harvester

The developed tractor operated Chinese potato harvester consisted of four major units *viz*., main frame, digging blade, conveyor system and discharge system. The digging blade was made up of boron steel and mounted horizontally on the machine. The blade digs the tuber and lifts it along with soil which is subsequently pushed onto a vibrating conveyor. The elevated chain conveyor is located behind the digging blade. The power is transmitted in two stages, first from P.T.O to machine gear box from which power is transmitted to the conveyer by belt. The spacing between mild steel rods used for the fabrication of the elevated vibrating conveyor is 18 mm. The slope of conveyor was fixed at an angle of 20°. The oval agitators are provided in the conveying system for providing vibration to the conveyor, thus separating the soil particles from the digged tubers. Finally, the tubers are passed through the discharge system where soil particles from the tubers are further separated in the sieve provided on the bottom of the discharge system and collected through discharge outlet. The isometric and orthographic views of the tractor operated Chinese potato harvester are shown in Fig. 1. and Fig. 2, respectively. The technical specifications of the harvester are presented in Table 1.

Fig.1. Isometric view of tractor operated Chinese potato harvestera

*All dimensions are in mm

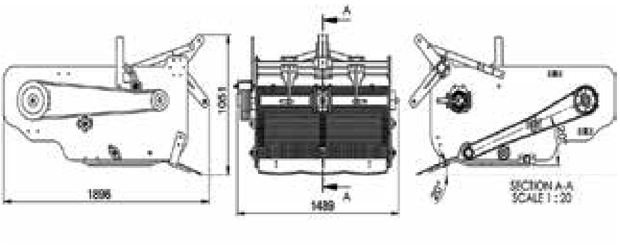

Fig. 2. Orthographic view of tractor operated Chinese potato harvester

Table 1. Technical specifications of the tractor operated Chinese potato harvester

Sl. No	Parameter	Specifications
1.	Overall dimensions, L×W×H, mm	2440 × 1830 ×1250
2.	Digging blade, length×width× thickness, mm	1200×350×7
3.	Coulter-Number Diameter, mm Thickness, mm	2 400 5.5
4.	Gear box speed ratio	2.6:1
5.	Type of conveyor blade Diameter of rod, mm Spacing between the conveyor rods, mm Number of conveyor rods Length of conveyor rods Slope of conveyor, degree	Chain conveyor made of M.S rod 8 18 180 2000 20°
6.	Wheels at rear of harvester Diameter, mm Width, mm	2 400 155
7.	Transmission unit Pulley diameter at a side of blade, mm Pulley diameter at a side of wheel, mm V-belt Idler diameter, mm	153 280 C 117 130
8.	Main frame	Mild steel

Performance evaluation

The performance of the tractor operated Chinese potato harvester was conducted in the experimental field of Horticulture orchard, Tamil Nadu Agricultural University, Coimbatore during March 2023. The performance of the machine was evaluated by observing the digging efficiency, percentage damage of tubers and fuel consumption. The plan of experiments for conducting performance evaluation is presented in Table 2.

Table 2. Plan of experiments for evaluating the performance of the harvester

Sl. No	Variables	Levels	Performance parameters
1.	Independent:		
	1. Machine parameter Rake angle (°)	15, 20, 25°	
	2. Machine parameter Digging blade geometry	Inverted V shape, Crescent shape, Straight	
	3. Tractor parameter Forward speed (km h$^{-1)}$	1.5, 2.0 2.5	
2.	Dependent: Machine performance		1. Digging efficiency 2. Damage of tubers 3. Fuel consumption

Digging efficiency (DE)

Digging efficiency was calculated using the following formula.

$$DE = \frac{A}{A+B} \times 100 \quad \ldots \text{Eqn (11)}$$

Where, A was the weight of the tuber successfully harvested in unit area (kg) and B was the weight of the tuber left in soil after harvesting in unit area (kg)

After each test run a sample area of 5 m × 5m was demarcated at three places randomly. The sampling area was thoroughly cleaned and weight of tuber, both exposed and covered with soil was recorded. The result was presented on percentage basis. The higher percentage of Chinese potato tubers harvested indicates better performance of harvester (Wajire et al., 2018).

Damage percentage (%)

Damage of tubers occurs due to cutting by blade or bruising during the harvest. After harvesting by the machine, damaged tubers are separately weighed using an electronic weighing balance. The percentage damage of coleus tubers during the operation was calculated using the following equation.

$$\text{Damage (\%)} = \frac{\text{Mass of damaged tubers (kg)}}{\text{Total harvested yield (kg)}} \times 100 \quad \text{... Eqn (12)}$$

Fuel consumption

The fuel consumption gives an idea of energy requirement by the harvester. The top fill method was used for measuring fuel consumption. The measurement was done by filling up the fuel tank to full capacity before starting each trial and after finishing the trial. Amount of refueling after the operation. The amount of refueling after the operation was measured as the fuel consumption for digging operation and it was expressed as litre per hour. While filling up the fuel tank, careful attention was given to keep the tank horizontal and not to leave empty space in the tank.

Statistical analysis

The interaction effects of the independent variables such as type of blade, rake angle, operating speed and dependent variables such as digging efficiency, percent damage and fuel consumption were studied using three factorial designs and Design Expert version 13.0.5.0 was sued for statistical analysis. The desirability index was used to find out the best optimal values separately. For several responses and factors, all goals got combined into one desirability function. The goal of optimization was to find out a set of conditions that will meet all the goals.

Cost economics

For estimating the cost of operation, straight line method was followed. The cost of operation was compared with conventional practice of manual harvesting of Chinese potato tubers with the mechanical harvesting in terms of savings in cost.

Results and Discussion

The optimum operating conditions for harvesting Chinese potato tubers were investigated in the field with a tractor-operated Chinese potato harvester. The parameters selected for testing and optimization of harvester in the field conditions were blade geometry (Inverted V-shaped, crescent shape and straight type), rake angle (15, 20 and 25°) and forward speed (2.0, 2.5 and 3.0 km h^{-1}). A soil moisture content of 15% (dry wt. basis) was used for the field test. The effect of operational parameters was studied to evaluate the performance of the harvester in terms of digging efficiency, percent damage and fuel consumption as detailed in the following sections.

Digging efficiency (%)

The effect of blade geometry, degree of slope of digging blade (rake angle) and operating speed on digging efficiency of Chinese potato harvester was presented in Table 3. The different efficiency for all treatments varied from 82.37 to 97.28%. The minimum digging efficiency of 82.37% was obtained for the straight blade at a rake angle of 15° when the harvester was operated at a operating speed of 2.5 km h^{-1}, while the maximum digging efficiency of 97.28% was recorded for the inverted V shape blade at a rake angle of 20° when the harvester was operated at a speed of 2.5 km h^{-1}. The desirable digging efficiency of 93.32% was obtained for the inverted V shape at a rake angle of 20° when the harvester was operated at a forward speed of 2.0 km h^{-1}. It was observed that the digging efficiency increased as rake angle increased from 15 to 20° but decreased with further increase (Table 2). It might be due to higher soil disturbance and lesser blade penetration. The lowest digging efficiency at lower rake angle and lower operating speed might be due to the insufficient depth of cut. At optimum rake angle of 20° and operating speed of 2.0 km h^{-1}, higher digging efficiency was obtained. This could be attributed to the optimum depth of cut and the resulting higher digging efficiency. The result was in agreement with that reported by Vatsa et al., (1993) and Kawale et al., (2018).

Analysis of variance (ANOVA) indicated that the independent variables *viz.*, blade geometry, rake angle and operating speed were individually significant at 5% level for the digging efficiency of Chinese potato harvester. The model was significant at 1.0% level and the coefficient of determination (R^2) was 0.93 indicating the high accuracy of digging efficiency with performance parameters as reported in Table 4. The mean, standard deviation and coefficient of variation were 87.88, 1.55 and 1.76 per cent, respectively.

Table 3. Effect of blade geometry, rake angle and operating speed on digging efficiency

Digging blade angle	Geometry of blade								
	Inverted V shape			Crescent shape			Straight blade		
	Operating speed (km h^{-1})								
	1.5	2.0	2.5	1.5	2.0	2.5	1.5	2.0	2.5
15°	91.11	92.56	92.11	86.25	85.14	87.36	84.18	84.25	82.37
20°	94.36	97.28	96.11	90.43	93.17	90.38	87.37	86.21	83.23
25°	95.27	96.15	96.57	92.30	91.12	94.23	88.17	89.34	87.31

Table 4. Analysis of variance (ANOVA) for digging efficiency

Source	Sum of squares	DF	Mean square	F-value
Model	2261.08	6	376.84	156.95*
Blade geometry (B)	2037.41	2	1018.70	424.28**
Rake angle (R)	162.41	2	82.20	34.23**
Operating speed (O)	60.85	2	30.42	12.66**
Residual	177.24	74	2.401	-
Corrected total	2437.92	80	-	-
Standard deviation	1.55		R^2	0.93
Mean	87.88		Adjusted R^2	0.92
CV (%)	1.76		Predicted R^2	0.91

**5% Level of significance *1% Level of significance

Percent damage of tubers

Different types of damages may occur to the tubers like cut, crush, sliced or bruished tubers during harvesting and hence percent damage is a prominent parameter to evaluate the performance of the harvester. The effect of blade geometry, rake angle and operating speed on percentage damage of Chinese potato tubers are presented in Table 5. The percent damage of tubers varied from 3.42 to 9.91%, with the minimum damage obtained with the inverted V shape blade at a rake angle of 20° when the harvester was operated at a forward speed of 2.0 km h^{-1}. However, the maximum damage of 9.91% was recorded for straight blade at a rake angle of 15° when the harvester was operated at a forward speed of 2.5 km h^{-1} (Table 5). From Table 5, it was also observed that the percent damage decreased as rake angle increased from 15 to 20° but increased with further increase in rake angle. The higher damage of tuber at lower rake angle might be due to the reduced penetration. The operating speed also had considerable effect on percent damage of Chinese potato tubers. At an optimum speed of 2 km h^{-1}, there was sufficient depth of cut and optimum soil loosening effect, hence less damage of tubers was observed. Further increase in operating speed up to 2.5 km h^{-1} resulted in higher tuber damage. This might be due to the reduced blade penetration and higher soil disturbance, which in turn resulted in increased damage. The results are in agreement with those of Vasta et al., (1993).

Analysis of variance results indicated that the independent variables *viz.*, blade geometry, rake angle, operating speed, interaction of blade geometry and rake angle and interaction of blade geometry and speed of operation were significant at 5% level for the percent damage of tubers while using the harvester (Table 6). The model was significant at 1.0% level and the coefficient of determination (R^2) was 0.98 indicating the high accuracy of the digging efficiency with performance parameters as reported in Table 4. The mean, standard deviation and coefficient of variation were 3.21, 0.20 and 6.33%, respectively.

Table 6. Analysis of variance (ANOVA) for percentage damage of tubers

Source	Sum of squares	DF	Mean square	F-value
Model	154.56	14	11.04	256.74*
Blade geometry (B)	115.16	2	57.58	1339.06**
Rake angle (D)	22.39	2	11.47	266.74**
Operating speed (O)	7.19	2	3.59	83.48**
B × D	5.96	4	1.49	34.65**
B ×O	3.26	4	0.81	18.83**
Residual	2.67	66	0.043	
Corrected total	157.66	80		
Standard deviation	0.20		R^2	0.98
Mean	3.21		Adjusted R^2	0.98
CV (%)	6.33		Predicted R^2	0.97

**5% Level of significance *1% Level of significance

Table 5. Effect of blade geometry, rake angle and operating speed on percentage damage of Chinese potato tubers

Digging blade angle	Geometry of blade								
	Inverted V shape			Crescent shape			Straight type		
	Operating speed (km h^{-1})								
	1.5	2.0	2.5	1.5	2.0	2.5	1.5	2.0	2.5
15°	6.10	6.85	7.73	8.66	9.34	9.86	9.54	8.65	9.91
20°	4.78	3.42	6.08	8.35	5.46	7.83	7.45	8.06	9.15
25°	4.95	4.09	6.89	5.84	5.56	7.49	6.79	7.12	8.25

Table 7. Effect of blade geometry, rake angle and operating speed on fuel consumption

Digging blade angle	Geometry of blade								
	Inverted V shape			Crescent			Straight		
	Operating speed (km h^{-1})								
	1.5	2.0	2.5	1.5	2.0	2.5	1.5	2.0	2.5
15°	4.75	4.77	4.87	5.12	5.12	5.23	5.51	5.56	5.56
20°	4.88	4.88	5.05	5.26	5.37	5.43	5.90	6.03	5.96
25°	5.00	4.97	5.03	5.39	5.44	5.50	5.98	6.04	6.24

Fuel consumption

The fuel consumption of Chinese potato harvester varied from 4.75 to 6.24 l h^{-1}. The minimum fuel consumption of 4.75 l h^{-1} was obtained for the inverted V shape blade at a rake angle of 15° when the harvester was operated at a forward speed of 1.5 km h^{-1} while the maximum fuel consumption of 6.24 l h^{-1} was recorded for straight blade at a rake angle of 25° when the harvester was operated at a forward speed of 2.5 km h^{-1} (Table 5). The desirable fuel consumption of 4.81 l h^{-1} was obtained for the inverted V shape at a rake angle of 20° when the harvester was operated at an operating speed of 2.0 km h^{-1}, respectively. From Table 7, it was evident that the increase in rake angle of the harvester increased the fuel consumption of the tractor. The similar results were earlier reported by Gulsoylu et al., (2012).

Analysis of variance results indicated that the independent variables *viz.*, blade geometry and rake angle were significant at 5 % level for the fuel consumption of Chinese potato harvester (Table 8). The model was significant at 1.0% level and the coefficient of determination (R^2) was 0.95 indicating the high accountancy of digging efficiency with performance parameters as reported in Table 8. The mean, standard deviation and coefficient of variation were 5.34, 0.10 and 1.97 per cent respectively.

Table 8. Analysis of variance (ANOVA) for fuel consumption

Source	**Sum of squares**	**DF**	**Mean square**	**F-value**
Model	14.53	10	1.45	131.81*
Blade geometry (B)	12.14	2	6.07	551.81**
Rake angle (R)	1.65	2	0.82	74.54**
Operating speed (O)	0.21	2	0.10	9.09
B × R	0.42	4	0.10	9.09**
Residual	0.78	70	0.011	
Corrected total	15.36	80		
Standard deviation	0.10	R^2		0.95
Mean	5.34	Adjusted R^2		0.94
CV (%)	1.97	Predicted R^2		0.93

** 5 % Level of significance * 1 % Level of significance

Economics of the technology

The cost associated with the manual harvesting of Chinese potato tubers was compared with the cost of operation of tractor operated Chinese potato harvester. The cost for the development of prototype of tractor operated Chinese potato harvester was ₹ 1,50,000/-. The cost per hectare of harvesting using the harvester was determined to be ₹ 18,400/- per hectare compared to ₹ 1,12,500/- for harvesting manually. The cost savings per hectare while harvesting with the mechanical harvester is ₹ 94,100/-.

Conclusion

A tractor operated Chinese potato harvester was developed, performance evaluation was conducted, and the operational parameters were standardized. Comparing the three types of digging blades, the highest digging efficiency of 97.28% was observed with the inverted V shape blade. The minimum damage percentage of 3.42% was also observed the inverted V shape digging blade. Among the different types of blade geometry, the minimum fuel consumption of 4.75 l h^{-1} was obtained for the inverted V shape digging blade at a rake angle of 15° and forward operating speed of 1.5 km h^{-1}, while the maximum fuel consumption of 6.24 l h^{-1} was recorded for the straight type digging blade at a rake angle of 25° and forward operating speed of 2.5 km h^{-1}. The cost per hectare of harvesting using the developed harvester was determined to be ₹ 18,400 per hectare compared to ₹ 1,12,500 for manual harvesting. The cost savings per hectare while harvesting with the mechanical harvester is ₹ 94,100.

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