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Development and Evaluation of Garlic Harvester for Raised Beds

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Harvesting is considered one of the most time-consuming and laborious agricultural operation in garlic cultivation. This work can be easily done by mechanical means, thereby saving time, labor and money. Working of a mechanical garlic harvester in vertisol soil is difficult under flat conditions but it can be made easier by making raised beds. There is a need for a machine that can perform the intended harvesting task with its uniquely designed blade that penetrates vertisol soil easily and is able to pull out the garlic without damaging the bulb. Therefore, a garlic harvester has been developed and its operating parameters were optimized for harvesting the garlic crop sown in raised beds. An experiment was carried out in the field to investigate the effect of forward speed, conveying speed, and dropping height of a garlic harvester on digging efficiency, bulb damage, and fuel consumption using Response Surface Methodology (RSM). A forward speed of 1.53 km/h, dropping height of 0.47 m and conveying speed of 0.65 m/s were found to be optimal for operation of the machine on raised bed. The RSM successfully optimized the operational parameters of machine and predicted the performance parameters with less error. The optimum operating parameters improved the performance of machine in field by lowering bulb breakage, reducing fuel consumption and increasing garlic digging efficiency. The effective field capacity of harvester was 0.21 ha/h at field efficiency of 72.1%. The savings in cost and labor requirement were found to be 63.4 and 96.2% respectively as compared to manual method of garlic digging. The developed machine with triangular point blade and optimized operating parameters makes it better for working in black cotton soil. It will help farmers, garlic growers and agricultural machinery manufacturers to increase mechanization in garlic cultivation.

Keywords: Bulb damage, Conveying speed, Raised bed, RSM, Vertisol soil

Introduction

In India, garlic is cultivated in an area of about 0.39 million hectares, with a production capacity of 31.9 lakh metric tons and a productivity of 8.1 metric tons/ha.[1] India is the second largest producer of garlic with 12% of the global area. Various agricultural steps in the cultivation of garlic such as sowing, weeding, hoeing, and harvesting are carried out with the help of labourers. It consumes time, cost and money to complete these tasks manually. Digging of garlic is also an important field operation. It is one of the most laborious and time-consuming step in garlic production. It is done manually by pulling the plants with hand in bending posture and requires about 50–60 man-days/ha.[2] Traditionally, garlic is cultivated on flat beds. The practice of cultivating garlic on raised beds is gradually increasing. There are many benefits of cultivating garlic on raised beds, but one of the main advantages is that the tractor can be easily driven in furrow between the beds.

Garlic harvesters have been developed by the researchers for sandy loam soil, but they are ineffective for digging garlic in vertisol. The vertisol hardens due to the less moisture, making it difficult to dig up garlic that has been planted on a flat surface. This can be made easier by sowing garlic on raised beds in vertisol. However, the machine need to be modified to make working in raised beds and harvest the garlic. The basic components of a garlic harvester available in India are the cutting blade, conveying unit, soil separation unit, and depth control wheels.[3] The correct design and adjustment of various components influence the performance of machine.[4] Various researchers have studied the effect of soil, machine and operational parameters on the performance of the garlic harvester. Borkar *et al.*[5] developed a tractor drawn garlic harvester for sandy loam soil and it was evaluated in field. The soil moisture content, machine forward speed and rake angle of blade were varied and their effect on harvesting percentage, bulb damage, soil separation index, power requirement, field capacity and field efficiency were studied. Khambe *et al.*[6] evaluated the performance of a garlic harvester under field conditions by taking into account the harvesting percentage (96.12%), plant damage (5.94%), soil separation index (0.26), power requirement

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4.54 kW), field capacity (0.24 ha/h) and field efficiency (68.7%). A bullock drawn garlic digger (without conveyer and separation units) for black soil has been developed and evaluated in terms of blade design and performance of fatigue score of bullocks.[7] The bulb damage was reported in the range of 3.62–5.40%. The parameters of digging shovel of garlic harvesting *i.e.* length, width, blade angle and speed were optimized using EDEM simulation.[8] An analysis of impact force acting on the garlic bulb by the roller of harvester was carried out using discrete element method.[9] Fatigue safety of the machine is a major concern because machinery and its components are subjected to a variety of loads during operation. Han *et al.*[10] assessed the fatigue loads of garlic-onion harvester and developed a machine that could withstand the sudden fatigue that occurs during operation.

Reviews of the various garlic harvesters have been carried out. This revealed that the developers did not consider the conveying speed and dropping height of the garlic. These parameters play an important role in separating the garlic from the soil after digging. Optimization of these operating parameters is of utmost importance for proper functioning of machine and precise digging operation with minimum bulb damage.

Mathematical modeling is a feasible means of simplifying the complexities of the problem and a useful optimization strategy where the output parameters are influenced by the associations of various input parameters. The Response Surface Methodology (RSM) was used in this study for the optimization of operational parameters of garlic harvester. The RSM is a combination of statistical and mathematical techniques that are useful for processes being analyzed, developed, improved and optimized. This helps to solve the complexities of non-linear behaviors in which numerical techniques fail.[11] The most widespread uses of RSM are in conditions where a number of input factors may have an impact on the performance and quality attributes of the operation. Application of RSM is gaining popularity nowadays to optimize the operational parameters of agricultural machinery i.e., mould board plough[12], thresher[13,14], row cleaner[15], straw loader[16] and sprayer[17]. In addition, this method is useful for soil bin study for the performance of puddling wheel[18], chisel plough[19], subsoiler[20], mould board plough[21] and seed drill.[22]

In this study, a tractor drawn harvester was developed for digging of garlic crop sown on raised beds in vertisols. In addition, an attempt was made to optimize the forward speed, dropping height and conveying speed and predict the digging efficiency, bulb damage and fuel consumption using RSM technique.

Materials and Methods

Functional and Design Requirements

Functional and design requirements are the prerequisites for better performance of the machine and execution of its intended function at actual condition. The functional requirements for the machine to work effectively were compiled as follows:

- The machine should accomplish its intended task of harvesting the garlic crop sown on raised beds in vertisol soil.
- The blade should penetrate into the soil and dug out the soil without damaging the garlic bulb.
- Garlic bulbs should be carried through the conveying unit and fall-off at the end of the conveying unit.
- The bulb and soil should be separated after falling from the conveying unit.

The following design requirements were considered to meet the functional requirements of the machine:

- The digging blade of machine was made of triangular point shovels instead of plain blade.
- The soil cutting discs were provided for easy operations in vertisol soil like the coulter of mould board plough.
- The forward speed of machine and peripheral speed of the conveyor belt were optimized such that it can transport the garlic bulb and soil without interruption.
- The dropping height of garlic bulb from the conveyor belt was optimized for minimizing the bulb damage.

Development of Garlic Harvester

A ten-row tractor operated garlic harvester was developed at ICAR-Central Institute of Agricultural Engineering, Bhopal, India (Fig. 1). The machine is suitable for harvesting of garlic crop sown on raised beds of 150 mm height and 1200 mm top width with 300 mm furrow width. The overall dimensions of the machine are 2470 × 1725 × 1375 mm. The garlic harvester consists of main frame, soil cutting disc, digging blade (Fig. 2), conveying-cum-separation unit, depth control wheel, three-point hitch and power transmission system. The details of developed garlic harvester for raised beds are given in Table 1.

Description of different components is given in following sections:

Main Frame

The main frame was made of mild steel square box of 65 × 65 × 5 mm. The digging blade, cutting disc, conveying-cum-separation unit, power transmission unit and depth control wheels were attached to the main frame.

Soil Cutting Disc

Two cutting discs are attached at both sides of the digging blade. This arrangement allows digging into the soil easier for the digging blade. The discs were made of a 5 mm thick mild steel sheet with a 400 mm diameter to cut and loosen the raised bed soil mass for easy harvest. The discs were designed to cut furrow sections vertically ahead of the blade at a bed edge.

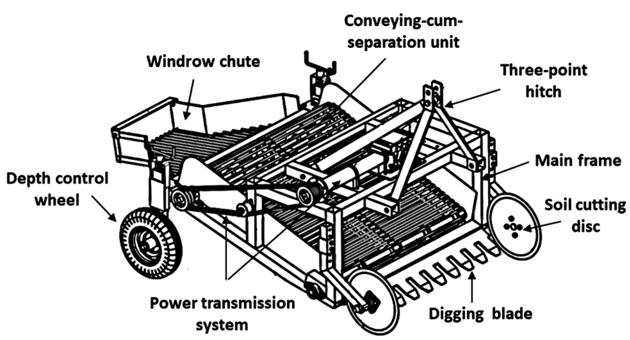

Fig. 1 — CAD view and fabricated garlic harvester for raised beds

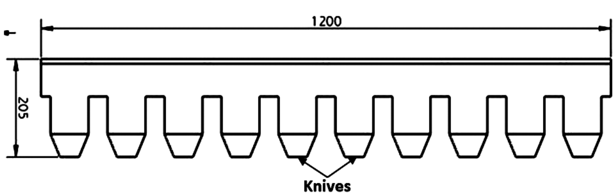

Fig. 2 — Triangular point blade of garlic harvester

Digging Blade

The working depth of garlic harvester mainly depends on the depth of the garlic bulb in the soil. Studies of biomaterial properties show that the depth of the garlic bulb is in the range of 30–60 mm.[23] Therefore, the digging depth of the blade was kept more than 60 mm to increase the digging efficiency with minimum damage to the bulbs. The slope of triangular point blade and conveyor-cum-separator slope were selected between 15–35° for its minimum draft, maximum digging efficiency and minimum damage to garlic bulb.[5,6,24] The length of the digger blade was kept at 1200 mm which was equal to the width of the raised bed. The digging blade consists of 10 knives made of 8 mm mild steel flat to withstand soil loads during operation. The blade was hardened to protect it from wear and tear and to resist the soil forces of the soil acting on it.

Conveying-cum-Separation Unit

The conveying-cum-soil separation unit was equipped immediately after the blade to receive dugout garlic and soil from the digging blade. Conveying-cum-separation unit was made of mild steel bars and a canvas belt. To separate the dugout garlic bulb from the soil mass, the 12 mm bars were arranged perpendicular to the direction of travel of the harvester. The spacing between the consecutive steel bars was chosen based on the polar and equatorial diameters of the garlic bulb. The mean polar and equatorial diameters of the selected variety (G-41) varied from 26.8–33.13 and 29.8–36.2 mm, respectively. For an effective soil separation system, the steel bar spacing was kept at 38 mm. The length of the conveyor was kept at 1150 mm. After receiving

Table 1 — Specifications of developed garlic harvester for raised beds

S. No.	Particulars	Details
1	Overall dimensions of machine (L × W × T), mm	2000× 1530 × 1130
2	Working width, mm	1200
3	Size of beds	Top width: 1200 mm, bottom width:1500 mm, furrow width: 300 mm and bed height: 150 mm
4	Power source	Tractor, New Holland 3630 was used
5	Blade type	Triangular point blades
6	Cutting disc type and size	Two plain cutting discs of 400 mm diameter
7	Depth control wheel	Two depth control wheels of 410 mm diameter
8	Power transmission	Gear box and belt pulley
9	Hitching arrangement	Three-point hitch

power from the tractor PTO and gearbox, the conveying unit rotates through belts and pulleys.

Depth Control Wheel

Two depth control wheels were provided on both sides of the machine for uniform depth of operation. The diameter and width of wheel were 400 mm and 80 mm, respectively. The wheels were attached to the main frame with the help of square box of 50 × 50 × 5 mm size.

Three-Point Hitch

Three-point hitch system was attached to the main frame. It was made up of mild steel flat of 50 × 16 mm size. The dimensions of hitching system were in accordance with the BIS.

Power Transmission System

The power from the PTO of tractor to the conveying unit was transferred with the help of PTO connecting shaft, bevel gears (1:1) and belt pulley.

Evaluation of Garlic Harvester in Field

The performance evaluation of garlic harvester was carried out in the garlic crop sown on raised beds at research farm of ICAR-Central Institute of Agricultural Engineering, Bhopal, India. The soil of the experimental site was classified as vertisols with 34% sand, 22% silt and 44% clay content. The garlic crop was planted at row to row and plant to plant spacings of 100 mm.The field experiment was conducted to study the effect of forward speed, dropping height and conveying speed of machine on digging efficiency, bulb damage and fuel consumption. The machine was operated in field at 120 days after sowing with the help of tractor (New Holland 3630). The depth of operation was maintained between 60–80 mm to dig the garlic from the soil. Moisture content of the soil during experiment was 13.2 ± 1.5% on dry basis (db). The operation of garlic harvester in field is shown in Fig. 3. The performance parameters selected for the testing of garlic harvester in field are given in Table 2.

Descriptions of different independent and dependent parameters are given in following sections:

Forward Speed

The speed of operation during field operation is the important factor for agricultural machinery. Higher speed during operation can increase the draft and power requirement and lower speed can reduce the field capacity of the machine. Therefore, an appropriate speed selection is necessary for proper functioning of the machine.

Dropping Height

It is the vertical distance between the top of the conveying unit to the soil surface. Dropping height was adjusted by shortening/lengthening the top link of the tractor three-point linkage and adjusting the depth control wheels.

Conveying Speed

It is the peripheral speed of conveying belt which is expressed in m/s. The different levels of peripheral speed were obtained by changing the size of pulley of conveyer unit.

Digging Efficiency

The rate at which the machine harvests work is referred as digging efficiency. The ratio of the total number of garlic bulbs dug by the machine to the total number of bulbs in a unit area was used to calculate the digging efficiency. A sample of 1 × 1 m^2 was taken for the calculation of digging efficiency.

$$\text{Digging efficiency} = \frac{\text{Garlic bulbs dug by machine}}{\text{Total number of garlic bulbs in a tested area}} \times 100$$

Fig. 3 — Garlic digging with harvester in field

Table 2 — Performance parameters for the testing of garlic harvester

Parameters	Level
Independent parameters	
1. Forward speed, km/h	1.0–3.0
2. Dropping height, m	0.3–0.6
3. Conveying speed, m/s	0.6–1.0
Dependent parameters	
1. Digging efficiency, %	
2. Bulb damage, %	
3. Fuel consumption, l/h	
Other parameters	
Depth of operation, mm	60–80
Soil moisture content, % (db)	13.2 ± 1.5%

Bulb Damage

It is the damaged done to garlic bulb during digging due to improper depth of cutting blade and more height of dropping of bulbs from conveyor belt. The optimum height of dropping and proper working depth of the machine can minimize this loss. The garlic bulb damaged during the operation of machine was recorded. Damaged bulbs were separated from the harvester bulbs and the following formula was used to calculate the bulb damage:

$$\text{Bulb damage (\%)} = \frac{\text{Number of damaged bulb}}{\text{Total number of bulb harvested}} \times 100$$

Fuel Consumption

The auxiliary tank method was used to calculate the amount of fuel consumed by the tractor during the harvesting operation. The auxiliary tank was filled with diesel and the level was recorded before the operation began. After harvesting, the level of the tank was measured again, as well as the time required to cover a 300 m^2 area. The difference between the tank's level before and after harvesting was calculated and converted to liters per hour.

$$\text{Fuel consumption (l/h)} = \frac{\text{Difference in level of tank before and after operation, l}}{\text{Time taken to cover the targeted area, h}} \times 100$$

Optimization of Performance Parameters of Garlic Harvester

The performance parameters of garlic harvester i.e. forward speed, dropping height and conveying speed were optimized using RSM. Second order polynomial regression models were developed for the digging efficiency, bulb damage and fuel consumption in terms of the coded value of the independent parameters. Optimum parameters were calculated for maximum digging efficiency at minimum bulb damage and minimum fuel consumption using Design Expert software (Version 7.1.6. Stat-Ease, Inc., MN, USA). The Analysis Of Variance (ANOVA) test was performed and the adequacy of the models was tested using F-value, p-value ($p < 0.05$ and $p < 0.01$) and coefficient of determination (R^2). The second order polynomial model is given in Eq. (1) as:

$$Y_i = \beta + \Sigma\beta_i X_i + \Sigma\beta_{ii} X_i^2 + \beta_{i\hat{j}} X_i X_{\hat{j}} \qquad \ldots (1)$$

where, Y_i is the predicted response (i.e. digging efficiency, bulb damage and fuel consumption), X_i, and X_j are input variables (i.e. forward speed; dropping height and conveying speed); β_0 is the offset term; β_i is the linear coefficient; β_{ii} the i^{th} quadratic coefficient and $\beta_{i\hat{j}}$ is the $\hat{j}^{th}$ interaction coefficient.[25] The validation of optimized parameters was done by operating garlic harvester at optimum forward speed, dropping height and conveying speed. The digging efficiency, bulb damage and fuel consumption were measured according to the aforementioned procedure. The experiments were replicated five times.

Fixed and Variable Costs

The total cost of operation was calculated based on fixed cost and variable cost following the test code IS: 1964–1979.[(26)] The cost of operation of garlic harvester was compared with manual harvesting.

Results and Discussion

The observed values of digging efficiency, bulb damage and fuel consumption at various combinations of forward speed, dropping height and conveying speed obtained from RSM are presented in Table 3. The ANOVA of the effect of different parameters on digging efficiency, bulb damage and fuel consumption is given in Table 4.

Effect of Machine Parameters on Digging Efficiency

RSM was used to study the effect of different machine parameters on the digging performance of garlic harvester. The ANOVA shows that the forward speed and dropping height had significant effect on digging efficiency, whereas, conveying speed had no significant effect on digging efficiency (Table 4). The interaction of forward speed and dropping height was found significant. The model of digging efficiency was developed using estimated regression coefficients of second order polynomial equation in coded terms. The model for digging efficiency is given in Eq. (2) as follows:

$$\text{Digging efficiency} = 97.24 + 2.69 \times A + 1.15 \times B + 0.27 \times C - 1.35 \times AB + 0.80 \times AC - 0.20 \times BC - 0.30 \times A^2 - 2.00 \times B^2 + 0.20C^2 \qquad \ldots (2)$$

The F value of 6.41 showed that the model is significant ($p < 0.01$). The value of R^2 (0.85) shows a very good relation between digging efficiency and independent variable. The digging efficiency increases with increase in speed of operation of machine (Fig. 4). The blade excavated a greater amount of soil as the forward speed of machine increased, which also increased the excavation of garlic, resulting in an increase in digging efficiency. Similar result for potato digger was reported by Younis *et al.*[27] Dropping height of garlic also affected

Table 3 — Results of experiment conducted in field for performance evaluation of garlic harvester

Experimental run	Forward speed, km/h	Dropping height, m	Conveying speed, m/s	Digging efficiency, %	Bulb damage, %	Fuel consumption, l/h
1	1.0	0.30	1.0	90.1	0.7	3.6
2	3.0	0.60	1.0	99.3	4.8	5.5
3	2.0	0.45	0.8	96.4	0.5	4.3
4	2.0	0.45	0.8	97.1	0.4	4.1
5	1.0	0.60	1.0	92.4	2.6	3.9
6	3.0	0.45	0.8	98.2	0.5	5.4
7	3.0	0.30	1.0	99.1	4.2	5.3
8	1.0	0.30	0.6	89.2	0.1	3.8
9	2.0	0.60	0.8	98.2	2.3	4.2
10	1.0	0.45	0.8	96.7	0.4	4.1
11	1.0	0.60	0.6	95.6	1.2	3.9
12	2.0	0.45	0.8	97.3	0.6	4.3
13	2.0	0.45	1.0	98.4	1.9	4.5
14	2.0	0.45	0.8	97.2	0.4	4.2
15	2.0	0.45	0.6	97.5	0.6	4.1
16	2.0	0.30	0.8	93.3	1.5	4.0
17	3.0	0.60	0.6	96.0	4.1	5.2
18	2.0	0.45	0.8	96.6	0.5	4.2
19	2.0	0.45	0.8	96.8	0.4	4.4
20	3.0	0.30	0.6	98.3	2.8	4.9

Table 4 — ANOVA of the effect of different parameters on digging efficiency, bulb damage and fuel consumption

Source	Digging efficiency		Bulb damage		Fuel consumption	
	F Value	p-value	F Value	p-value	F Value	p-value
Model	6.41	0.0038^{S}	12.25	0.0003^{S}	58.71	< 0.0001^{S}
Forward speed	32.58	0.0002^{S}	38.31	0.0001^{S}	440.45	< 0.0001^{S}
Dropping height	5.95	0.0348^{S}	9.58	0.0113^{S}	10.88	0.0080^{S}
Conveying speed	0.33	0.5794^{NS}	8.60	0.0150^{S}	7.28	0.0224^{S}
Forward speed × Dropping height	6.56	0.0283^{S}	0.45	0.5194^{NS}	0.11	0.7444^{NS}
Forward speed × Conveying speed	2.31	0.1599^{NS}	0.0037	0.9528^{NS}	9.10	0.0130^{S}
Dropping height × Conveying speed	0.14	0.7122^{NS}	0.0037	0.9528^{NS}	0.11	0.7444^{NS}
Forward speed^2	0.11	0.7417^{NS}	0.024	0.8797^{NS}	50.06	< 0.0001^{S}
Dropping height^2	4.98	0.0498^{S}	15.79	0.0026^{S}	9.89	0.0104^{S}
Conveying speed^2	0.047	0.8322^{NS}	4.51	0.0598^{NS}	0.000	1.0000^{NS}
Coefficient of determination (R^2)	0.85		0.93		0.98	

the digging performance of the machine. The adjustment of dropping height of machine is directly linked with blade angle. The rake angle of the blade changes as the dropping height is changed, which also affects the penetration of digging blade in to soil and digging performance of machine. An increase of 0.30 to 0.50 m in the dropping height (or an increase in blade angle) resulted in an increase in digging efficiency, whereas, an increase of 0.50 to 0.60 m resulted in lower digging efficiency. On the other hand, the conveying speed is mainly related to the transportation of garlic after digging, so changes in the conveying speed have no effect on the digging performance of the machine.

Effect of Machine Parameters on Bulb Damage

The independent variables had a significant effect on forward speed, dropping height and conveying speed (Table 4). The forward speed was the most significant factor that influenced the bulb damage followed by dropping height and conveying speed. The second order equation of bulb damage derived in terms of coded factors of independent variable is given in Eq. (3) as follows:

$$\text{Bulb damage} = 0.48 + 1.140 \times A + 0.57 \times B + 0.54 \times C - 0.14 \times AB + 0.013 \times AC + 0.013 \times BC - 0.06 \times A^2 + 1.40 \times B^2 + 0.75 \times C^2 \quad \ldots (3)$$

The model is significant ($p < 0.01$) with an F value of 12.25. The value of R^2 (0.93) indicates a strong

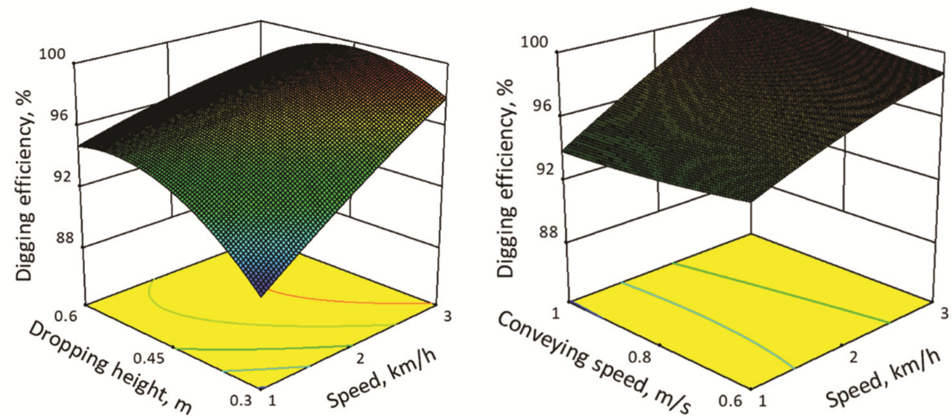

Fig. 4 — Surface graph showing the effect of different parameters on digging efficiency

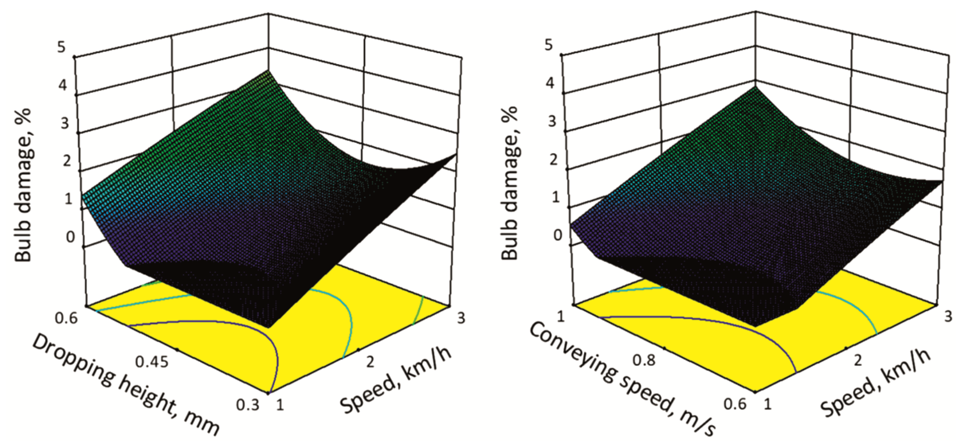

Fig. 5 — Surface graph showing the effect of different parameters on bulb damage

relationship between bulb damage and the various factors. Table 3 shows that the bulb damage ranged from 0.1 to 4.8% at different combinations of independent parameters. Mechanical harvesting of garlic damages the bulb by direct contact with the cutting blade or by friction with the soil clods during conveying and dropping. The bulb damage increased with increase in forward speed, dropping height and conveying speed of machine, whereas, it was decreased with decrease in values of different independent parameters (Fig. 5). All the factors significantly influenced the garlic bulb damage but the forward speed of the machine is the most important factor that was responsible for the damage. This may be due to an increase in soil disturbance with the increase of machine speed. As a result, a large amount of soil is dug along with the garlic bulb, which leads to an increase in bulb damage due to brushing with soil. The damage was more when the bulb and soil pass through the conveyor-cum-separation unit at a high conveying speed (1 m/s). The findings were in confirmation with the results reported by researchers.[28] When the forward speed of machine is increased, the soil and garlic flow towards the conveyor unit also increases but the conveyor unit runs at a fixed speed, so that the soil and garlic bulb do not flow easily and the damage increases. The damage to the bulb was found to be more due to the increase in dropping height. While passing through the conveyor unit, there is no complete separation of soil and garlic, and bulb loss increases as the garlic falls along with the soil from a height above the conveyor's end.

Effect of Machine Parameters on Fuel Consumption

The forward speed, dropping height and conveying speed of the machine had a significant effect on fuel consumption. The effect of interaction of these parameters was not significant (Table 4). The model of fuel consumption was developed with the help of coded terms of significant variables. The developed model of fuel consumption is as follows (Eq. 4):

$$\text{Fuel consumption} = 4.27 + 0.70 \times A + 0.11 \times B + 0.09 \times C + 0.01 \times AB + 0.11 \times AC + 0.013 \times BC + 0.45 \times A^2 - 0.20 \times B^2 + 0.00 \times C^2 \quad \ldots (4)$$

The F value of 58.71 shows that the model is significant at 1% level of significance with R^2 of 0.98. The minimum fuel consumption (3.8 l/h) was found at forward speed of 1 km/h at dropping height of 0.3 m and conveying speed of 0.6 m/s, whereas, it was maximum (5.5 l/h) at forward speed, dropping height and conveying speed of 3 km/h, 0.6 m and 1 m/s, respectively (Table 3). The graphical representation of effect of different variables on fuel consumption is shown in Fig. 6. The response surface graph shows that fuel consumption increases with an increase in the forward speed of the machine, in accordance with the findings reported by the authors.[26,27] Dropping height of garlic bulbs also affects fuel consumption. The blade angle and inclination of the conveyor-cum-separator unit increase, as the dropping height rises. As a result, more power is required to operate the machine, resulting in increased fuel consumption.[29,30] An increase in fuel consumption was also observed with increase in conveying speed. This is because higher conveying speeds require more PTO power which increases fuel consumption. Similarly, an increase in fuel consumption with forward speed during potato digging was reported by Issa *et al*.[31]

Optimization of Parameters, Model Validation and Performance of Machine

The different operational parameters of the garlic harvester were optimized using numerical optimization technique of RSM. The values of forward speed, dropping height and conveying speed of machine were kept within the limit specified for the experiment. The goal assigned for the effective operation of the machine was maximum digging efficiency with minimum bulb damage and minimum fuel consumption. The optimized operational parameters of machine and predicted values of responses are given in Table 5. The forward speed of 1.53 km/h, dropping height of 0.47 m and conveying speed of 0.65 m/s were found as optimum for the operation of machine in vertisol (Table 5). The conveyor speed should be higher than the forward speed of machine that the manufacturers and researchers recommend.[32] In this study also the optimum value of conveyor speed was obtained higher than the forward speed of the machine. The

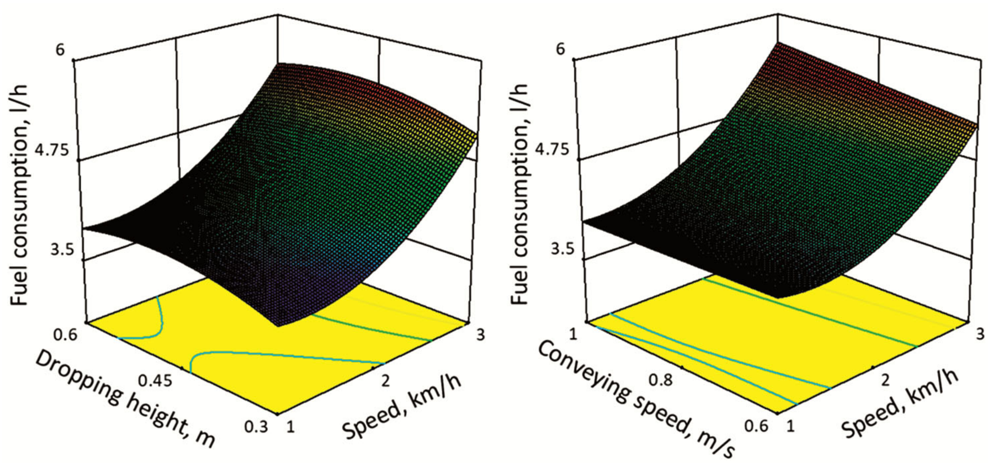

Fig. 6 — Surface graph showing the effect of different parameters on fuel consumption

Table 5 — Optimized factors and predicted values of responses

Variable	Goal	Minimum	Maximum	Optimized/Predicted value
Forward speed, km/h	In range	1.0	3.0	1.53
Dropping height, m	In range	0.3	0.6	0.47
Conveying speed, m/s	In range	0.6	1.0	0.65
Digging efficiency, %	Maximum	89.2	99.3	96.4
Bulb damage, %	Minimum	0.1	4.8	0.10
Fuel consumption, l/h	Minimum	3.6	5.5	4.02
Desirability	Maximum	—	—	0.88

ratio of conveyor speed to forward speed of the machine was found to be 1.5, similarly, the ratio of 1.25 was optimized for onion harvester.[28] At the optimized values of independent parameters, the predicted values of digging efficiency, bulb damage and fuel consumption were obtained as 96.4%, 0.1% and 4.02 l/h respectively. The overlay plot was prepared by superimposing the critical response contours (Fig. 7). The plot made with graphical optimization techniques shows the optimal region that satisfies the goals of each dependent parameter. Both numerical and graphical optimization techniques produce the same optimal values for the independent parameters.

The results obtained from the various models developed were validated to ascertain the veracity of the models. The machine was set up in the field with same condition for garlic harvesting using the optimized values of the parameters. The actual values of digging efficiency, bulb damage and fuel consumption were recorded as 96.1%, 0.13% and 4.34 l/h compared to the predicted values of 96.4%, 0.1% and 4.02 l/h, respectively. The predicted and actual values of performance parameters are very close, as seen in the Fig. 8. The developed models are perfectly predicting the responses with minimal error. The machine performed well with the optimum values of operational parameters.

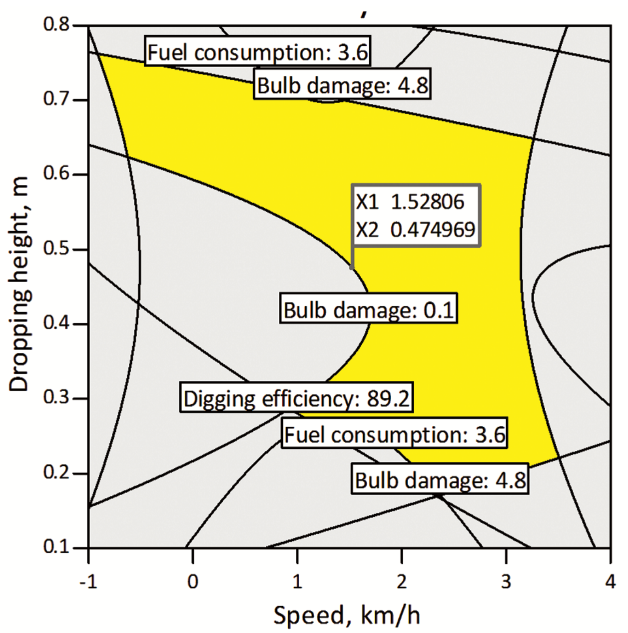

Fig. 7 — Overlay plot of dropping height and forward speed of machine

The machine was operated in field at the optimized forward speed of 1.53 km/h and working depth of 60–80 mm for digging garlic crop. The effective field capacity of harvester was 0.21 ha/h with field efficiency and digging efficiency of 72.1, 96.6%, respectively. The bulb damage (0.13%) was found to be very less during operation with the developed garlic harvester.

Cost Economics

The cost of operating a garlic harvester was calculated and compared with the manual harvesting method. The initial costs of tractor and garlic harvester were taken to be ₹550000 and ₹45000 respectively. The service life of tractor and harvester was assumed to be 10 years. The cost of operation of machine was found to be 768 ₹/h which includes a fixed cost of 153 ₹/h and a variable cost of 615 ₹/h respectively (Table 6). The cost of manual harvesting of garlic was around 10000 ₹/ha, which was 2.7 times higher than the cost of machine harvesting (3658 ₹/ha). The savings in cost and labor requirement were found to be 63.4 and 96.2% respectively as compared to manual method. The garlic digging with a developed harvester is found as cost effective and labor-saving technology.

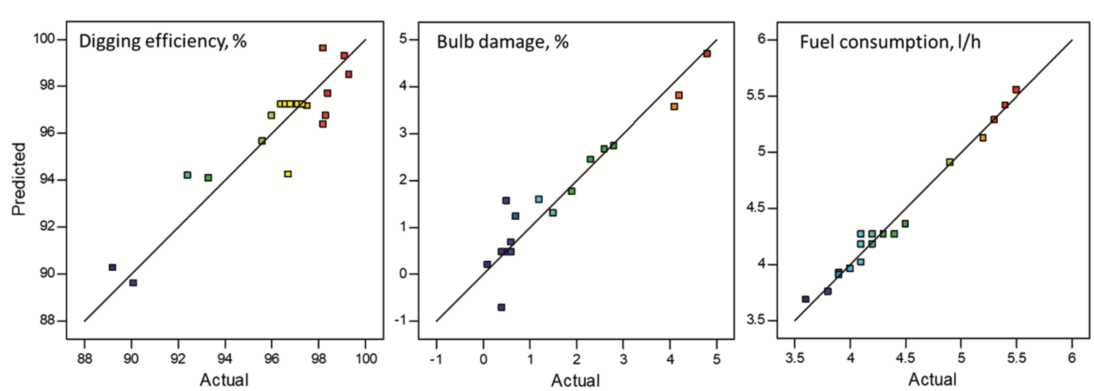

Fig. 8 — predicted and actual values of parameters

Table 6 — Cost economics of tractor drawn garlic harvester for raised beds

	Parameters	Tractor	Garlic harvester
(A) Fixed cost			
i	Initial cost of tractor, ₹	550000	45000
ii	Salvage value @ 10% of initial cost, ₹	55000	4500
iii	Service life, years	10	10
iv	Depreciation {(i-ii)/iii}, ₹/year	49500	4050
v	Annual uses, h/year	1000	200
vi	Interest on investment @ 8.8% per year, ₹/year	48400	3960
vii	Effective field capacity of machine, ha/h	—	0.21
viii	Insurance, taxes and housing @ 2% of (i), ₹/year	11000	900
ix	Total fixed cost (iv+vi+viii), ₹/year	108900	8910
x	Fixed cost of operation, ₹/h	108.9	44.55
xi	Total fixed cost of operation, ₹/h	153	
(B) Variable cost			
i	Repair and maintenance cost, ₹/h	27.5	11.25
ii	Fuel required, l/h	4.3	—
iii	Fuel cost @94₹/l, ₹/h	405	—
iv	Cost of lubricants @ 20% of fuel cost, ₹/h	81	—
v	Labour required with machine @ 8 h/day, No.	2	—
vi	Labour cost (₹/h) @50 for skilled and40for unskilled labour	50	40
vii	Variable cost (i+iii+iv+vi), ₹/h	563.5	51.25
viii	Total variable cost, ₹/h	615	
(C) Cost of operation with machine			
	Total cost of operation (Fixed cost + Variable cost), ₹/h	768	
	Cost of operation, ₹/ha	3658	
(D) Labour and cost saving			
	Labour required in manual harvesting, man-h/ha	250	
	Manual cost of harvesting @ ₹ 320 per day, ₹/ha	10000	
	Labour required in machine, man-h/ha	9.5	
	Saving in cost, %	63.4	
	Saving in labour, %	96.2	

Conclusions

Garlic digging is one of the most cumbersome and time-consuming tasks in garlic cultivation, especially in vertisol soil. The present scenario necessitates a mechanical solution to this problem. So that time, labor and money can be saved and the cost of cultivation can be reduced. In the present study, a mechanical harvester was developed for digging garlic crops sown on raised beds and its operational parameters were optimized using RSM. The following conclusions were drawn from the study:

1. The forward speed of the machine was found to be the most important factor in causing bulb damage and increasing fuel consumption during operation.
2. Garlic can be harvested mechanically with ease, and the machine developed is capable of completing its task in vertisol with raised beds.
3. The use of this machine reduces operational cost and labour requirements as compared to traditional manual harvesting method.

The optimum operating parameters of the harvester will help the machine to work with better field capacity, less bulb damage and less fuel consumption as compared to other harvesting machines. This developed machine will help farmers, garlic growers and agricultural machinery manufacturers to mechanize the process of garlic harvesting.

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