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Development of Vetiver (*Vetiveria Zizianoides)* Root Digger Equipment and Optimization of its Parameters under Field Condition

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Vetiver (*Vetiveria zizanioides*) is a significant aromatic crop cultivated for its essential oil extracted from its roots, widely used in the soap, cosmetics, and perfumery industries. However, harvesting Vetiver roots presents a considerable challenge due to their deep root system up to 45–50 cm in clay soils. Hence, in order to dig these roots, a suitable digger with a novel type of soil penetration tool has been developed to harvest the roots at a depth of 45 to 50 cm. The performance of the developed equipment was assessed under varying operational parameters, rake angles of 15°, 20°, and 25°, forward speeds of 0.72, 1.2, and 1.8 km/h, and soil conveyor speeds of 0.55, 0.69, and 0.83 m/s. The results revealed that the highest harvesting efficiency (80%) was noticed at a lower forward speed of 0.72 km/h, a conveyor speed of 0.83 m/s, and a rake angle of 25°. Fuel consumption of the tractor during operation was found to increase with higher forward speeds and greater rake angles. The maximum soil separation efficiency of 71% was achieved at a forward speed of 0.72 km/h, conveyor speed of 0.55 m/s, and rake angle of 15°. The developed equipment demonstrated the capability to harvest the roots at a depth of 45 cm and separate the soil and roots in a 300 m^2 area of vetiver crop in one hour. The newly developed digging equipment provides an effective solution for both harvesting Vetiver roots and soil separation in clay soils.

Keywords: Drudgery, Harvesting, Mechanization, Optimization, Roots

Introduction

Vetiver (*Vetiveria zizanioides*) is a significant aromatic crop belonging to the family Poaceae and is native to India. Generally, it is cultivated as an important aromatic crop for the production of its highly valued essential oil, which is used as a preservative in the perfumery and cosmetic industries. Vetiver essential oil is widely used in flavours and fragrances and also has several medicinal applications, including antifungal, anti-inflammatory, and antioxidant activities, making it valuable in the pharmaceutical industry.[1] In addition, the Vetiver crop develops a strong root system, increasing the soil's shear strength and resistance to disintegration, thus making it suitable for growing on slopes to prevent soil erosion in all types of soil and to stabilise it along riverbanks and other water bodies.

Several researchers, such as Islam *et al.*[2] and Wang *et al.*[3], have reported that Vetiver roots significantly increase the shear strength and cohesion of soils. Odum *et al.*[4] reported that the unit draft of heavy clay soils is 0.26 kg/cm^2, whereas Machado *et al.*[5] reported that the corresponding value for Vetiver-grown soils is 18.3 kg/cm^2 — nearly 70 times higher than that of heavy clay soils. This increased soil strength can be attributed to the adhesion between the soil and the extensive root system, which provides more contact area. As a result, harvesting of these roots presents a major challenge. Moreover, in the cultivation of Vetiver, approximately 65 – 70 % of the total expenses are incurred in harvesting the roots alone.[6] Therefore, many farmers are reluctant to cultivate this crop, which significantly hampers the expansion of its cultivation area and leads to a decline in the production of Vetiver essential oil.

Worldwide, various types of digging equipments are available for harvesting root crops such as potatoes, carrots, onions, groundnuts, cassava, ginger, and garlic. These machines are typically designed to dig up to a depth of only 20 – 25 cm. However, such equipment cannot be used for harvesting Vetiver roots which grows much deeper. For example, in the coastal sandy soils of Karnataka and Tamil Nadu, Vetiver roots can reach upto depths of 80 – 90 cm.[7] In

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these areas, farmers use backhoe loaders (Fig. 1) for harvesting, which not only increases the harvesting cost but also makes the field uneven. This demands additional energy for the next crop.

In the northern plains of India, Vetiver is predominantly cultivated in clayey soils. However, in such soil conditions, the root system typically grows to a depth of only 45 – 50 cm. Especially in the state of Uttar Pradesh, many farmers continue to employ manual digging methods, which are both time-consuming and labour-intensive. Consequently, harvesting Vetiver roots presents significant challenges due to their relatively deep growth and the compact nature of the soil. Among all operations involved in the cultivation of root crops, harvesting consumes the highest amount of energy.[8] This is primarily due to the increased draft force required to operate digging equipment in hard and compact soils. Various methods have been proposed to reduce the draught force needed for such operations, including the use of vibration[9] and fluid injection techniques.[10] However, these approaches involve complex setups that are not conducive to the simple design and fabrication typically desired in agricultural machinery. Nasr *et al*.[11] developed harvesting equipment suitable for potato crops and evaluated its performance in clay loam soils. Their findings indicated that increasing the operational speed from 1.5 km/h to 2.5 km/h led to a decrease in harvesting efficiency at digging depths of 16, 20, and 24 cm. Similarly, Kheiry *et al*.[12] assessed a potato digger at three operating speeds (4.4, 5.6, and 6.7 km/h) and digging depths of 16, 18, and 21 cm. Their results demonstrated that while increasing the digging depth from 16 cm to 21 cm enhanced the quantity of lifted potatoes, it concurrently reduced the field capacity.

Fig. 1 — Digging of Vetiver roots with the help of a backhoe loader and a tractor-mounted backhoe

Further studies by Kumar and Tripathi[13], Al-Dosary[14], and Hevko *et al*.[15] also reported the development and evaluation of potato diggers. These studies found that the maximum effective operating depth for such equipment generally ranged between 20 and 24 cm. A comprehensive review of the literature indicates that no existing machinery is currently capable of efficiently digging root crops at depths exceeding 30 cm. These findings highlight a significant gap in the development of harvesting equipment for deep-rooted crops such as Vetiver, underscoring the need for innovative solutions tailored to challenging soil conditions and deeper digging requirements.

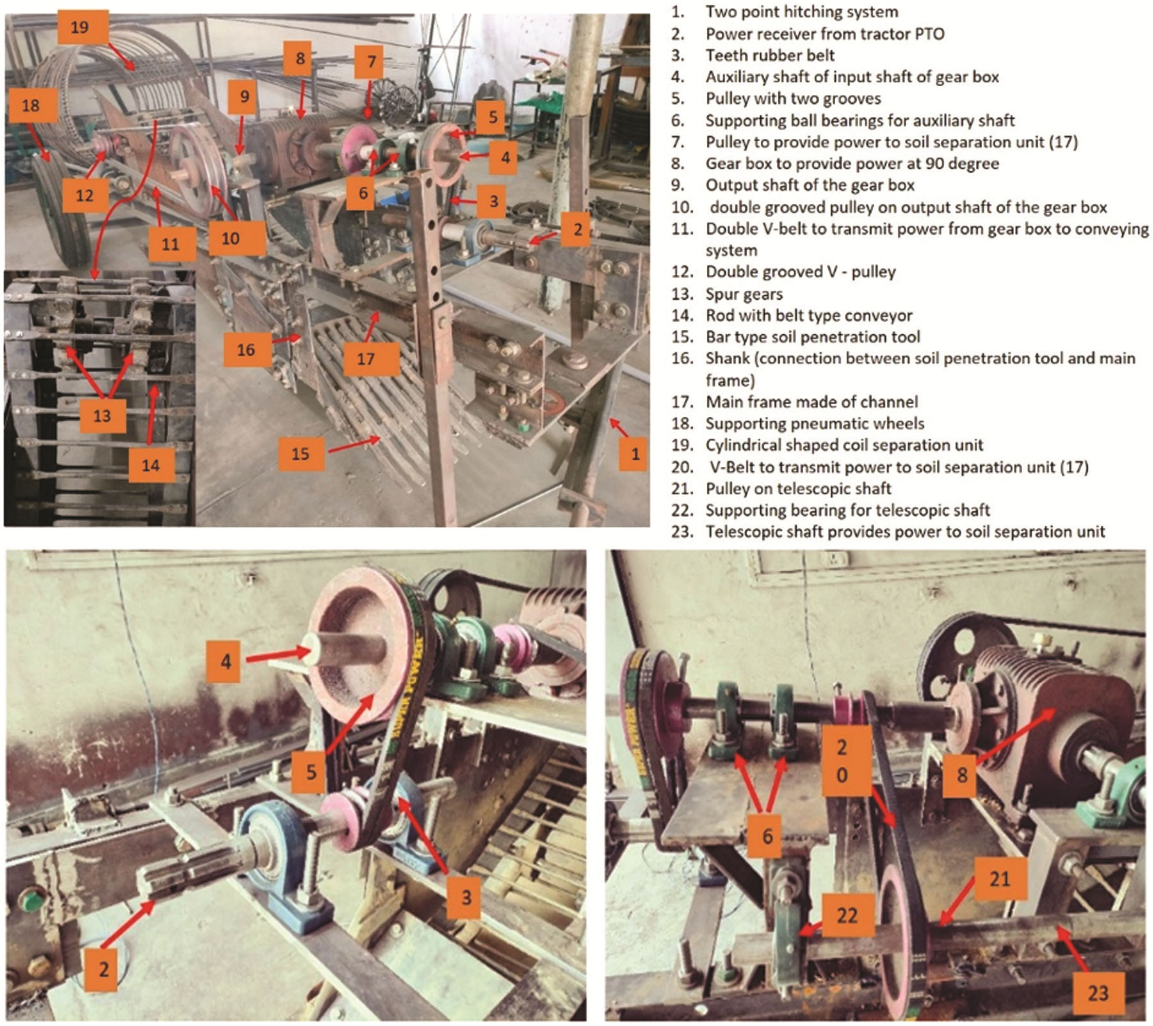
On Similar lines, CSIR-CIMAP has developed a tractor-operated digging equipment a few years ago, which was capable of penetrating the soil to a depth of only 30 cm. As a result, it was unable to harvest the maximum quantity of Vetiver roots.[6] Therefore, there is a need for suitable equipment capable of digging to greater depths to ensure efficient root recovery and to reduce the overall cost of the digging operation. In light of these considerations, an attempt was made to design and develop an improved digging equipment specifically suited for harvesting Vetiver roots at greater depths, with the objective of maximising root yield and enhancing operational efficiency.

Materials and Methods

Structural Components of the Digger

A tractor-operated Vetiver root-digging equipment was designed and developed at the CSIR–Central Institute of Medicinal and Aromatic Plants, Lucknow. The equipment was evaluated on a farmer's field near Mahmudabad, Uttar Pradesh, India (27.27° N, 81.08° E). The developed equipment (Fig. 2) consists of the following major components: an innovative bar-type soil penetration tool [15], a soil-root conveying system [13, 14], a power transmission system, a rotating cylindrical unit for soil-root separation [19], and a main structural frame [17] onto which all components are mounted.

As shown in Fig. 2, the bar-type soil penetration tool [15], fabricated from mild steel, initially penetrates the soil. As the tractor moves forward, this tool facilitates the loosening of the soil-root matrix, which is then transferred with reduced friction to the conveying system [13, 14]. The equipment requires two types of power inputs: (i) drawbar power for traction and forward movement, and (ii) rotational power from the Power Take-Off (PTO) shaft of the



1. Two point hitching system
2. Power receiver from tractor PTO
3. Teeth rubber belt
4. Auxiliary shaft of input shaft of gear box
5. Pulley with two grooves
6. Supporting ball bearings for auxiliary shaft
7. Pulley to provide power to soil separation unit (17)
8. Gear box to provide power at 90 degree
9. Output shaft of the gear box
10. double grooved pulley on output shaft of the gear box
11. Double V-belt to transmit power from gear box to conveying system
12. Double grooved V - pulley
13. Spur gears
14. Rod with belt type conveyor
15. Bar type soil penetration tool
16. Shank (connection between soil penetration tool and main frame)
17. Main frame made of channel
18. Supporting pneumatic wheels
19. Cylindrical shaped coil separation unit
20. V-Belt to transmit power to soil separation unit (17)
21. Pulley on telescopic shaft
22. Supporting bearing for telescopic shaft
23. Telescopic shaft provides power to soil separation unit

Fig. 2 — Overall structure of the Vetiver root digging equipment

tractor for operating the soil conveying and separation mechanisms. The soil-root mixture collected by the penetration tool is conveyed rearward through the soil conveying system [13, 14] and subsequently fed into a rotating cylindrical soil separation unit [19]. This unit, powered by the tractor's PTO shaft [2] via a belt-pulley arrangement and a telescopic shaft [23], facilitates the separation of adhesive soil from the Vetiver roots. All components are mounted on a robust main frame [17] constructed from steel channel sections, supported by pneumatic wheels [18] to ensure mobility and stability during field operations.

Soil Penetration Tool

The soil penetration tool is one of the most critical components in root crop harvesting equipment, as it consumes significantly more power compared to other parts of the digger.[16] Structural parameters such as the tool's shape and size, rake angle, depth of operation, and working width greatly influence both the quality of operation and the draught force required for digging.[17,18] Md Akhir *et al.*[19] reported that hoe-type soil penetration tools require less draught force compared to flat and V-shaped shovels. Similarly, Zhao *et al.*[17] observed that fence-like soil penetration tools reduce draught force due to minimal contact between the tool surface and the soil. Based on these insights, and the required depth of operation (45 to 50 cm), a simple bar-type soil penetration tool was designed and integrated into the developed digging equipment (Fig. 3a). This tool configuration is intended to reduce soil resistance while maintaining effective root lifting capability at a depth of 45 to 50 cm in the clay soils.

Soil-Root Conveying System

The soil conveying system is responsible for transporting the soil-root mixture received from the soil penetration tool to the soil separation unit, which

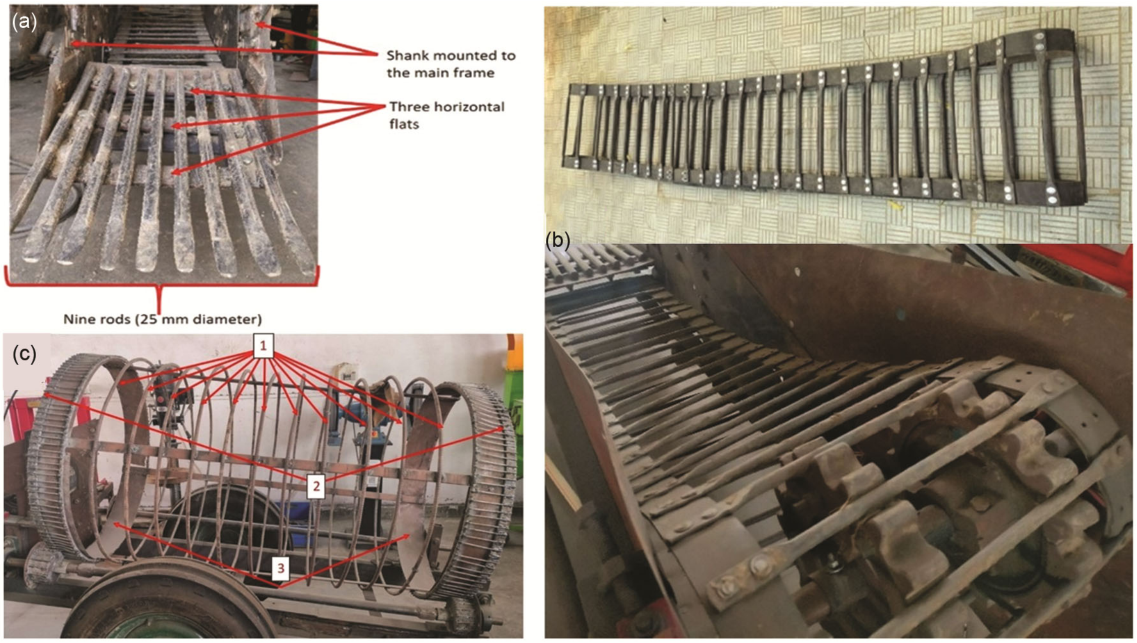


Fig. 3 — Various functional components of the vetiver root digging equipment: (a) Bar-type soil penetration tool, (b) Soil-root conveying system and (c) Soil separation unit mounted on two shafts

is mounted on the rear side of the equipment's main frame. The performance of the conveying system is primarily influenced by three factors: conveyor speed, conveyor length, and the inclination angle relative to the horizontal plane.[20]

To achieve optimal efficiency, previous studies and industrial standards recommend that the conveyor speed should be approximately 1.5 times the forward speed of the digging equipment.[18,21] However, in the present case, the equipment is designed to operate at a depth of 45 to 50 cm, substantially deeper than that of traditional root crop diggers. As a result, the volume of soil handled per unit area is significantly greater. To ensure efficient and continuous transfer of the soil-root mixture, the conveyor speed was increased to 2.5 times the forward speed of the equipment. Most conventional digging equipment performs optimally at a forward speed of 2.5 to 3.0 km/h[22], but these machines typically operate at depths not exceeding 25 cm. In contrast, the present equipment is designed for a much deeper digging range (45–50 cm), necessitating a considerably lower forward speed to maintain digging efficiency and reduce power requirements. Therefore, the forward speed for this equipment was set between 0.72 and 1.8 km/h. Modi *et al*.[23] reported that rod-belt type conveyors yield promising results for soil transport at higher conveyor speeds. Accordingly, a similar conveyor system was developed with the required specifications. The soil conveyor (Fig. 3b) is mounted at a 30° inclination, with a total length of 1.27 meters, and operates at a speed ranging from 0.55 to 0.83 m/s.

Soil Separation Unit

A cylindrical soil separation unit was developed as shown in Fig. 3c. The unit has a total length of 150 cm and a diameter of 80 cm. It was fabricated using mild steel (MS) bars, flats, and sheets. Specifically, twelve MS bars of 12 mm diameter [1], two MS flats measuring 25 × 4 mm [2], and MS sheets of 1 × 100 mm [3] were used in its construction. The twelve MS bars and two MS flats were bent into a circular shape to form the cylinder with an outer diameter of 80 cm.

Power Transmission

Power is required to operate two key components of the equipment: the soil-root conveying system and the cylindrical soil separation unit, both mounted at the rear of the equipment. The power source for the Vetiver root-digging equipment was a 45 kW tractor (Make: Sonalika, Model: 60DI). The equipment was specifically designed to operate using the tractor’s Power Take-Off (PTO) shaft. The power transmission system (Fig. 4) was designed and fabricated as per the PTO speed and the required conveyor speeds of 0.55, 0.69, and 0.83 m/s. These speeds were achieved by adjusting the pulley sizes accordingly. Power was transmitted to the telescopic shaft from an auxiliary

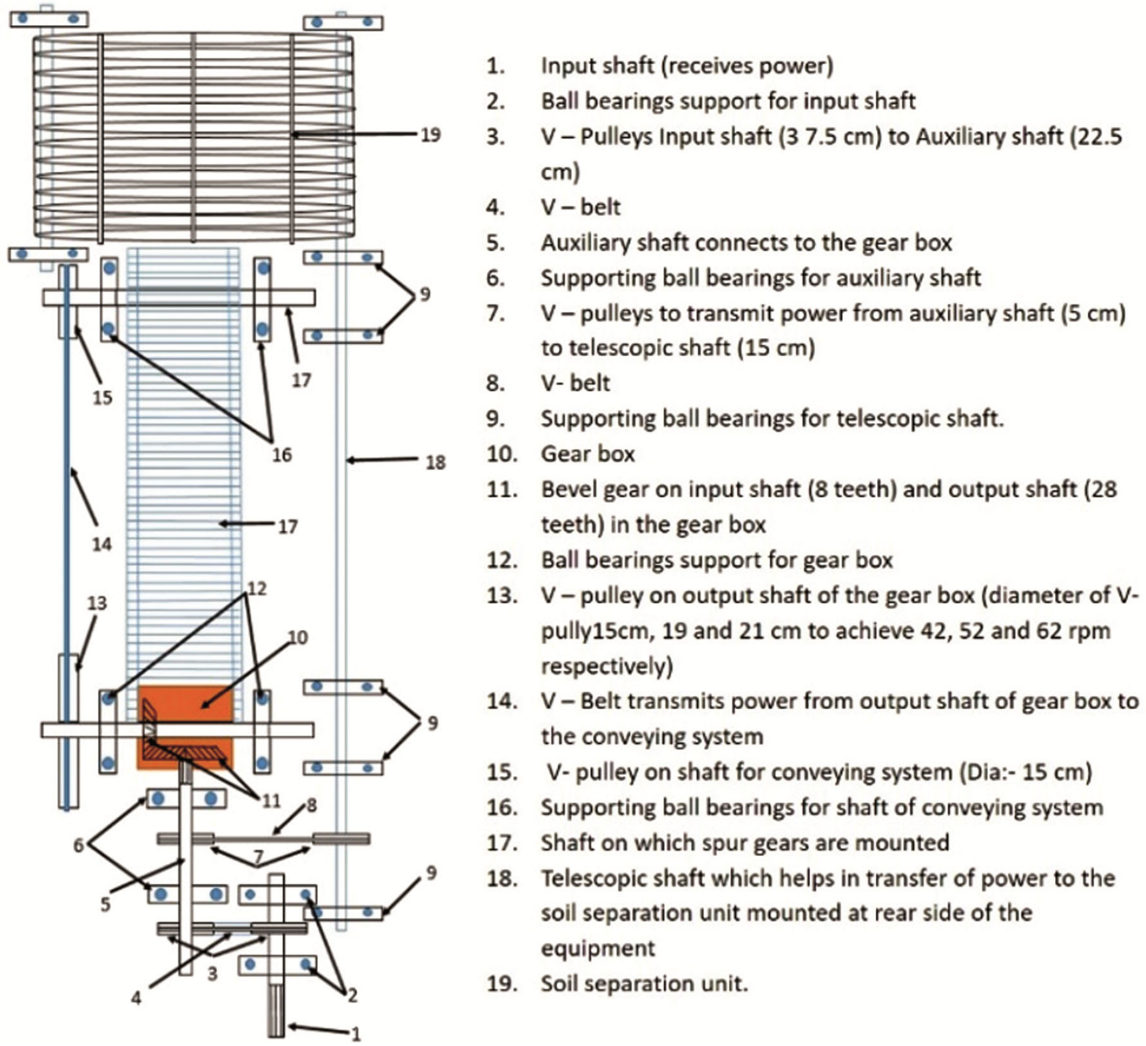


Fig. 4 — Power transmission system

shaft running at 400 rpm, ensuring that the cylindrical unit rotated at a speed of 50 rpm to achieve maximum efficiency of soil separation.

Main Frame

The main frame of the digging equipment is a critical structural component designed to withstand the combined loads generated by all other components, including the soil penetration tool, shanks, soil–root conveying system, power transmission system, and the soil separation unit. In particular, the soil penetration tool is subjected to substantial draught forces due to the hard and compact nature of the soil in the target fields. To meet these demands, the main frame was fabricated using a steel channel section with dimensions of 50 mm in width, 100 mm in height, and 6 mm in thickness. To provide additional support at the rear end of the equipment, two pneumatic wheels of size 6.00–16 were mounted on the main frame.

Performance Evaluation of the Digger

Description of the Field and Crop

Field trials were conducted in the Vetiver crop (Variety: CIM-Vridhi developed by CSIR–CIMAP), at a farmer’s field located near Mahmudabad, Uttar Pradesh, India. The crop was planted in sandy clay soil in the month of February, maintaining a spacing of 40 cm between plants as well as rows. To ensure optimal soil conditions for harvesting, the field was irrigated five days prior to the digging operation. Before initiating the field trials, soil samples were collected from multiple locations across the field to assess soil texture, bulk density, and moisture content. During the root harvesting trials, the moisture content of the soil was measured at 20 ± 2% (wet basis). The soil texture was determined to be 40.5% sand, 6.1% clay, and 53.4% silt, indicating a sandy clay loam composition. The cone index of the soil was recorded as 1100 kPa, and the bulk density of the same was measured at 1.5 g/cm³.

Experimental Design

The performance evaluation of the developed Vetiver root digging equipment was carried out in a farmer's field near Mahmudabad, in the state of Uttar Pradesh, India. The field performance was assessed under actual working conditions, following the guidelines specified in Indian Standard IS 13818:1993(24) for tractor-operated potato diggers. Three key independent variables were considered in the evaluation: (i) the forward speed of the equipment, (ii) the rake angle of the soil penetration tool, and (iii) the conveyor speed of the soil–root conveying system. Field trials were conducted on 20 m × 10 m Vetiver plots. Performance parameters, including harvesting efficiency, fuel consumption, power requirement, and soil separation efficiency, were recorded. Measurements were taken from a test area of 0.4 m × 1.0 m at three different locations per run to ensure accuracy and repeatability. The field operation of the Vetiver root digging equipment is illustrated in Fig. 5.

The optimum performance of the developed Vetiver root-digging equipment depends on key operating parameters, including the forward speed of the equipment, the rake angle of the soil penetration tool, and the conveyor speed of the soil–root conveying system.[20] These parameters were optimised using a central composite design (CCD) within the framework of response surface methodology (RSM) to statistically analyse and model the influence of each factor on equipment performance. The physical structure of Vetiver roots resembles fine hairs, with diameters ranging from approximately 1.5 mm near the stem to 0.2 mm at the root tips. Due to the delicate and fibrous nature of the roots, it is extremely difficult to accurately quantify root damage. Therefore, root damage was excluded as a response variable in this study. The levels and range of the independent variables used in the experimental design are presented in Table 1. A total of 20 experimental trials were conducted based on the Central Composite Design (CCD) for three independent variables. The data was analysed using the Design Expert software.

Fig. 5 — Vetiver root digging equipment in the field condition

Harvesting Efficiency

Harvesting efficiency represents the percentage of Vetiver roots successfully extracted from the field using the developed digging equipment. It is defined as the ratio of the number of roots harvested by the equipment to the total number of roots present in the field prior to the digging operation. To determine harvesting efficiency, Vetiver roots were first harvested manually at various locations to establish the actual root count in the field. Subsequently, the developed digging equipment was operated under the previously mentioned independent variables within the same field. The number of roots harvested by the equipment was recorded for each clump. Based on these data, the harvesting efficiency was calculated using the following formula.[22,25,26]

$$\text{Harvesting efficiency} = \frac{\text{No.of roots digged by digging equipmet}}{\text{No.of roots present in the field prior to digging operation}} \times 100\% \qquad \ldots (1)$$

Fuel Consumption

Fuel consumption during the Vetiver root digging operation was measured using the top-up method. Prior to initiating the field trials, the tractor's fuel tank was filled to full capacity. After operating the digging equipment for a specific duration, the tank was refilled to the same level. The volume of fuel required to refill the tank was considered as the amount of fuel consumed during that particular period of operation.[22,25,26]

Table 1 — Operating variables and their levels of Central Composite Design in Response Surface Methodology

Variables	Levels of operating variables		
	Lower value	Medium value	Upper value
A: Forward speed, km/h	0.72	1.2	1.8
B: Rake Angle, degrees	15	20	25
C: Conveyor speed, m/s	0.55	0.69	0.83

*Values within the enclosure indicate the coded values of CCD in RSM

$$\text{Fuel consumption l/h} = \frac{Valume\ of\ consumed\ fuel\ (liters)}{Time\ of\ vetiver\ root\ digging\ operation\ (hours)} \quad \ldots (2)$$

Power Requirement

The power requirement of the root-digging equipment was calculated using fuel consumed during the digging operation using the following equation.[26] The fuel consumption per unit time is directly proportional to the power requirement of the digging equipment.

$$P = F_c \times \frac{1}{60 \times 60} \times \rho_f \times L.C.V \times 427 \times \eta_{th} \times \eta_m \times \frac{1}{75} \times \frac{1}{1.36}, \text{kW} \quad \ldots (3)$$

where, P = Total power requirement to operate digger, kW; Fc = Fuel Consumption of the tractor, L/h; ρ_f = Fuel Density, 0.85 kg/l; η_{th} = Thermal efficiency of the tractor engine, (For Diesel engine:-36%); η_m = Mechanical efficiency of the engine (80 – 85%); L.C.V = Lower Calorific value of the fuel used in the tractor (i.e. Diesel:-10000 – 11000) kcal/kg; 427 = Thermo-mechanical equivalent J/kcal.

Soil Separation Efficiency

Following the harvesting of Vetiver roots, soil separation remained a labor-intensive task, traditionally requiring significant manual effort. To address this challenge, a cylindrical soil separation unit was designed and mounted at the rear end of the digging equipment. This unit facilitated immediate separation of soil from the roots after harvesting, thereby reducing labor requirements and improving operational efficiency. Soil separation efficiency was determined by comparing the amount of soil adhered to the Vetiver roots before and after passing through the separation unit. It was calculated using the following formula:

$$Soil\ separation\ efficiency\ (\%) = \left(\frac{Weight\ of\ soil\ adhered\ before\ separation - weight\ of\ soil\ adhered\ after\ separation}{Weight\ of\ soil\ adhered\ before\ separation}\right) \times 100 \quad \ldots (4)$$

Results and Discussion

The data obtained from the field trials of the Vetiver root digging equipment, conducted under various combinations of operating parameters, were analyzed and are presented in Table 2. The developed digging equipment was able to operate at a depth of 45 cm continuously. Thus nearly 95% of the roots were able to extract from the soils. Remaining 5% roots remain in the soil. Furthermore, the analysis of variance (ANOVA) was performed to evaluate the effect of different operating variables on key performance indicators, including harvesting

Table 2 — Field data of the digger obtained at various levels of operating variables

Operating variables			Dependent variables			
Rake angle, degrees	Forward speed, km/h	Conveyor speed. m/s	Harvesting efficiency, %	Fuel consumption, lph	Power Requirement, kW	Soil separation efficiency, %
20.00	0.35	0.69	72	6.54	19.08	67
12.00	1.26	0.69	61	6.10**	17.80**	68
15.00	1.80	0.83	61	6.85	19.99	48
15.00	1.80	0.55	58**	8.89*	25.94*	60.
15.00	0.72	0.83	72	6.12	17.86	62
15.00	0.72	0.55	71	6.15	17.94	70*
20.00	1.26	0.93	69	6.75	19.70	48
20.00	1.26	0.69	65	8.01	23.37	60
20.00	1.26	0.69	67	7.92	23.11	59
20.00	1.26	0.45	63	7.89	23.02	66
20.00	1.26	0.69	65	8.05	23.49	60
20.00	1.26	0.69	66	7.94	23.17	60
20.00	1.26	0.69	65	7.98	23.28	60
20.00	1.26	0.69	67	7.86	22.93	60
20.00	2.17	0.69	61	8.50	24.80	44
25.00	0.72	0.83	80*	7.45	21.74	51
25.00	0.72	0.55	79	7.43	21.68	64
25.00	1.80	0.83	65	8.03	23.43	40**
25.00	1.80	0.55	65	8.16	23.81	55
28.40	1.26	0.69	71	8.20	23.93	56

*, ** indicate the highest and lowest values of the variables, respectively

Table 3 — Analysis of variance of performance parameters

	Harvesting efficiency		Fuel consumption		Power requirement		Soil separation efficiency	
	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value
Model	8.20	0.001*	19.99	2.96E-05*	19.99	2.9E-05*	65.64	1.04E-07*
A-Farword speed	50.12	0.00003*	68.98	8.47E-06*	68.98	8.4E-06*	238.43	2.64E-08*
B-Rake angle	18.67	0.00151*	45.95	4.86E-05*	45.95	4.8E-05*	95.44	1.97E-06*
C-Conveyor speed	2.00	0.18693^{NS}	17.75	0.00179*	17.75	0.0018*	213.0	4.55E-08*
AB	0.78	0.39693^{NS}	8.42	0.01577**	8.42	0.0157**	1.15	0.308431^{NS}
AC	0.01	0.91082^{NS}	8.42	0.01577**	8.42	0.0157**	1.18	0.302226^{NS}
BC	0.08	0.77984^{NS}	6.93	0.02500**	6.93	0.0250**	3.98	0.073999^{NS}
A^2	1.11	0.31644^{NS}	3.84	0.07836^{NS}	3.84	0.0783^{NS}	25.62	0.000491*
B^2	0.67	0.42908^{NS}	14.80	0.00322*	14.80	0.0032*	2.17	0.171049^{NS}
C^2	0.78	0.39765^{NS}	8.88	0.01379**	8.88	0.0138**	9.74	0.010834*

Level of significance * = 1%, ** = 5%, and NS: Non-significant

efficiency, fuel consumption, power requirement, and soil separation efficiency. The results of this statistical analysis are summarized in Table 3.

Influence of Operating Variables on the Performance Parameters of the Digger

Harvesting Efficiency

Harvesting efficiency is a critical parameter for evaluating the performance of root-digging equipment. The maximum and minimum harvesting efficiencies, 80% and 58%, respectively, were recorded at a forward speed of 0.72 km/h and 1.8 km/h, a rake angle of 25° and 15°, and a conveyor speed of 0.83 m/s and 0.55 m/s, respectively (Table 2). Regardless of the specific levels of the operating parameters, the overall performance indices related to harvesting efficiency are summarised in Table 4. The analysis of variance (ANOVA) indicated that forward speed and rake angle had a statistically significant effect on harvesting efficiency, while conveyor speed had no significant influence (Table 3). Similar findings were reported by Jat *et al.*[21] during garlic harvesting on raised beds. A predictive model for harvesting efficiency was developed by analyzing the experimental data using Design-Expert software. The second-order polynomial model for harvesting efficiency is presented in Eq. (5) as follows:

$$Harvesting\ efficiency = 65.64 - 5.19A + 3.17B + 1.04C - 0.85AB + 0.11AC - 0.27BC + 0.75A^2 + 0.59B^2 + 0.63C^2 \quad \ldots (5)$$

The developed model exhibited an F-value of 8.2 (Table 3), indicating that the model is statistically significant ($p < 0.01$) for all three operating variables.

Table 4 — Performance indices of the Vetiver root digging equipment

Operating parameters	SD	R square	Mean	Adj R square	CV
Harvesting efficiency	2.71	0.88	66.98	0.77	4.04
Fuel consumption	0.26	0.95	7.54	0.90	3.49
Power requirement	0.77	0.95	22.00	0.90	3.49
Soil separation efficiency	1.45	0.98	57.91	0.97	2.50

The coefficient of determination ($R^2 = 0.88$) suggests a comparatively strong correlation between harvesting efficiency and the operating parameters (Table 4). The interaction effects of the parameters on harvesting efficiency were further analyzed using response surface plots. The results indicate that harvesting efficiency increases with an increase in rake angle, while it decreases with an increase in forward speed (Fig. 6a). This trend can be attributed to the deeper penetration of the soil-engaging tool at lower forward speeds, and improving the ability of the soil penetration tool to dislodge and recover more roots. A lower forward speed provides more time for the digging tool to penetrate deeper into the soil, especially when combined with a higher rake angle. In contrast, at higher forward speeds, the reduced interaction time results in shallower penetration and lower root recovery. Similar findings were reported by Naik *et al.*[20] and Omar *et al.*[27] for onion harvesting equipment, and by Nasr *et al.*[11] for potato harvesting equipment. Further, it was observed that the conveyor speed has minimal influence on harvesting efficiency (Fig. 6b), consistent with the findings of Jat *et al.*[21] in garlic harvesting studies. Overall, the results demonstrate that the highest harvesting efficiency is achieved at lower forward speeds and higher rake angles. Similar trends were observed by Ibrahim and Attia[22] in their study on potato tuber harvesting.

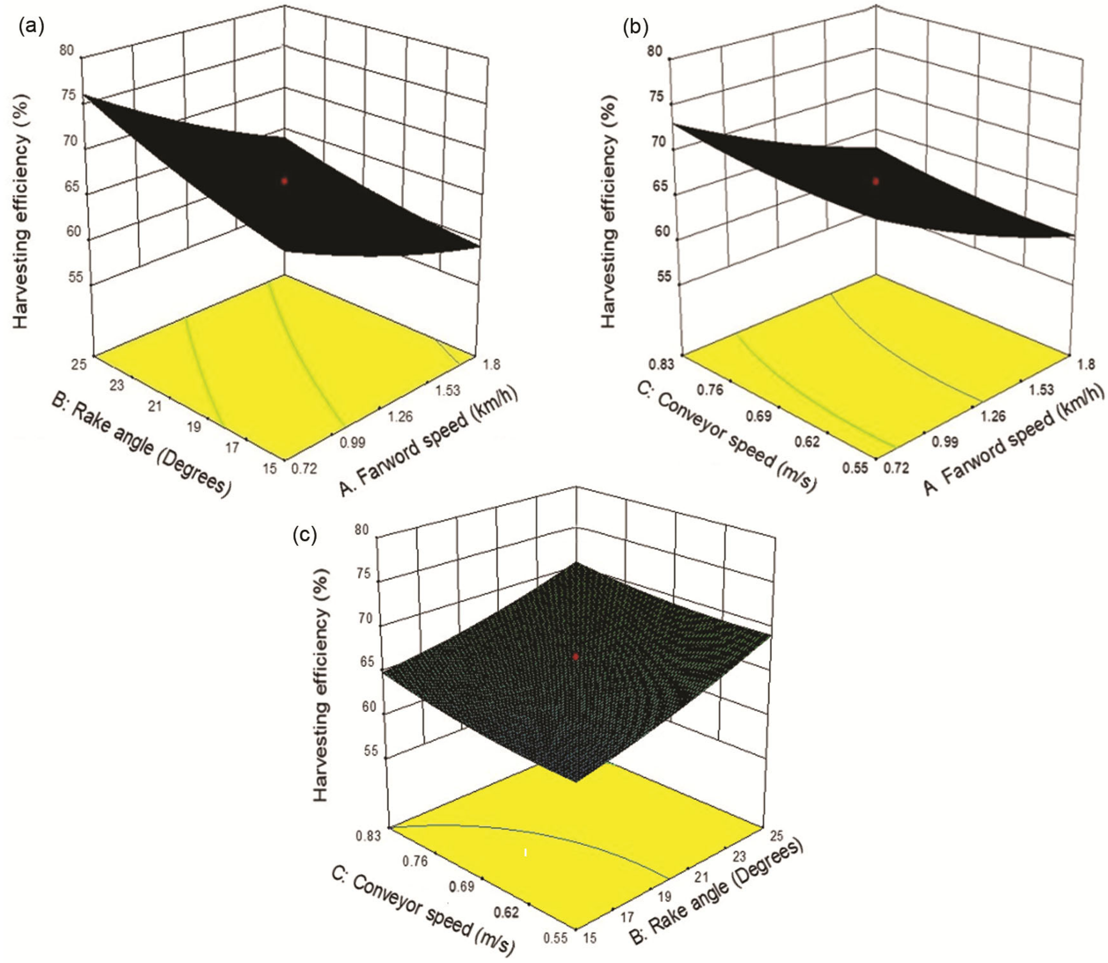


Fig. 6 — Interaction effect of rake angle, conveyor speed and forward speed on harvesting efficiency of the equipment

Fuel Consumption

Fuel consumption for operating the Vetiver root-digging equipment was recorded using the top-up method. Variations in fuel consumption with respect to different levels of forward speed, rake angle, and conveyor speed are illustrated in Fig. 7. The maximum and minimum fuel consumption of 8.89 and 6.1 L/h was recorded at a forward speed of 1.8 and 1.26 km/h, a rake angle of 12 and 15°, and a conveyor speed of 0.69 and 0.55 m/s (Table 2). The analysis of variance (Table 3) revealed that all three operating variables—forward speed, rake angle, and conveyor speed—significantly influenced the tractor's fuel consumption during operation. Furthermore, the interaction effects of these parameters were found to be statistically significant at the 5% significance level ($p < 0.05$). A predictive model for fuel consumption was developed using coded variables and is presented in Eq. (6) as follows:

$$Fuel\ Consumption\ (lph) = 7.96 + 0.59A + 0.48B - 0.3C - 0.27AB - 0.27AC + 0.25BC - 0.14A^2 - 0.27B^2 - 0.21C^2 \quad \ldots (6)$$

The developed model for fuel consumption exhibited an F-value of 19.99, indicating that the model is statistically significant at the 1% level ($p < 0.01$) for all three operating variables. The high coefficient of determination ($R^2 = 0.95$) confirms a strong correlation between fuel consumption and the selected operating parameters (Table 4). The analysis revealed that fuel consumption increased with increasing forward speed and rake angle of the equipment (Fig. 7b). These findings are consistent with the results reported by Jat *et al.*[21] for garlic harvesting and Younis *et al.*[28] for potato tuber harvesting. Further, the response surface is inclined towards lower levels of forward speed and rake angle, indicating that lower draught forces are required

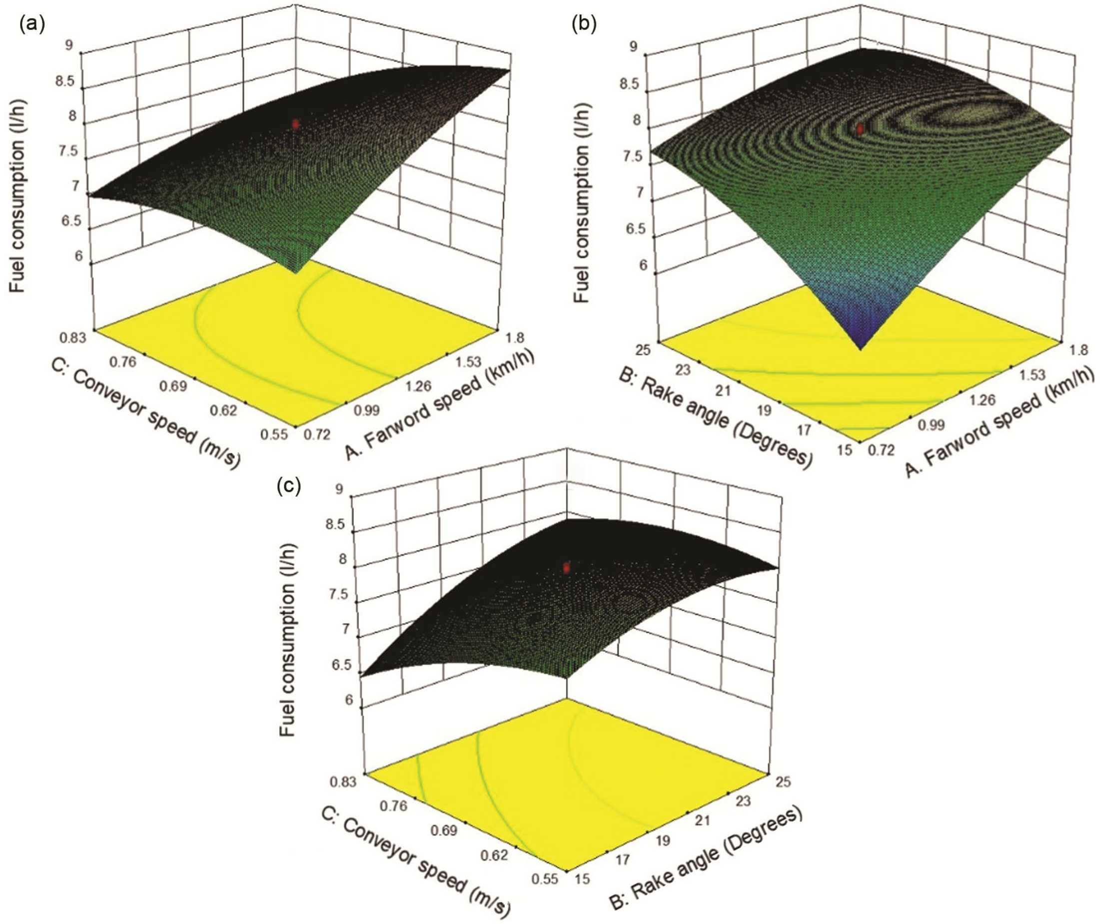


Fig. 7 — Interaction effect of rake angle, conveyor speed and forward speed on Fuel Consumption of the Tractor

when operating the digger at reduced levels of these variables. A similar trend was reported by Kheiry *et al.*[12] for potato-digging operations.

Further, Fig. 7(a) indicates minimal variation in fuel consumption with respect to conveyor speed. Overall, the study shows that the minimum fuel consumption was observed at lower levels of forward speed, rake angle and irrespective of conveyor speed. Although variation in fuel consumption due to conveyor speed was minor, an increase in rake angle led to a noticeable rise in fuel consumption. A slight inclination of the response surface towards higher conveyor speeds was also observed with increasing rake angle (Fig. 7c). This may be attributed to the inefficiency of the soil conveyor at lower speeds when the tractor moves at higher forward speeds. Under such conditions, the conveyor fails to effectively transfer the soil-root mixture, resulting in higher resistance as the mixture moves from the soil penetration tool to the conveyor.

Power Requirement

The power requirement for digging equipment depends on the fuel consumption of the power source. Like fuel consumption, all three operating parameters demonstrated a significant impact on power requirement at a 1% level of significance. The F value of the model for power requirement is also the same as fuel consumption, i.e. 19.99. Thus, the developed model also shows an impact on power requirement at 1% level of significance. The model for the prediction of power requirement using operating parameters is as follows (Eq. 7).

$$Power\ requirement = 23.22 + 1.73A + 1.41B - 0.88C - 0.79AB - 0.79AC + 0.71BC - 0.4A^2 - 0.78B^2 - 0.6C^2 \quad \ldots (7)$$

Furthermore, it is observed that the response curves are inclined towards lower rake angles and forward speed levels (Fig. 8a). This shows that the power requirement is directly proportional to the rake angle and forward speed of the root-digging equipment.

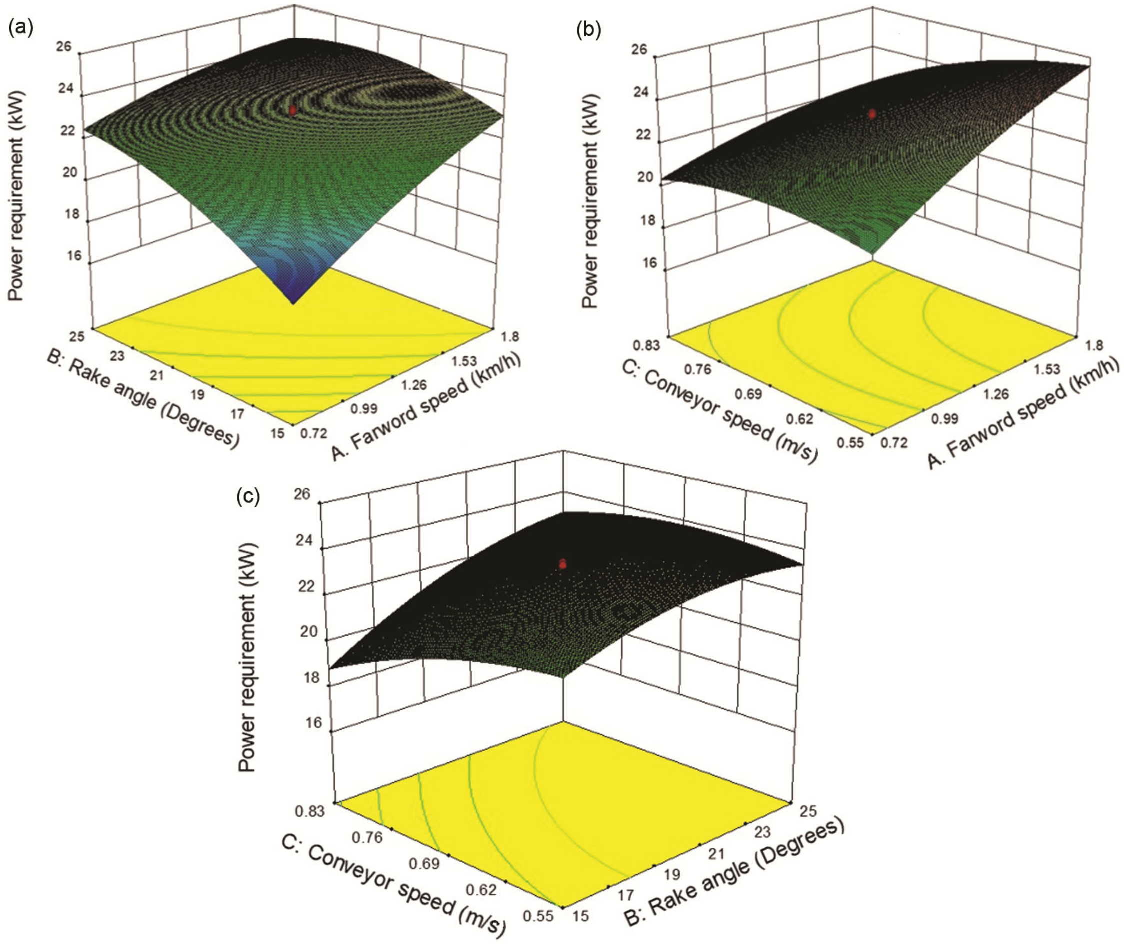


Fig. 8 — Interaction effect of rake angle, conveyor speed and forward speed on power requirement of the digger

These results are in close agreement with the findings of Nasr *et al.*[11] for potato harvesting equipment. Further, the F-values (Table 3) imply that the forward speed significantly impacts power requirement more than the rake angle. In the combination of conveyor speed and forward speed, the variation of power requirement with respect to change in conveyor speed is much less than that of forward speed. The intensity of work done with respect to the change in rake angle is much higher than the change in conveyor speed. Data presented in Table 3 shows that all individual, as well as interaction combination influences, power requirement at a 1% level of significance.

Soil Separation Efficiency

The separation of adhesive soil from Vetiver roots presents a significant challenge, particularly during harvesting from depths of 40 to 45 cm. Manual separation of soil is labor-intensive and increases operational costs for farmers. The maximum and minimum soil separation efficiencies, 70% and 40%, respectively, were recorded at a forward speed of 0.72 and 1.8 km/h, a rake angle of 15° and 25° and a conveyor speed of 0.55 m/s and 0.83 m/s, respectively (Table 2). The p-values associated with all three parameters were less than 0.01 (Table 3), indicating that each parameter significantly affects soil separation efficiency. The F value of the model for soil separation efficiency is observed as 65.64. Thus, the developed model also shows an impact on soil separation efficiency at a 1% level of significance. The model for the prediction of soil separation efficiency using operating parameters is as follows (Eq. 8).

$$Soil\ separation\ efficiency = 59.66 - 6.06A - 3.83B - 5.73C + 0.55AB - 0.56AC - 1.02BC - 1.93A^2 + 0.56c - 1.19C^2 \quad \ldots (8)$$

Higher soil separation efficiency was achieved at lower forward speeds and smaller rake angles (Fig. 9a). This can be attributed to a reduced volume

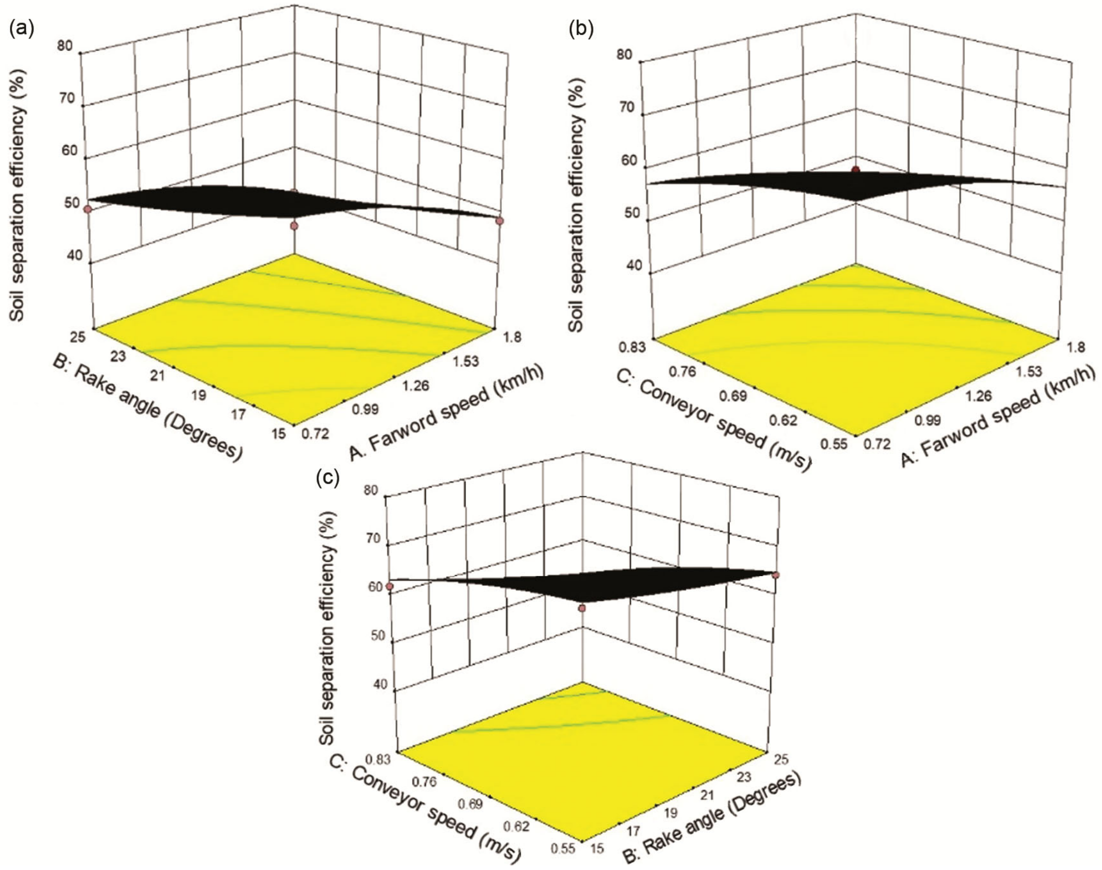


Fig. 9 — Interaction effect of rake angle, conveyor speed and forward speed on soil separation efficiency of the digger

of the soil-root mixture entering the separation unit per unit time, which allows more effective processing. In contrast, at higher forward speeds and larger rake angles, a greater volume of material is introduced into the separation unit, thereby reducing the soil separation efficiency due to increased throughput demands in a limited timeframe. At lower conveyor speeds, the soil separation efficiency is higher compared to that at higher speeds. The reduced conveyor speed allows more time for the separation mechanism to act on the soil-root mixture, resulting in improved efficiency.

Table 5 — Constraints of operating parameters for optimisation of performance parameters

Parameter	Goal	Lower limit	Higher Limit	Optimized values
A: Forward speed	is in range	0.72	1.8	0.72
B: Rake angle	is in range	15	25	15
C: Conveyor speed	is in range	0.55	0.83	0.79
Harvesting efficiency, %	Maximize	58	80	70
Fuel consumption, lph	Minimize	6.1	8.89	5.88
Power requirement, kW	Minimize	17.79	25.93	17.17
Soil separation efficiency, %	Maximize	40	70	65

Optimization of Operating Parameters on Responses

To determine the optimum conditions for the performance of the Vetiver root-digging equipment, Response Surface Methodology (RSM) was employed. Initially, based on the developed models and response surfaces, the operating parameters were defined within specific ranges, while the performance parameters were set to achieve either maximum or minimum values according to the functional requirements of the equipment, as presented in Table 4. The optimal values (Table 5) —forward speed of 0.72 km/h, rake angle of 15°, and conveyor speed of 0.79 m/s—resulted in the following predicted performance outcomes: harvesting efficiency of 70%, fuel consumption of 5.88 L/h, power requirement of 17.17 kW, and soil separation efficiency of 65%. At these optimal settings, the corresponding machine performance parameters were: theoretical field capacity of 0.035 ha/h, actual field capacity of 0.0288 ha/h, and field efficiency of 82%. Subsequently, the equipment was tested under these

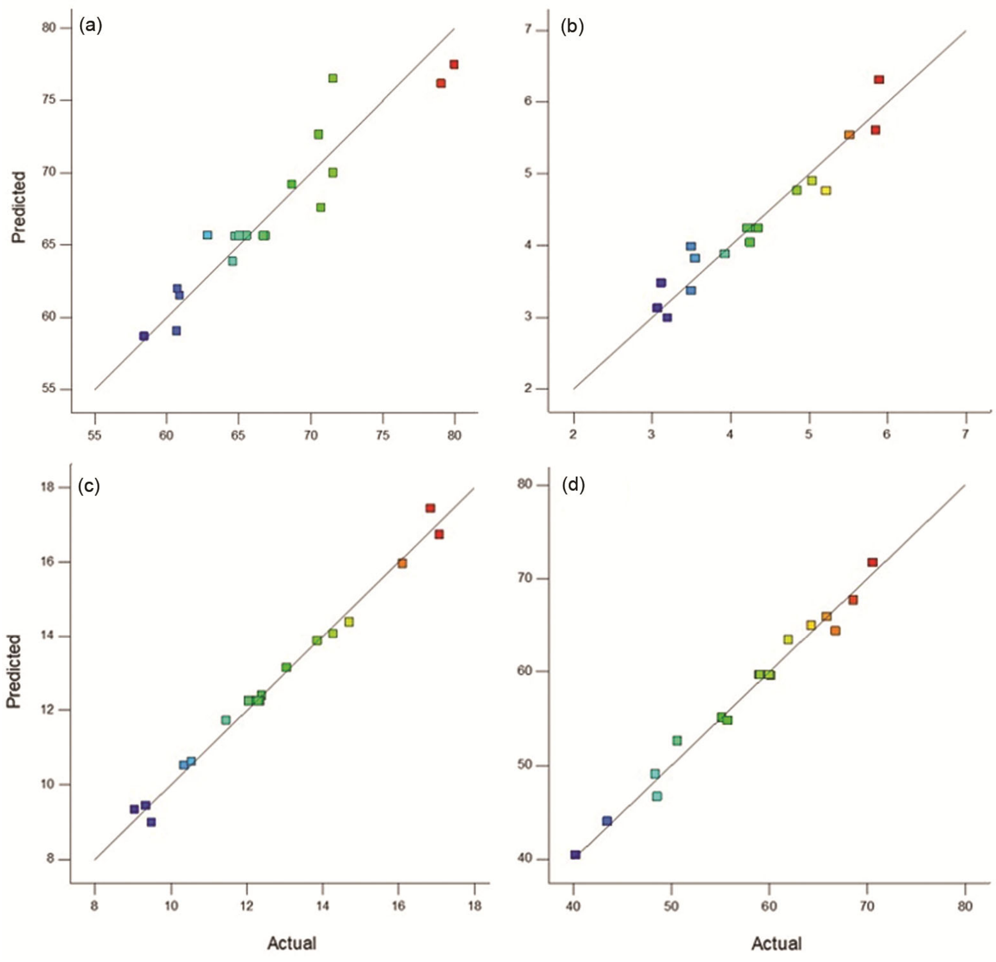


Fig. 10 — Actual and predicted values of operating parameters: (a) Harvesting efficiency, (b) fuel consumption, (c) Power requirement and (d) Soil separation efficiency

optimized conditions. The actual measured performance values were: harvesting efficiency of 72%, fuel consumption of 5.95 L/h, power requirement of 17.81 kW, and soil separation efficiency of 66%. These observed values were closely aligned with the predicted values, as depicted in Fig. 10, demonstrating the robustness and accuracy of the developed predictive models. The minimal deviation between the predicted and actual results confirms that the models can reliably estimate the performance parameters with a high degree of precision.

Economics of the Vetiver Root-digging Operation

A cost analysis of vetiver root harvesting operations using three different methods was conducted and is presented in Table 6. In the case of manual digging, a total of 286 man-days are required to harvest vetiver roots and separate them from the soil over one hectare of land. Assuming a labour charge of ₹300 per day in rural areas, the total cost of harvesting one hectare by the manual method is estimated at ₹85,800. In contrast, the harvesting operation using the CIMAP-developed old digger incurs a total cost of ₹50,273 per hectare. This estimate includes the fixed cost of the equipment, operational costs of the tractor and digger, and associated labour costs. The newly developed digging equipment, however, offers a more economical solution, with an estimated cost of ₹38,841 per

Table 6 — Economics of harvesting of Vetiver roots by different methods

	Fixed Cost (₹/ha)	Operational Cost (₹/ha)	Labour Cost (₹/ha)	Total (₹/ha)
Novel digging equipment	₹ 8661	₹ 28680	₹ 1500	₹ 38841
Old CIMAP digger	₹ 7895	₹ 30378	₹ 12000	₹ 50273
Manual Digging			₹ 85800	₹ 85800

hectare. This represents a substantial reduction in cost compared to both the CIMAP old digger and the traditional manual method.

In addition to cost savings, the developed digging equipment was able to extract approximately 95% of the vetiver roots from the soil. In comparison, the CIMAP old digger and manual methods enabled recovery rates of only 60 to 70%. These findings indicate that mechanised harvesting significantly improves root extraction efficiency while reducing operational costs. Thus, the adoption of the developed digging equipment presents a promising alternative to traditional harvesting methods for vetiver root cultivation

Conclusions

In this study, tractor-drawn digging equipment for the harvesting of Vetiver roots was developed and evaluated under field conditions. All three operating parameters—forward speed, rake angle, and conveyor speed—significantly influenced the key performance indicators: harvesting efficiency, fuel consumption, power requirement, and soil separation efficiency. The developed equipment demonstrated the capability to harvest Vetiver roots at a depth of 40 – 45 cm effectively. The cost of vetiver root harvesting by a developed digger is recorded as 45 % less than that of the traditional method. Further design modifications are needed in the soil separation unit to improve soil separation efficiency. Optimisation of the material used in the fabrication of the digging equipment to reduce production costs is required.

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Declarations

Conflict of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work in this paper.

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