International Engineering Journal For Research & Development

Vol.11
Issue 1

PERFORMANCE EVALUATION OF TRACTOR DRAWN CARROT DIGGER

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ABSTRACT

Performance evaluation of a tractor-drawn carrot harvester was conducted to determine its field efficiency, harvesting capacity, root damage, and suitability for medium-scale carrot production. The study addressed the limitations of manual harvesting, which is labor-intensive, time-consuming, and results in high post-harvest losses. Field experiments were carried out on a farmer's field at Bate Kebele. The experiment was arranged in a factorial randomized block design with three replications, using forward speed (2.5, 3.0, and 3.5 km h^{-1}) and rake angle (15°, 20°, and 25°) as factors. Performance was evaluated in terms of draft force, digging efficiency, root damage, soil separation efficiency, field capacity, field efficiency, wheel slip, and fuel consumption. The optimum operating condition was a rake angle of 20° at a forward speed of 3.5 km h^{-1}. At this setting, digging efficiency, root damage, effective field capacity, field efficiency, soil separation efficiency, and wheel slip were 91.87%, 3.29%, 0.25 ha h^{-1}, 84.93%, 89.49%, and 17.68%, respectively. Fuel consumption per hectare was 17.56 L, with a maximum draft force of 6111.4 N. The results demonstrate that the harvester improves efficiency and reduces labor demand, making it suitable for commercial carrot production.

Key words:* *Rake angle, forward speed, performance evaluation, digging efficiency, field capacity, operating parameters

INTRODUCTION

Carrot is one of the most important root vegetables cultivated worldwide for both fresh consumption and processing industries. Its production requires timely and efficient harvesting to maintain quality, reduce post-harvest losses, and ensure profitability. Traditionally, carrot harvesting in many developing regions including Africa and Asia is performed manually using hand tools. This method is highly labor-intensive, slow, and often constrained by seasonal labor shortages [1]. Manual harvesting also exposes roots to mechanical injuries, contamination, and uneven harvesting depth, which compromises market quality and increases losses during handling and storage [2].

Mechanization of root crop harvesting has therefore become critical for modern horticultural production. Tractor-drawn harvesters offer improved operational efficiency, greater uniformity, and reduced dependence on labor. These machines typically employ digging blades, conveyor mechanisms, and soil separation units to lift and collect carrots with minimal damage. Previous studies on mechanized root crop harvesters such as those for potatoes and sweet potatoes have demonstrated significant gains in field capacity, reduced harvesting time, and lower operational costs [3]. Despite these benefits, the performance of tractor-drawn carrot harvesters varies with soil moisture, root size, field conditions, and machine settings, making localized evaluation essential for optimizing operation [4].

Performance evaluation of a tractor-drawn carrot harvester is necessary to determine its adaptability, efficiency, and economic feasibility under specific field and agro-climatic conditions. As carrot cultivation expands due to increasing demand in urban markets, producers face challenges associated with labor shortages, rising wages, and the need for timely harvesting. A properly evaluated mechanized harvester can significantly reduce labor requirements by up to 60–70%, improve timeliness of operations, and enhance overall productivity [5].

Previous studies on root crop harvesting equipment have shown that mechanization can significantly enhance field efficiency and reduce harvesting time, but the results vary depending on machine configuration and field conditions. For instance, research on root crop diggers and bed loosening implements has demonstrated that factors such as soil bulk density, draft force, and digging depth significantly affect performance outcomes [6]; while soil physical properties and measurement methods also play a critical role in evaluating machine effectiveness [7]. Additionally, the mechanics of tractor-implement interaction and the theoretical basis of machine performance provide foundational understanding for evaluating and improving carrot harvesting systems [8].

Given the increasing push toward horticultural mechanization and the need for scalable solutions for medium-scale farmers, a performance evaluation study provides scientific evidence to support decision-making, equipment modification, and farmer adoption. This research is therefore justified to ensure that tractor-drawn carrot harvesting technology is efficient, economically viable, and capable of meeting the growing demands of commercial carrot production. The objective of this project was intended to evaluate the performance of tractor drawn carrot harvester machine.

MATERIALS AND METHODS

Measuring Devices and Instruments

The materials selection was critically considered based on strength, availability, durability, resistance to corrosion, ease of fabrication, maintenance and repair. Instruments and materials used was given in table 1.

Table 1: List of Materials

No	Materials	Application
1	Caliper	To measure the dimension of carrot crop
2	Stop watch	To record the time of operation of the harvester
3	Weighting scale	To determine the weight of crop
4	Graduated cylinder	To measure the fuel consumption of the machine
5	Carrot variety	The variety that was used
6	Tractor	To draw the implement
7	Soil drying oven	To dry soil sample to desired level
8	Penetrometer	To measure soil penetrability
9	Direct shear testing machine	To measure soil strength

Performance Evaluation

Performance evaluation of the machine was conducted in the Haramaya district Bate kebele on farmer's site. The operational parameters of the digging unit were evaluated. The selected rake angles were 15, 20 and 25° and forward speeds were 2.5, 3 and 3.5 km h^{-1}.

Properties of Soil during Harvest

Moisture content

To determine the soil moisture content of the field, soil samples were taken. It was a percentage of mass difference before and after the oven in dry weight basis as indicated. The moisture content of the sample in percent dry basis was determined by using the Equ. (1) [7].

$$MC = \frac{W1-W2}{W1} \times 100 \qquad (1)$$

Where:

MC = soil moisture content, % (db)

W1 = wet weight of soil sample, g

W2 = dry weight of soil sample, g

Bulk density

Soil amples were weighed and kept in the oven at 105°C for 24 hours. The weight of dry soil was recorded and bulk density on a dry weight basis was evaluated using Equ. (2). This volume includes the volume of soil particles and the volume of pores among soil particles [9].

$$\rho = \frac{M}{V} \qquad (2)$$

Where:

ρ = Bulk density of soil, g cm^{-3}

M = Mass of the oven dried soil, g

V = Volume of core sampler, cm^3

Penetration resistance

Soil cone index or resistance to penetration was calculated using Equ. (3) [10].

$$Pz = \frac{F_a}{A_b} \qquad (3)$$

Where:

Pz = penetration resistance, MPa

F_a =Force applied, N

A_b = Cone base area, mm^2

Shear Strength

The shear strength of the soil was calculated by using a direct shear testing method. To measure the undrained shear strength Equ. (4) was applied to identify the shear strength in the field. Soil shear strength is determined by particle cohesion and the resistance of particles sliding over one other due to friction or interlocking [11].

$$S=c+\sigma_n \tan\phi \qquad (4)$$

Where:

S= shear strength of soil

c= apparent cohesion.

ϕ= angle of internal friction.

σ_n= normal stress on the failure plane.

Physical properties of carrot root

The properties such as size, mass, bulk density, and coefficient friction were measured and an average value was computed.

Size

- **Geometric mean**

The geometric mean of the was determined by measuring the major, minor and intermediate axes of the carrot. The geometric mean was calculated using the equ. (5) described by [12].

$$Geometric\ mean = XYZ^{\frac{1}{3}} \qquad (5)$$

Where:

X=Major diameter of carrot, mm

Y=Intermediate diameter of carrot, mm

Z=Minor diameter of carrot, mm

- **Carrot Index**

Carrot index is the percentage ratio of carrot's greatest length to the product of greatest width and greatest thickness of carrot [13].

$$I = \frac{L}{W \times T} \times 100 \qquad (6)$$

Where:

I=Carrot index

L=Greatest length of carrot, mm

W=Greatest width of carrot, mm

T=Greatest thickness of carrot, mm

- **Surface Area**

The surface area was estimated using the relationship given by [14]. The surface area was calculated by.

$$S = \pi Gm^2 \qquad (7)$$

Where:

S = Surface area, mm^2

Gm = Geometric mean diameter, mm

Bulk Density

The bulk density of the carrot was determined as the ratio of bulk weight of carrot to the bulk volume of carrot [15]. A known-volume container was used, and its contents was weighed in a physical balance and was analyzed using standard procedures. Equ. 8 were used.

$$BD = \frac{W_{tc} - W_c}{V_c} \qquad (8)$$

Where:

BD = Bulk density of carrot, kg m^{-3}

W_{tc} = Weight of container filled with carrot, kg

W_c = Weight of empty container, kg

V_c = Volume of container, m^3

Coefficient of static friction

The coefficient of static friction (m) on mild steel sheet was measured for carrot roots by using the inclined plane method. The material was kept on a horizontally level surface and the slope was increased gradually. The angle (a) at impending slip was recorded and computed. The coefficient of friction was calculated by equ. (9) [16].

$$\mu = \tan\theta \qquad (9)$$

Where:

μ=Static Coefficient of friction, decimal.

θ=Angle of inclination, deg.

Machine performance parameter

Digging efficiency(η_h)

It was computed on 2m length of row demarcated randomly, using a mass of carrot dugout by harvester in unit area and mass of carrot left in soil after harvesting in the same unit area and calculated in percentage, using Equ. (10). Digging efficiency was calculated using the following formula [17].

$$\text{Digging Efficiency}(\%) = \frac{A}{A+B} \times 100 \qquad (10)$$

Where;

A = mass of carrot dugout by harvester in unit area, kg

B = mass of carrot left in soil after harvesting in unit area, kg

The percentage of damage (d)

It was computed on 2m length of row demarcated randomly, collected and counted all visible roots through an outlet of a machine. The damaged carrots were separated, counted and undamaged carrot roots after harvesting and calculated in percentage, using Equ. (11) [17].

$$\text{Damage}(\%) = \frac{B}{A} \times 100 \qquad (11)$$

Where:

A= Total no of carrot before harvesting

B= No of damaged carrot

Soil separation efficiency (h_l)

It was computed by taking a sample of 2m distance on a row was randomly marked and measured the carrot roots and other impurities/soil clod by collecting at the outlet of a machine. Then separation efficiency was computed as a ratio weight of root to the sum of root and impurities and recorded as h_l, in %. The separation efficiency was expressed as presented in Equ. (12) [6].

$$\eta_l = \frac{M_h}{M_s} \times 100 \qquad (12)$$

Where:

M_h= Mass of carrot-soil after conveying, kg

M_s= Theoretical mass of carrot -soil mix dug by digger, kg

Wheel slip (*S*%)

It was wheel slip of the machine with load and without load measured at 10m distance. Wheel slip was calculated by counting the number of revolutions in a given distance (distances for a given number of wheel revolutions) and calculated in %. Slip is defined in Equ. (13) [8].

$$S(\%) = \frac{R-r}{R} \times 100 \qquad (13)$$

Where:

R=Loaded revolutions

r=Unloaded revolutions

Draft (D)

It was calculated using width of the blade, working depth of the machine and at three speed level i.e. 2.5, 3 and 3.5 km/hr. Typical draft requirements can be calculated by Equ. (14) [18].

$$D = Fi(A + BV + CV^2)xwd \qquad (14)$$

Where:

D = implements draft, N,

F = dimensionless soil texture adjustment parameter

i =1 for fine, 2 for medium and 3 for coarse textured soils

A, B and C are machine-specific parameters

v = speed, km/h.

w =width, m or number of rows or tools

d = tillage depth

Fuel consumption (f*c*)

The fuel tank was filled up to the neck of the fuel tank before and after the digging operation. The amount of refilling measured after the test was the fuel consumption for digging operation and it was expressed as liter per hectare. The amount of fuel used to refill the fuel tank was recorded and calculated by Equ. (15) [17].

$$Fc = \frac{Q}{t} \tag{15}$$

Where:

Q = amount of fuel in liter consumed by the tractor drawing the carrot harvester

t = time taken in (hr.).

Theoretical field capacity (T_{fc})

It was calculated based on the full operating width of the machine and the average travel speed in the field and computed using Equ 16 [19].

$$TFC = \frac{S \times W}{C} \tag{16}$$

Where:

TFC = theoretical field capacity, ha/h

S = forward speed, km/hr

W = working width, m

C = conversion factor 10

Effective Field capacity (FC)

It was an actual field capacity computed by the actual average time consumed during digging operation (lost time and productive time) and recorded as fc in ha/h as shown in Equ. (17) was calculated as follows [19].

$$EFC = \frac{A}{T}C \tag{17}$$

Where:

EFC = effective field capacity, ha/h

A = plot area, m^2

T= time, sec

C = conversion factor, 0.36

Field Efficiency (FE)

Field efficiency refers to the productivity of machinery in a field. Was calculated using equ (18) using the following formula [19].

$$\text{Field Efficiency} = \frac{EFC}{TFC} \times 100 \tag{18}$$

Where:

EFC = effective field capacity, ha/h

TFC = theoretical field capacity, ha/h

Cost Economics

The economics of the tractor operated root crop harvester is helpful in decision making for purchasing a root crop harvester for individual farmer to own a machine or its custom hiring. The total cost of the tractor mounted root crop harvester was calculated. The performance was compared with conventional method of harvesting in terms of savings in cost and improvement in harvesting efficiency.

Experimental Design

The experiment was laid in factorial with completely randomized design (CRD) with three forward speeds (2.5 3 and 3.5km/hr) three levels of rake angle (15, 20 and 25 degrees). The rake angle of a blade was adjustable through, a semi-circular slot that slides on the shank that used for lifting and lowering down the digging blade at required angle. Other soil and crop conditions were assumed constant. The experimental layout was with three replications in complete block design, i.e. a 3 x 3 x 3 factorial design. This gave a total of 27 sets of test runs.

Statistical Analysis

Analysis of variances was performed on the data using GenStat 18th edition statistical software and a protocol appropriate for the experiment's design (Gomez and Gomez, 1984). Treatment means that differed at 5% levels of significance were separated using the least significant difference (LSD 5%) test. The least significant difference (LSD) test was used to examine the mean values in relation to forward speed and rake angle.

RESULTS AND DISCUSSIONS

Properties of Soil during Harvesting

The soil of the field was a sandy clay loam soil with 55% sand, 20% silt, 25% clay, and pH of 7.6, while the average soil moisture and bulk density were found 17.6% (which was adequate for digging operation to reduce the soil sticking to the carrots (Reddy et al., 2018))and 1.29g/cm^3 at harvesting time respectively. The shear strength and penetration resistance of soil on the ridge at depth of 25cm of the experimental field were 0.17kN/cm^2 and 0.45kN/cm^2 respectively.

Physical, Biometric and Frictional properties of carrot roots

Measurements made on *Nantes* carrots varieties, which were the most common varieties grown in the study area revealed that length, width, thickness, geometric mean diameters, density, surface area and carrot index were 19.25cm, 2.71mm, 2.70mm, 5.18mm, 80.32%, 85.03cm^2, 0.49g/cm^3 and 269.33%, respectively.

The average distance between rows was 24.2cm. The measured average center-to-center distance between ridges, mean heights and bottom width of the ridges were 60, 27.54 and 45.91 cm, respectively. The depth of the carrot in soil varied from 16 to25.3 cm and average depth was 20.65 cm. The average carrot population density in per meter square were found out as 63 in numbers. Plant to plant spacing of carrots were varied from 6-12cm and average plant spacing was 9.4cm. Average static coefficient on mild steel was 0.62.

Performance of the carrot roots digger

Draft and Power Requirement

The draft requirement for the tractor to draw the implement with a forward speed of 2.5, 3 and 3.5km/hr was 5202.7, 5857 and 6111.4N respectively.

Digging efficiency (η_H)

Table (2) indicates that digging efficiency was affected by both rake angle and forward speed, showing a clear decrease with increasing speed. The highest mean digging efficiency (95.94%) was obtained at 2.5 km hr^{-1}, which declined to 93.96% and 91.23% at 3.0 and 3.5 km hr^{-1}, respectively.

With respect to rake angle, the highest mean digging efficiency (94.24%) was obtained at 20°, followed by 15° (93.79%), while the lowest efficiency (93.11%) occurred at 25°. Among treatment combinations, the maximum digging efficiency (96.37%) was achieved at 20° and 2.5 km hr^{-1}, whereas the minimum (90.83%) was recorded at 25° and 3.5 km hr^{-1}.

Treatment differences were statistically meaningful (LSD = 3.973), and the low coefficient of variation (2.4%) indicates good experimental precision. However, ANOVA revealed that the interaction between rake angle and forward speed was not significant ($p > 0.05$), consistent with findings reported by [15].

Table 2: Effect of rake angles and speeds on digging efficiency (%)

Treatments	**Speed (Km/hr)**			**Main effect**
Rake angle (°)	2.5	3	3.5	**of rake angle**
15	96.12^{cd}	94.23^{abcd}	91.00^{ab}	93.79
20	96.37^{d}	94.48^{abcd}	91.87^{abc}	94.24
25	95.32^{bcd}	93.17^{abcd}	90.83^{a}	93.11
Main effect of speed	95.94	93.96	91.23	

Rake angle x forward speed

Grand mean	93.71
C.V(%)	2.4
LSD	3.973

LSD: Least significance difference; CV: Co-efficient of variation; Means followed by the same letters are not significantly different at 5% level of probability.

Damage of carrots(*d*)

Root damage was influenced by both rake angle and forward speed. Rake angle showed a relatively small effect as it increased from 15° to 25°, since a higher blade cutting angle operated further below the carrot roots. In contrast, root damage increased with increasing forward speed.

Analysis of variance (Table 3) revealed that the effects of rake angle and speed on root damage were not statistically significant ($P > 0.05$). The maximum root damage (6.24%) occurred at a 15° rake angle and 3.5 km hr^{-1}, while the minimum damage (1.11%) was recorded at 25° rake angle and 2.5 km hr^{-1}. Higher root damage at the 15° rake angle was attributed to the blade tip acting directly within the root zone, reducing soil lift and increasing direct contact between the blade and carrot roots. Similar trends were reported by [20].

Table 3**:** Effect of rake angles and speeds on damage of roots (%)

Treatments	**Speed (Km/hr)**			**Main effect**
Rake angle (°)	2.5	3	3.5	**of rake angle**
15	4.57^{bc}	6.09^{c}	6.24^{c}	5.63
20	3.20^{ab}	4.07^{bc}	3.29^{ab}	3.52
25	1.11^{a}	3.68^{bc}	4.33^{bc}	3.04

Main effect of speed	2.96	4.61	4.62	

Rake angle x forward speed	
Grand mean	4.06
C.V(%)	32.9
LSD	2.31

LSD: Least significance difference; CV: Co- efficient of variation; Means followed by the same letters are not significantly different at 5% level of probability.

Soil separation efficiency (h_y)

The main effect of rake angle showed a decreasing trend in separation efficiency as the angle increased, declining from 90.97% at 15° to 88.76% at 20° and remaining nearly constant at 25° (88.75%) (Table 4). Similarly, separation efficiency decreased with increasing forward speed, dropping from 93.20% at 2.5 km hr^{-1} to 88.83% at 3.0 km hr^{-1} and further to 86.44% at 3.5 km hr^{-1}.

Analysis of variance indicated that the effects of rake angle and forward speed on separation efficiency were not statistically significant ($P > 0.05$). The highest separation efficiency (93.73%) was achieved at a 15° rake angle and 2.5 km hr^{-1}, while the lowest (84.93%) occurred at 20° rake angle and 3.5 km hr^{-1}. The overall grand mean and coefficient of variation were 89.49% and 1.8%, respectively, indicating good experimental precision.

The reduction in separation efficiency at higher rake angles and speeds was attributed to increased penetration depth and greater soil–root mass accumulation on the separator and blade, leading to soil buildup and rolling-back effects. Similar trends were reported by [20].

Table 4: Effect of rake angles and speeds on separation efficiency (%)

Treatments	**Speed (Km/hr)**			**Main effect of**
Rake angle (°)	2.5	3	3.5	**rake angle**
15	93.73^{e}	90.66^{cd}	88.52^{bc}	90.97
20	92.42^{de}	88.92^{bc}	84.93^{a}	88.76
25	93.46^{de}	86.90^{ab}	85.88^{ab}	88.75
Main effect of speed	93.20	88.83	86.44	

Rake angle x forward speed	
Grand mean	89.49
C.V(%)	1.8
LSD	2.83

LSD: Least significance difference; CV: Co- efficient of variation; Means followed by the same letters are not significantly different at 5% level of probability.

Field Capacity (FC)

The operational performance of the carrot digger was evaluated in terms of field capacity at different forward speeds. Based on rated speeds of 2.5, 3.0, and 3.5 km hr^{-1} and a blade width of 0.9 m, the theoretical field capacities were 0.225, 0.270, and 0.315 ha h^{-1}, respectively. Actual field capacity varied due to differences in time required to harvest a unit area (100 m^2).

Analysis of the main effects showed that field capacity was significantly influenced by forward speed ($P < 0.05$) (Table 5). Field capacity increased with increasing speed and was also affected by rake angle. The maximum field capacity (0.27 ha h^{-1}) was achieved at a rake angle of 15° and a speed of 3.5 km hr^{-1}, while the minimum (0.17

ha h^{-1}) occurred at 20° rake angle and 2.5 km hr^{-1}. Higher speeds reduced the time required to cover a given area, resulting in increased field capacity. Similar trends were reported by [20].

Table 5: Effect of rake angles and speeds on field capacity (ha/h)

Treatments	**Speed (Km/hr)**			**Main effect of**
Rake angle (°)	2.5	3	3.5	**rake angle**
15	0.18^{a}	0.23^{c}	0.27^{e}	0.23
20	0.17^{a}	0.21^{b}	0.25^{d}	0.21
25	0.18^{a}	0.21^{b}	0.24^{d}	0.21
Main effect of speed	0.18	0.22	0.25	
	Rake angle x forward speed			
Grand mean	0.22			
C.V(%)	3.0%			
LSD	0.011			

LSD: Least significance difference; CV: Co- efficient of variation; Means followed by the same letters are not significantly different at 5% level of probability.

Field efficiency (FE)

The main effect of rake angle on field efficiency showed that the highest and lowest efficiencies, 83.06% and 78.18%, were obtained at rake angles of 15° and 25°, respectively. Similarly, the main effect of forward speed indicated that maximum and minimum field efficiencies of 81.94% and 77.98% were achieved at speeds of 3.5 and 2.5 km hr^{-1}, respectively.

The interaction effects of rake angle and forward speed on field efficiency, along with the analysis of variance, are presented in Table 6. ANOVA results revealed that the interaction between rake angle and speed had no significant effect on mean field efficiency ($p > 0.05$). The maximum field efficiency (86.24%) was recorded at a speed of 3.5 km hr^{-1} and a rake angle of 15°, while the minimum efficiency (77.19%) occurred at 2.5 km hr^{-1} and 20° rake angle. The corresponding grand mean and coefficient of variation were 80.05% and 4.52%, respectively. Field efficiency increased as rake angle and speed increased from 15° to 20° and from 2.5 to 3.0 km hr^{-1}, respectively, but declined at higher levels (25° and 3.5 km hr^{-1}). The reduction at higher rake angles was attributed to increased draft requirements during harvesting, as also reported by [21].

Table 6: Effect of rake angles and speeds on field efficiency (%)

Treatments	**Speed (Km/hr)**			**Main effect of**
Rake angle (°)	2.5	3	3.5	**rake angle**
15	78.37^{a}	84.56^{bc}	86.24^{c}	83.06
20	77.19^{a}	78.64^{a}	80.95^{ab}	78.93
25	78.37^{a}	77.53^{a}	78.63^{a}	78.18
Main effect of speed	77.98	80.25	81.94	
	Rake angle x forward speed			
Grand mean	80.05			

C.V(%)	4.52
LSD	3.3

LSD: Least significance difference; CV: Co- efficient of variation; Means followed by the same letters are not significantly different at 5% level of probability.

Wheel slip factor (S)

Wheel slip increased with increasing rake angle and, to a lesser extent, with forward speed. The main effect of rake angle shows that mean wheel slip rose from 15.96% at 15° to 18.04% at 20°, reaching 20.09% at 25°, indicating a strong influence of rake angle on tractor traction.

The main effect of speed shows a slight increase in wheel slip from 17.22% at 2.5 km hr^{-1} to 18.35% and 18.52% at 3.0 and 3.5 km hr^{-1}, respectively. The highest wheel slip (22.10%) occurred at 25° rake angle and 3.5 km hr^{-1}, while the lowest (15.31%) was recorded at 15° and 2.5 km hr^{-1}**.**

Differences among treatments were moderate, as reflected by the LSD value of 5.416 and a relatively higher CV of 17.4%, with a grand mean of 18.03%. Overall, increasing rake angle had a more pronounced effect on wheel slip than increasing forward speed [22].

Table -7: Effect of rake angles and speeds on wheel slip factor (%)

Treatments	**Speed (Km/hr)**			**Main effect of**
Rake angle (°)	2.5	3	3.5	**rake angle**
15	15.31^{a}	16.80^{ab}	15.77^{a}	15.96
20	16.79^{ab}	19.64^{ab}	17.68^{ab}	18.04
25	19.56^{ab}	18.60^{ab}	22.10^{b}	20.09
Main effect of speed	17.22	18.35	18.52	
	Rake angle x forward speed			
Grand mean	18.03			
C.V(%)	17.4			
LSD	5.416			

LSD: Least significance difference; CV: Co- efficient of variation; Means followed by the same letters are not significantly different at 5% level of probability.

Fuel consumption

Tractor fuel consumption constitutes a significant parameter that affects tractors performances for ploughing operations. The fuel tank was filled up to the neck of the fuel tank before and after the digging operation. The amount of refilling measured after the test was 17.56*l*/ha.

Economic Evaluation of the Machine

The cost–benefit of the developed carrot digger was evaluated by comparing its operational cost with that of traditional manual harvesting, considering raw material, production, labor, and operating costs. The estimated cost of the machine was approximately 16,000 Birr. The operational cost of harvesting using the carrot digger was 2,100.16 Birr ha^{-1}, requiring 110 man-h ha^{-1}, including haulm removal and root picking. In contrast, manual hand digging required 620 man-h ha^{-1} for haulm removal, digging, and picking, with an operational cost of 8,950 Birr ha^{-1} [23]. The use of the carrot digger resulted in a cost saving of 6,850 Birr ha^{-1}, representing a 76.5% reduction

Figure 1: Experimental site and data collection

in harvesting cost and a substantial reduction in labor requirement compared to traditional manual harvesting cost of harvesting using the carrot digger was 2,100.16 Birr ha^{-1}, requiring 110 man-h ha^{-1}, including haulm removal and root picking.

Conclusion

The performance evaluation showed that the tractor-drawn carrot harvester is technically feasible and effective under the tested field conditions. It significantly reduced labor and harvesting time compared to manual methods while maintaining acceptable harvesting efficiency and root quality, addressing major constraints such as labor shortage and post-harvest losses.

Operational parameters notably influenced performance: forward speed and rake angle significantly affected field efficiency, digging efficiency, harvesting capacity, and root damage. Higher speeds improved field efficiency and capacity, but inappropriate speed-angle combinations increased root damage and unharvested losses. At optimized settings, root damage remained within acceptable limits, indicating suitability for medium-scale production.

Overall, the harvester is a viable alternative to manual harvesting, offering higher productivity and timely operation. Adoption with optimized parameters is recommended, and further research is suggested to test different soil types, moisture levels, and carrot varieties, and to refine design for reduced root damage and better adaptability.

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