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Development of Tractor Drawn Potato Digger

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ABSTRACT

The post-harvest loss of potatoes in Ethiopia is more than 25% which includes harvesting loss. In the conventional method, the potato is harvested either manually with a hand hoe or by animal-drawn equipment, which is a tedious, labor-intensive, and time-consuming operation. To overcome these problems, the tractor-drawn potato digger was developed, and evaluated for its performance. The performances were evaluated in terms of harvesting efficiency, exposing efficiency, percentage of tuber damage, effective field capacity, field efficiency, and fuel consumption. The developed digger is tested at three levels of forward speeds (2.5, 3, and 3.5 km/h) and three different rake angles (10, 15, and 20°). The performance of the digger was found to be optimum at rake angles of 20° and forward speed of 2.5 km/hr. The results revealed that maximum harvesting efficiency of 98.21% was obtained with lower potatoes damage of 4.32% whereas the exposing efficiency, undug potatoes, effective field capacity, field efficiency, and fuel consumption were found to be 91.48%, 1.79%, 0.11ha/hr, 84.71%, and 1.17 l/hr, respectively. The analysis of variance revealed that forward speed and rake angle had significant effects on harvesting efficiency, undug potatoes, potato damage, effective field capacity, field efficiency, and fuel consumption at a ($P<0.05$) level of significance. The costs of harvesting per hectare were 2876 and 6050 ETB/ha for the developed potato digger and traditional potato digging methods, respectively. The cost of operation per hour for tractor-drawn potato diggers and traditional methods was 169.23 and 700 ETB/hr, respectively. The saved cost of harvesting was 52% and the saved in time was 75% compared to traditional potato harvesting. From these performance indicators, it can be concluded that this digger is efficient, effective, and economical, and it is recommended that the technology be promoted for potato producer farmers.

INTRODUCTION

Potato (*Solanum tuberosum L.*) is the fourth most important food crop in the world based on production after maize, rice, and wheat, with annual production accounting for nearly 300 million tons (Ayalew *et al.*, 2014). Out of these, over half of production occurs in developing countries (Devaux *et al.*, 2014). According to data from the Central Statistics Agency for the 2019/2020 production year, Ethiopia produced 1,044,436.359 tons of potatoes (76,677.64 ha) in 2019, yielding 13.62 tons/ha. In 2020, however, the yield was 924528.361 tons (70362.22 ha), yielding 13.13 tons/ha of productivity (CSA, 2019/20). Oromia is the primary potato-producing region, accounting for 51 percent of the country's total production (CSA, 2015). West Arsi, a significant potato-growing zone in the Oromia Regional State is home to smallholder farmers who have transitioned from producing basic foods for subsistence to more market-oriented, high-value commodities (Bezabih & Mengistu, 2011). In the Shashemene district, potatoes are a key food and cash crop (DOA, 2016).

The Ethiopian government has identified potato as a key crop with the goal of improving food security and economic advantages for the country (EIA, 2012). Post-harvest loss (20–25%) is one of the main issues with potato production, though. This implies a large loss to the smallholders who could have contributed to food security, income production, and nutrition (BoFED, 2007). Therefore, it is important to develop and promote relevant technology in order to reduce post-harvest losses. Food availability would rise by 20% with a 50% decrease in postharvest losses without needing to cultivate an extra hectare of land to boost crop productivity (Ayandiji *et al.*, 2011). One factor that has been identified as contributing to the food crisis is post-harvest losses (Babalola & Agbola, 2008). According to Oyekanmi (2007), post-harvest loss prevention technology solutions become increasingly important as more produce is moved to non-producing areas to feed the expanding population. Potato harvesting is carried out using human, animal, and mechanical force. Manual harvesting of potatoes is very labor intensive, time-consuming, and causes lots of damage to the potatoes. The damage induced by digging ranges between 16 and 21%, with 11% attributable to cutting and bruising and 5 to 10% remaining undug. Farmers employ animal power. In this form of digging, the tubers lose 13 to 16%, with 9% due to cutting and bruising and 4 to 7% remaining undug (Asheesh *et al.*, 2017). According to Arthur *et al.* (2017), the findings confirmed that 38% of tubers are either destroyed during harvesting or left un-harvested in the ground. This means that more effective harvesting equipment is urgently required. The tested lifters dramatically reduced the proportion of tubers (7 to 9%) that had cuts and bruises and were thus unmarketable.

Any manufacturing system needs knowledge inputs

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to increase yields and reduce costs. The absence of technological solutions is the primary barrier to increasing the yield and caliber of vegetable crops in Ethiopia. Growing vegetables requires a lot of labor. The low level of mechanization is one of the key obstacles to growing the area under vegetable crops as well as their production. The most important prerequisite for cultivation of vegetables is timeliness. The use of harvesting devices shortens operating times and prevents losses from unfavorable weather during the process; the time saved during harvesting can be put to better use during post-harvest procedures, extending the harvest's shelf life. Furthermore, because the majority of vegetables are perishable, they must be harvested, handled, and stored with care before being processed or eaten. With the exception of field preparation, the majority of processes are manual and labor-intensive. Compared to hand harvesting, mechanical harvesting of potatoes results in 65% more thrifty harvesting during harvest time and 45% more harvest costs. These findings indicate the significance of the agricultural-related activities that reported by Muhammad *et al.* (2003). The post-harvest losses of potatoes are more than 25% due to poor harvesting while digging to expose the tubers. Thus, to alleviate this post-harvest loss problem, different organizations and research centers tried to develop, adapt, modify, and import potato harvesting technology. Governmental and nongovernmental organizations like German Corporation for International Cooperation (GIZ) import large potato harvesting implements. Asella Agricultural Engineering Research Center has tried to develop and adapt an animal-drawn potato digger and a good result was obtained. The center also developed a power tiller-operated potato digging implement but the result was not satisfactory because it was difficult to manage the implement with that of the power tiller and the power transmission system was also somewhat difficult. The technology is very important for the farmers in digging potatoes within a short period and reducing human drudgery.

Nowadays the best opportunity is for the government to give due attention to strength agriculture through importing and distributing mechanization machinery out of which tractors are one. So currently farmers and micro enterprises who participate in agriculture can get these tractors for tillage purposes. These tractors can also be used for mounting other implements for planters, cultivators, sprayers, harvesters, threshers, transportation, and others. In general, traditional harvesting of potatoes results in lower exposure efficiency, a higher percentage of tubers remaining in the field, greater tuber damage, lower workability, very laborious and time-consuming. Consequently, to overcome harvesting loss, drudgery, labor requirements, and time-consuming problems, it is necessary to develop and evaluate appropriate potato-digging technology is mandatory. However, this activity was initiated to develop and evaluate the performance of a tractor-drawn potato digger and ultimately for import substitution.

MATERIALS AND METHODS

Materials

Materials used for performing this activity were different sizes of sheet metal, angle iron, MS round bar, MS shaft; square pipe, flat iron, tractor, PTO shaft, potato crop, and instruments like digital balance, measuring tape, graduated cylinder, stopwatch, electric oven, and core sampler were used.

Methods

Description of the Developed Potato Digger

The tractor-drawn potato digger was made from locally accessible materials, was easier to handle and run, and required less work. It was also simple to maintain. The implement was developed in order to address issues with the large proportion of losses and damage that occurred during the harvesting process, as well as the inefficiency of using an existing digger for successful root crop harvesting. The developed prototype's overall dimensions were 750 mm in height, 655 mm in width, and 1520 mm in length. It consists of the following components: mainframe, separating unit, soil cutting blade, shanks, depth control wheels, transmission system, eccentric (arm), PTO shaft, and three-point linkage as shown in Figure 1. The prototype development was done in the Asella Agricultural Engineering Research Center (AAERC) metal workshop.

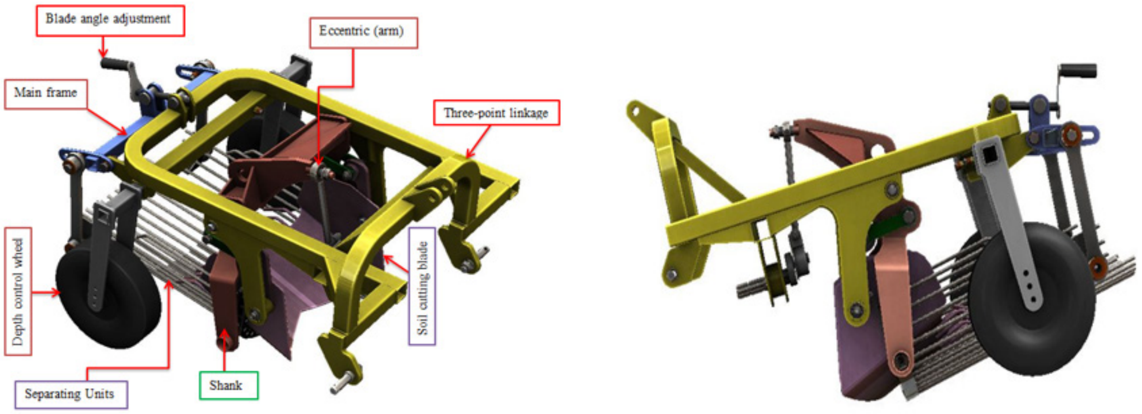

Figure 1: Diagram of the developed prototype of a tractor-drawn potato digger

Main frame

The frame of the digger has to be stiff and strong as all parts were mounted on it. The soil cutting blade, shank, conveyer rod, and three-point hitch were attached to the frame. The frame was made from mild steel (M.S) square pipe of 50 × 50 × 4 mm thickness. The overall dimension of the frame was 1520 mm in length, 655 mm in width, and 750 mm in height. All components of the digger were assembled and fitted on the frame.

Separating unit

The separating unit was made up of a V-shaped blade with round bars or rods spaced at a specific distance apart. This frame was attached to a vibrating blade at the end of a longitudinally provided frame using nuts and bolts. The separating system consisted of a parallel round bar made of iron steel with an 18 mm diameter welded on a blade with a V shape. The separator was mounted at the rear end of the digger blade. A parallel rod with an 18 mm diameter and 600 mm length was welded at 40 mm spacing on the cutting soil blade. The slope of the separator was adjustable from 0 to 25o to the horizontal through a semi-circular slot produced on both sides of the side shank. The separator oscillated due to the PTO shaft and eccentric discs rotating.

Oscillation system

The output shaft's rotary motion was converted to reciprocating motion by the oscillation system, which produced the 40 mm maximum oscillation amplitude that was advised in order to oscillate, shake, and separate the soil tuber mass (Al-Jubouri & McNulty, 1983). The eccentric disc was attached to both ends of the output shaft to convey the push force and convert the output shaft's rotating motion into the oscillatory motion of the separation system. A separator is made of parallel rods welded to the blade. During the harvesting process, pairs of eccentric discs at both ends of the output shaft generated vertically reciprocating motion, oscillating and shaking the separating system with soil tuber mass.

Transmission system

A spindle that transfers rotating motion from the PTO to a cam at its end and two additional longitudinal rods that are attached to longitudinal frames make up the transmission system. The linkage shaft receives reciprocating motion from the cam in place of rotating motion. The digger blade was attached to this shaft via the longitudinal frame.

Eccentric Arm

The eccentric arm's primary purpose is to transform the cam's rotating action into reciprocating motion. Bolts and nuts were used to connect the cam and follower. Cam and follower were linked together utilizing bolts and nuts.

Depth control wheel

Harvesting depths provided a basis for the depth control system's mechanism construction. The wheel is utilized to support and carry the weight of the potato harvester's entire body while in operation. The clearance between the blade's cutting edge and the bottom of the wheel was adjusted using the rotating screw. The structure's height above ground was decreased with the use of wheels, allowing it to be appropriately sized for underground root crops.

Working Principle of the Machine

As the machine moved on forward, the V-shaped blades separated the ridges, allowing the potatoes to be dug out and dumped into the elevator. The potatoes were further transferred to the elevator's rear end. Soil clods accompanied the potatoes as they were dug. These soil clods were shattered and dropped as a result of the gap given between the elevator rods. The manual laborers can easily pick up the potatoes.

Figure 2: Data collection during performance evaluation of tractor-drawn potato digger

Performance Test and Evaluation Parameters

The following performance parameters were determined to evaluate the developed potato digger.

Soil parameters

Soil moisture content

To determine the field's soil moisture content, soil samples were collected up to a depth of 25 cm. Samples were obtained at random from five places on each test plot. These samples were weighed and baked at 1050C for 24 hours, and the moisture content was measured using the formula provided by (Khura, 2008).

$$M = \frac{M_w - M_d}{M_d} \times 100 \qquad (1)$$

Where,

M = Moisture content of soil, %

M_w = Weight of wet soil, gm and

W_d = Weight of oven-dry soil, gm

Bulk density

Soil samples were collected at random from the field using a core sampler. The bulk density of soil samples has been assessed using a core sampler with an inner diameter of 7 cm and a height of 12 cm. Soil samples were taken at depths ranging from 0 to 25 cm prior to digging. The bulk density was measured by dividing the weight of oven-dried soil samples (at 1050C for 24 hours) by the volume they occupied and using the equation provided below (Khura, 2008).

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

Where, ρ_b = bulk density of soil (g/cm^3)

M = oven-dry mass of soil (gm), and

V = volume of the core sampler (cm^3)

Crop parameters

Number of tubers per meter row length

The number of tubers was counted in one-meter rows. The counting was done before the crop was harvested. The data was collected at ten randomly selected locations.

Depth of crop

The crop's depth was measured at ten different random places. During the removal of soil from the bed's side, the depth was measured using a measuring meter.

Machine Performance Parameters

The machine performance parameters such as harvesting and exposing efficiency, percentage of undug potato, percentage of potato damage, effective field capacity, field efficiency, and fuel consumption of the digger machine were determined for the performance evaluation as follows.

Harvesting Efficiency (ηh)

The percentage of harvesting/digging efficiency of the potato digger was measured as the ratio of the total number of dug tubers by the tractor-drawn potato digger to the summation of the total number of tubers dug and the tubers that remained un-dug by the machine. After being harvested by a potato digger drawn by a tractor in the quadrant, the tubers that were dug out were gathered and weighed. With the use of a hand hoe, the potato tuber that had been left in the ground was once more removed without causing any harm to the tubers. After being gathered, these tubers were weighed. We were able to determine the total weight of tubers in the quadrant by adding the two readings. It was the measure of the ability of a developed tractor-drawn potato digger to harvest tubers from the soil. It was calculated using Eqn. (3) (Ibrahim *et al.*, 2008).

$$Eh = \frac{M_l}{M_l + M_{ud}} \times 100 \qquad (3)$$

Where,

Eh = percentage of harvesting efficiency

M_l = Amount of tuber dugout/exposed on the surface in the sample area, kg

M_{ud} = Amount of tuber remained inside the soil in the sampled area, kg

Undug Potato Percentage

To find out how much of the potato remained undug, the undug potato was estimated. It was defined as follows:

$$Ud = \frac{A}{B} \times 100 \qquad (4)$$

Where,

A = total number of undug potatoes (dug manually after the operation)

B = total number of potatoes (dug and undug both)

Exposing Efficiency

The amount of exposed tubers at beginning and the amount dug by hand at the end were utilized for determining the lift percentage/exposing efficiency. The quantities mass of lifted potato root crop over the soil surface and the mass of unlifted root crop were expressed in percentage as follows: The following equation given below was utilized to compute the lift percentage (Ibrahim *et al.*, 2008).

$$Ee = \frac{M_l}{M_{ul} + M_l} \times 100 \qquad (5)$$

Where,

Ee = percentage of exposing efficiency

M_{ul} = Mass of un-lifted potatoes, kg

M_l = Mass of lifted potatoes, kg

Damaged Potato Tubers

The percentage of damage also can be assessed by taking a sample of tubers randomly after harvesting from the test plot by weighing and taking into consideration the mass of the tuber (kg), which has no bruise or cut for each of the samples, and the mass of damaged tuber. Through collecting and weighing all visible tubers, the damaged tubers were separated, measured (seriously damaged and avoid slight damage), and undamaged potato tubers after harvesting and recorded as a percentage. The percent could be determined using the following (Ibrahim *et al.*, 2008).

$$Pd = \frac{M_d}{M_{nd} + M_d} \times 100 \qquad (6)$$

Where,
Pd = percentage of damage, %
M_d = Mass of seriously damaged or cut (bruised) root crop (potato), kg
M_{nd} = Mass of potatoes tuber exposed and not damaged, kg

Effective Field Capacity

The time spent on actual work as well as time spent on additional tasks like turning, cleaning, adjusting the machine, and troubleshooting it were all taken in when determining the effective field capacity. The plot's width and length were measured, and the area covered in that amount of time was computed. It was possible to determine the actual field capacity by calculating the area covered each hour. It is the machine's actual average coverage rate. The operation's total time needed was recorded, and the following formula was used to determine the effective field capacity (Kepner *et al.*, 2005)

$$EFC = \frac{A}{T_p + T_i} \times 100 \qquad (7)$$

Where,
EFC = Effective field capacity, ha/hr
A = Actual area covered, ha
T_p = Productive time, hr,
T_i =Non-productive time, hr

Field Efficiency

The effective field capacity divided by the theoretical field capacity is commonly referred to as the field efficiency, and it is usually expressed as a percentage. It takes into account the consequences of not using the entire width of the machine and lost time in the field (Kepner *et al.*, 2005).

$$\eta = \frac{EFC}{TFC} \times 100 \qquad (8)$$

Where,
η = Field efficiency (%)
TFC = Theoretical field capacity (ha/h),
EFC = Effective field capacity (ha/h)

Fuel Consumption

Fuel consumption directly affects the harvesting machine's profitability. By using the top-fill method, it was measured. Prior to testing, the fuel tank was filled to the proper level. The amount of fuel used during the test was corresponding to the amount needed to top off after the testing process was finished. This observation was used for the computation of fuel consumption in l/ha (Nkakini *et al.*, 2010).

$$Fc = \frac{fr}{A} \qquad (9)$$

Where,
Fc = fuel consumption (l/ha)
fr = Re-filled quantity of fuel (l),
A = Harvesting area (ha)

Experimental Design and Treatment

To evaluate the performance of the potato harvesting machine, three levels of forward speed (2.5, 3, and 3.5 km/hr) and three levels of rake angle (10, 15, and 20°) were used. The experimental design was a randomized complete block design (RCBD) with 32 factorial experiments and three replicates as a block. The experimental design was arranged as (3×3) with three replications and took a total of 27 test runs.

Statistical Analysis

The results of the performance of the potato harvesting machine were analyzed by analysis of variance (ANOVA) using statistical R software. Statistical differences in the effects of treatment mean were tested at 5% levels of significance and separated using the least significant difference (LSD). The least significant difference (LSD) tests were performed for the mean values of effective field capacity, field efficiency, exposing efficiency, harvesting efficiency, percentage of tuber damage, and fuel consumption. The levels of significance (P) for these relations were obtained by F-test based on an analysis of variance. The mean values and standard deviation (Mean ± Standard deviation) were used to present the results.

Cost Analysis

There were two steps involved in the cost analysis. The cost of the materials and the manufacture must be estimated beforehand. The operational cost of the developed digger needs to be determined in the second step. Two parameters were computed and investigated to assess the developed digger's economic viability. The system that was developed operation cost and savings costs were these criteria. According to Huang *et al.* (1979), the operational cost components of the 25-hp tractor and the digger prototype were estimated in Birr (EB). The tractor is estimated to have an economic life of ten years and 720 hours annually, while the implement is anticipated to be used for 260 hours annually.

Fixed Cost

Depreciation

It served as an indicator for how much the implement worthwhile declined over time. In accordance with Kepner *et al.* (2005), the annual depreciation was computed as follows:

$$D_P = \frac{PP - SV}{L + H}, (ETB / hr)$$

Interest

Interest was calculated using the machine's average investment, accounting for the digger's profitability in the first and last years. Usually, these are computed annually. The annual interest on the investment was calculated according to Kepner *et al.* (2005) as follows:

$$I = \left(\frac{PP + SV}{2}\right) \times \left(\frac{I\%}{H}\right), (ETB/hr)$$

Insurance & taxes (IT)

The annual insurance and taxes on the investment were calculated according to Kepner *et al.*, (2005) as follows:

$$IT = 1.5\% \times PP, (ETB/hr)$$

$$\text{Housing (H), H} = 1\% \times PP, (ETB/hr)$$

$$\text{Total fixed cost} = D_P + I + IT + H, (ETB/hr)$$

Variable cost

The digger and tractor's repair and maintenance costs have been determined as 5% of the cost of their purchase, and the workers' actual daily or hourly compensation were used for determining wages.

Total cost of potato digger per hour

The total cost of digging per hour of the developed tractor-drawn potato digger was calculated by summation of the total fixed cost per hour with the total variable cost per hour. The total cost of digging was the summation of the variable costs of the digger and fixed costs of the digger, finally, the average effective field capacity of the digger was multiplied by the total cost of operation to determine the digger's cost of operation.

RESULTS AND DISCUSSION

The field experiment was carried out in a 20 x 50 m2 area of sandy loam soil on a farmer's field. As shown in Table 1, the average bulk density of the soil was 0.96 g/cm3 and the average moisture content of the soil was 11.15% during the crop harvesting periods. The average value of the crop parameters at the time of digging the potato crop is shown in Table 2.

Table 1: Soil moisture content and bulk density of soil sample

S. No.	Moisture Content, %	Bulk density, g/cm3
1	11.45	0.86
2	10.99	0.99
3	11.44	1.05
4	10.73	0.92
5	11.11	0.98
Ava.	11.15	0.96

Table 2: Average (range of variation) values of various physical parameters for potato crop

S/N	Physical Parameters	Replication					Average
		1	2	3	4	5	
1	Row to row spacing, cm	90	85	100	90	90	91
2	Ridge height, cm	25	24	27	28	23	25.4
3	Base width, cm	63	64	60	58	61	61.2
4	Depth of potato zone, cm	14	21	19	15	20	17.8

From above Table 2, the average value of ridge height, depth of potato root zone, and base width at the time of digging the potato by tractor-drawn potato digger were 25.4, 17.8, and 61.2 cm, respectively.

Performance Evaluation of the Machine

Tractor drawn potato digger was evaluated under field conditions to determine the operational performance parameters. Three levels of rake angles (10, 15, and 20°) and three forward speeds (2.5, 3, and 3.5 km/hr) were the parameters used for the purpose of the investigation. The performance of the potato harvester had been evaluated in terms of harvesting efficiency, undug potato, exposing efficiency; potato damage, effective field capacity, field efficiency, and fuel consumption. The effects of forward speeds and rake angle were investigated, and the findings are presented below.

Harvesting Efficiency

The effects of forward speed and rake angle on harvesting efficiency have been presented in Figure 3 and Table 4. It is evident that as the rake angle increased from 10 to 20°, the harvesting efficiency increased from 96.88 to 98.21% at a tractor forward speed of 2.5 km/hr and also rake angle increased from 10 to 20°, the harvesting efficiency increased from 95.15 to 96.69% at a tractor forward speed of 3 km/hr. Similarly, an increasing trend of harvesting efficiency was observed from 96.88 to 98.21% and 94.58 to 96.48% as the speed increased from 2.5 to 3.5 km/hr at rake angles of 10° and 20°, respectively. Similar trends of increase in harvested tuber with an increase in forward speed of root-crop digger have been reported by Yasin *et al.* (2003).

The main effect of forward speed and rake angle on harvesting efficiency is summarized in Table 3. The results revealed that as the rake angle increased from 10 to 20°, the harvesting efficiency increased from 95.54 to 97.13% and as a tractor forward speed increased from 2.5 to 3.5 km/hr, the harvesting efficiency decreased from 97.60 to 95.63. The relationship between harvesting efficiency with forward speeds and rake angles was given by $y = -0.985x + 98.363$ with an R^2 of 0.8681, and $y = 0.7945x + 94.805$ with an R^2 of 0.9823, respectively. This could lead to the fact that at higher rake angles more soil pulverization occurred but at the same time, the high accumulation of soil slices on the surface of the blade that imparted on tubers was high, hence, causing a decrease in harvested tubers. Analysis of variance revealed that the main effect of forward speed and rake angle had a significant effect on the harvesting efficiency at ($P < 0.05$) whereas, the interactions of forward speed and rake angle had no significant effect on the harvesting efficiency at ($P > 0.05$). The maximum harvesting efficiency of 98.21% was obtained when the machine was operated at a forward speed of 2.5 km/hr and a rake angle of 20° whereas the minimum harvesting efficiency of 94.58% was obtained when the machine operated at a forward speed and the rake angles of 3.5 km/hr and 10°, respectively.

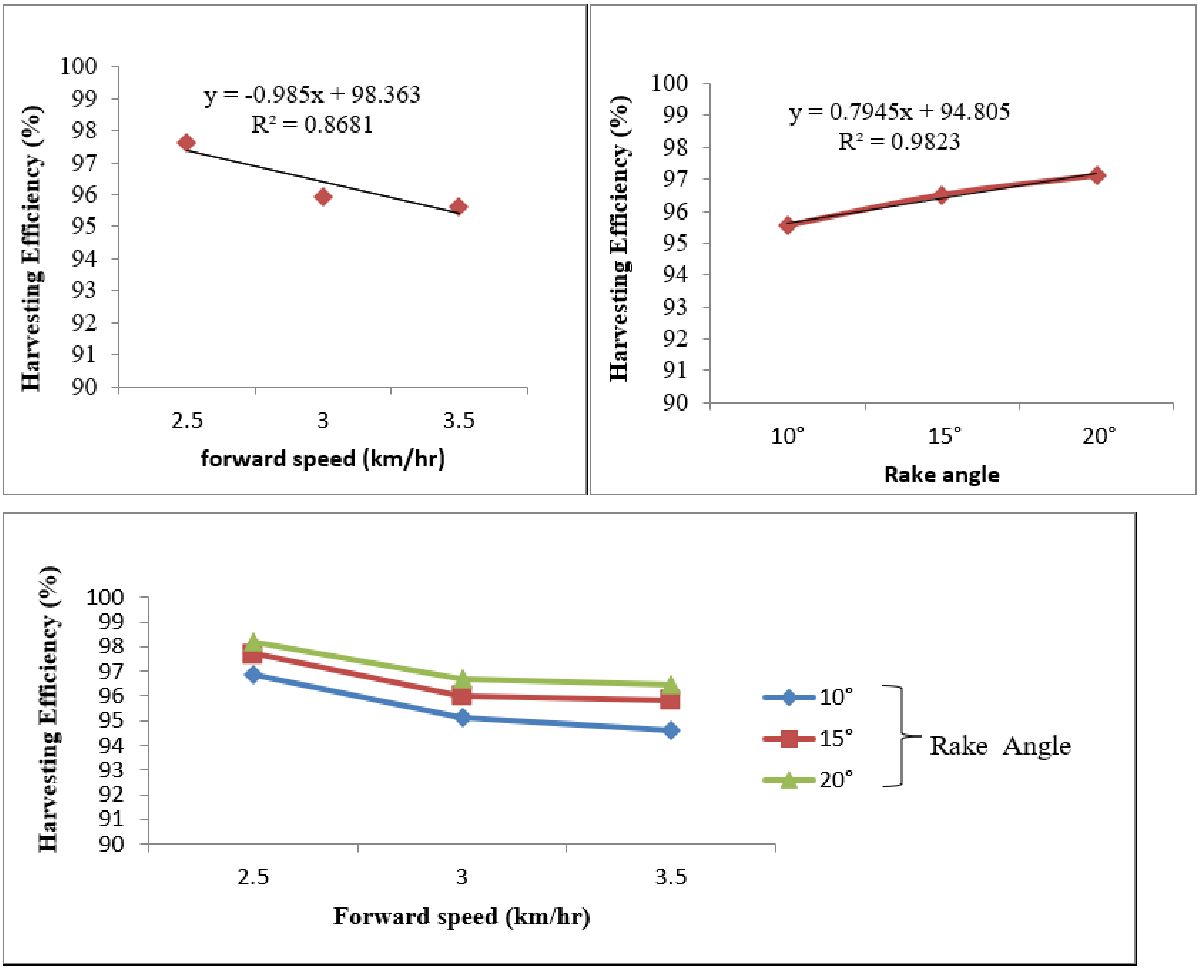

Figure 3: Relationship between forward speed and rake angle on harvested potatoes

Undug Potatoes Percentage

The interaction mean values of undug potatoes at different forward speeds and rake angles are shown in Table 4 and Figure 4. The results revealed that, as the rake angle of the digger increased from 10° to 15°, the undug potatoes decreased from 3.12 to 2.28% at a forward speed of 2.5 km/hr and further decreased from 5.42 to 3.52% as the rake angle increased from 15 to 20° at a forward speed of 3.5 km/hr. Similarly, the undug potatoes decreased from 4.85 to 3.99% and 5.42 to 4.17% as the rake angle increased from 10 to 15° at forward speeds of 3 km/hr and 3.5 km/hr, respectively. From Table 3, it can also be seen that as the forward speed of the digger increased from 2.5 to 3 km/hr, the undug potatoes increased from 2.39 to 4.37%. Similarly, the undug potatoes showed a decreased trend from 4.46 to 2.87 % as the rake angle increased from 10 to 20°, respectively. The results revealed that increased undug potato tuber with an increased forward speed and decreased with increased rake angle. Similar trends were reported by Narender *et al.* (2019)

The maximum undug potato of 5.42% was obtained when the machine was operated at a forward speed of 3.5 km/hr and the rake angles of 10° whereas the minimum of 1.79% was obtained when the machine operated at a forward speed and the rake angles of 2.5 km/hr and 20°, respectively. The main and interaction effects of forward

Table 3: Main effect of forward speed and rake angle on digger performance

Speed (km/hr)	ηH (%)	UD (%)	ηE (%)	PD (%)	EFC (ha/hr)	FE (%)	FC (l/hr)
2.5	97.60± 0.79a	2.39±0.79b	92.42±1.09b	4.76±0.43c	0.12±0.01c	86.42±1.37a	1.17± 0.03c
3	95.94± 0.73b	4.05±0.73a	92.79±1.47ab	6.54±0.31b	0.13±0.01b	84.12±1.19b	1.70±0.04b
3.5	95.63± 0.84b	4.37±0.84a	93.21±1.06a	7.69±0.26a	0.15±0.01a	82.93±0.05c	2.11±0.03a
Rake angle							
10°	95.54± 1.08c	4.46±1.08a	93.86±0.52a	6.40±1.38a	0.12±0.02b	84.31±1.81b	1.63±0.42c
15°	96.52± 1.01b	3.48±1.01b	93.13±0.83b	6.58±1.08a	0.13±0.01a	85.49±2.10a	1.68± 0.37a
20°	97.13± 0.87a	2.87±0.87c	91.43±0.60c	6.01±1.41b	0.13±0.02a	83.65±0.81c	1.67± 0.42b
CV (%)	0.34	8.89	0.49	3.05	2.90	0.04	0.53
LSD (5%)	0.32	0.32	0.46	0.19	0.004	0.03	0.008

Where, ηH = Harvesting efficiency, UD = undug potato percentage, ηE = Exposing efficiency, PD = Potato damage, EFC = Effective field capacity, FE =Field efficiency, FC = Fuel consumed, CV = coefficient of variation; LSD = least significance difference, Values are Mean ± SD. Mean values comparison arranged according to descending order followed by the same letter in a column are not significantly different at a 5% level of significance.

speed and rake angle on the undug potato were analyzed statistically and presented in Tables 3 and 4, respectively as well. The statistical analysis of data on the influence of forward speed and rake angle on the undug potatoes indicated that the undug potatoes were highly influenced by rake angle and forward speed at ($P < 0.05$) level of significance whereas, the interactions of forward speed and rake angle had no significant effect on the undug potato. Similar trends were reported by Narender *et al.*, (2019).

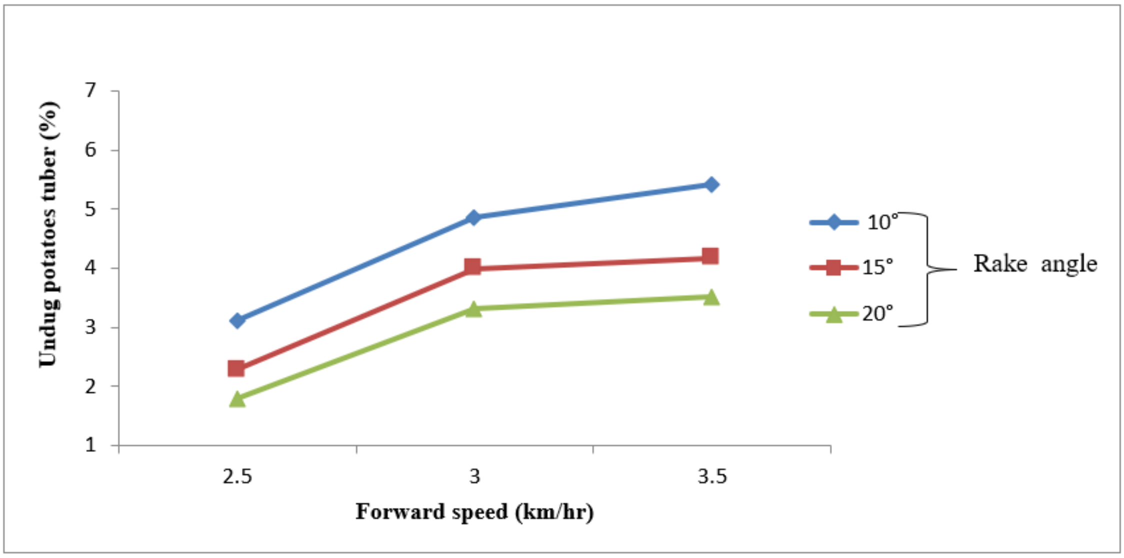

Figure 4: Effect of forward speed and rake angle on undug potatoes

Exposing Efficiency

The effects of forward speed and rake angle on exposing efficiency are presented in Table 4 and Figure 5. It can be seen that as the forward speed of the digger increased from 2.5 to 3.5 km/hr, the exposed potatoes increased from 93.47 to 93.91% at a rake angle of 10°. Similarly, an increasing trend was observed for the exposed potatoes from 92.31 to 93.82% and 91.48 to 91.90% as the speed increased from 2.5 to 3.5 km/hr at a rake angle of 15° and 20°, respectively.

The main effect of forward speed and rake angle on exposing efficiency is summarized in Table 3. The results show that as the rake angle increased from 10 to 20°, the exposing efficiency decreased from 93.86 to 91.43% whereas a tractor forward speed increased from 2.5 to 3.5 km/hr, the exposing efficiency increased from 92.42 to 93.21%. From Figure 5, it was observed that an increased potato tuber was exposed with an increase in forward speed and later decreased with an increased rake angle. Similar trends of increase in exposed tuber with an increase in forward speed of root-crop digger have been reported by Singh (2006). This is due to an increase in rake angle may have increased soil penetration below the potato tuber zone, which in turn dressed the tubers with more soil layers. Therefore, the exposed potato was decreased at the maximum value of the rake angle. The maximum exposing efficiency of 94.21% was obtained when the machine was operated at a forward speed of 3 km/hr and the rake angles of 10° whereas the minimum exposing efficiency of 91.48% was obtained when the machine operated at forward speed and the rake angles of 2.5 km/hr and 20°, respectively.

The statistical analysis (ANOVA) on exposing the efficiency of the prototype potato digger results revealed that the main effect of rake angle had a significant effect on the exposing efficiency at ($P< 0.05$) whereas, forward speed and the interaction effects of forward speed and rake angle had no significant effect on the exposing efficiency at ($P > 0.05$).

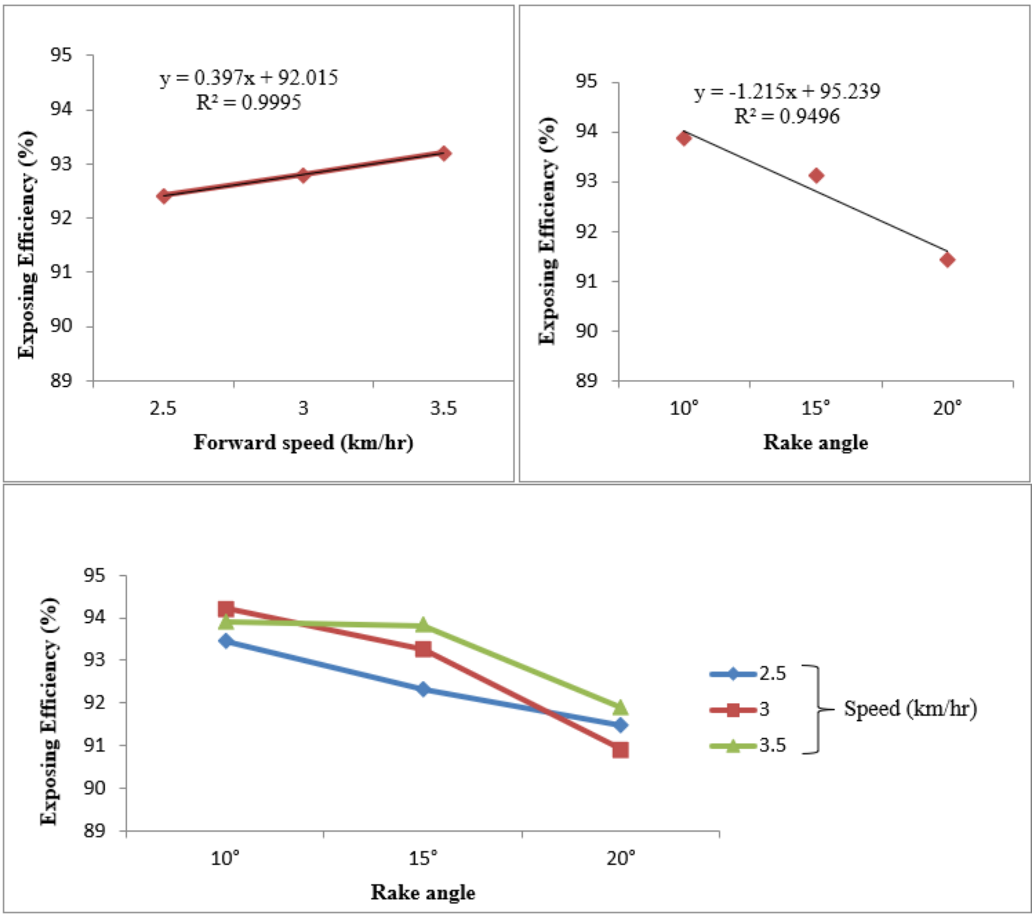

Figure 5: Effect of forward speed and rake angle on exposing efficiency

Damage Percentage of Potato Tuber

The mean value of damaged potatoes at different forward speeds and rake angles is presented in Table 4. The results revealed that as the forward speed of the digger increased from 2.5 to 3.5 km/hr, the damaged potatoes showed increasing values ranging from 4.69 to 7.82% at a rake angle of 10°. Similarly, the damaged potatoes increased from 5.28 to 7.73% and 4.32 to 7.54% as the forward speed of the digger increased from 2.5 to 3.5 km/hr at rake angle of 15° and 20°, respectively. Similar trends of increase in damaged potatoes with the increase in forward speed of root-crop digger have been reported by Ibrahim *et al.*, (2008).

From Table 4, it wan also be seen that as the rake angle of the digger increased from 10° to 15°, the damaged potatoes decreased from 4.69 to 4.32% at a forward speed of 2.5 km/hr. Similarly, the damaged potatoes decreased from 6.76 to 6.17% and 7.82 to 7.54% as the rake angle increased from 10° to 20°, at a forward speed of 3 km/hr and 3.5 km/hr, respectively. At 10° rake angle maximum tuber damage losses were observed because the point of action of digging blade tip was directly on the tuber zone in the soil. Furthermore, it decreased the raised potato soil layer, which led to the direct impact between the blade, and tubers, hence more damaged tubers were expected.

The maximum value of damaged potatoes 7.82% was obtained when the machine was operated at a forward speed of 3.5 km/hr and the rake angle of 10° whereas the minimum value of 4.32% was obtained when the machine operated at a forward speed and the rake angles of 2.5 km/hr and 20°, respectively. The analysis of variance (ANOVA) on the damaged potato digger results revealed that the effect of forward speed on damaged potatoes was significant at ($P <0.05$) level of confidence. The effect of rake angle was also significant at ($P <0.05$) level of confidence whereas the interaction effect of forward speed and rake angle was non-significant.

Table 4: Interaction effect of forward speed and rake angle on performance parameters of potato digger

Speed (km/hr)	Rake angle (°)	ηH (%)	UD (%)	ηE (%)	PD (%)	EFC (ha/hr)	FE (%)	FC (l/hr)
2.5	10	96.88±0.56b	3.12±0.56e	93.47±0.57ab	4.69±0.11e	0.11±00g	86.72±0.06b	1.14± 0.00i
	15	97.72±0.80a	2.28±0.80f	92.31±0.87c	5.28±0.09d	0.12±00f	87.82±0.02a	1.21± 0.00g
	20	98.21±0.41a	1.79±0.42f	91.48±0.84de	4.32±0.10f	0.11±01f	84.71±0.00d	1.17± 0.00h
3	10	95.15±0.08e	4.85±0.08b	94.21±0.06a	6.69±0.10b	0.13±00e	83.34±0.01e	1.66± 0.01f
	15	96.01±0.40cd	3.99±0.40cd	93.27±0.01b	6.76±0.11b	0.14±00cd	85.71±0.00c	1.75± 0.01d
	20	96.69±0.40b	3.31±0.40e	90.92±0.01e	6.17±0.22c	0.13 ±01d	83.33±0.02e	1.68± 0.01e
3.5	10	94.58±0.01f	5.42±0.01a	93.91±0.58ab	7.82±0.11a	0.14±01bc	82.88±0.06g	2.10± 0.01b
	15	95.82±0.01d	4.17±0.01c	93.82±0.48ab	7.73±0.31a	0.14±01ab	82.96±0.02fg	2.07± 0.02c
	20	96.48±0.12bc	3.52±0.12de	91.90±0.21cd	7.54±0.31a	0.15±00a	82.93±0.04f	2.15± 0.01a
CV (%)		0.33	8.89	0.49	3.05	2.90	0.04	0.53
LSD (5%)		0.56	0.55	0.79	0.33	0.01	0.06	0.02
Grand Mean		96.39	3.61	92.81	6.33	0.132	84.49	1.66

Where, ηH = Harvesting efficiency, UD = undug potato percentage, ηE = Exposing efficiency, PD = potato damage, EFC = Effective field capacity, FE =Field efficiency, FC = Fuel consumed, CV = coefficient of variation; LSD = least significance difference, Values are Mean ± SD. Mean values comparison arranged according to descending order followed by the same letter in a column are not significantly different at a 5% level of significance.

Effective Field Capacity

The operation of a potato digger was measured by field capacity, which was accomplished at a given rate that was recorded during the test. The rate of field coverage of the machine based on the rated speed (2.5, 3, and 3.5 km/hr) and covering of its rated width (0.53 m), i.e. the average theoretical field capacity calculated was (0.131, 0.162, and 0.185 ha/hr) respectively. Hence, effective field capacity was the only dependent variable due to changes in time for harvesting.

The effective field capacity was not significantly affected by the rake angle but significantly affected by the forward speed at ($P< 0.05$) level of confidence. The interaction effect of forward speed and rake angle had no significant effect on effective field capacity at ($P<0.05$) level of significance. From Table 3 and Figure 6, the effective field capacity increased from 0.12 to 0.15 ha/hr and 0.12 to 0.13 ha/hr with increased forward speed from 2.5 to 3.5 km/hr and rake angle 10 to 20°, respectively. The effective field capacity increased with the increase of forward speed, due to more area covered in less time. The effective field capacity was not changed much with the rake angle. The maximum value of effective field capacity 0.15 ha/hr was obtained when the machine was operated at a forward speed of 3.5 km/hr and the rake angles 20° whereas the minimum value of 0.11 ha/hr was obtained when the machine operated at forward speed and the rake angles of 2.5 km/hr and 10°, respectively.

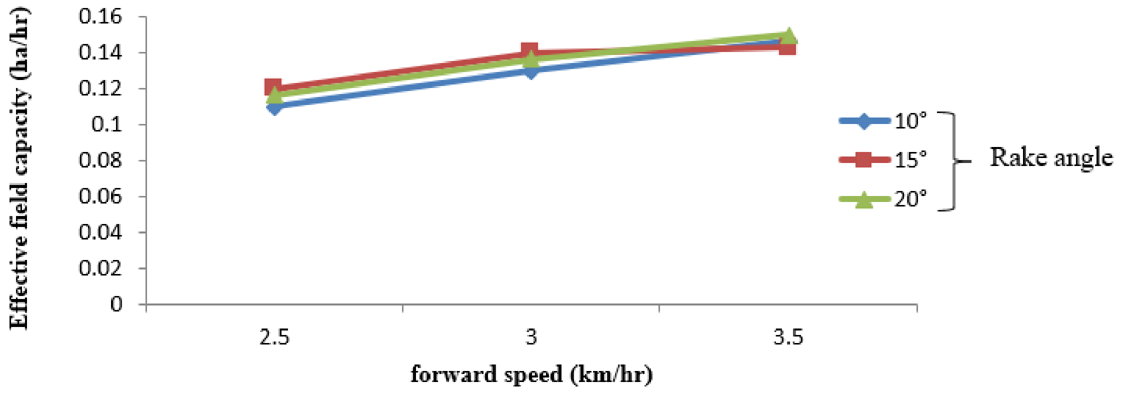

Figure 6: Effect of forward speed and rake angle on effective field capacity

Field Efficiency

The effects of forward speed and rake angle on the field efficiency of the tractor-drawn potato digger are presented in Tables 3 and 4. The results revealed that an increase in forward speed from 2.5 to 3 km/hr decreased field efficiency from 86.42 to 84.12%; further increase in forward speed to 3.5 km/hr, resulted in decreasing field efficiency to 82.93%. On the other hand, an increase in rake angle from 10 to 15° increased field efficiency from 84.31 to 85.49%; further increase in rake angle, to 20°, resulted in decreasing the field efficiency to 83.65%. This may be due to the penetration depth increment, which enhances soil tuber mass accumulation between the conveyors' rod, and blade hence increasing the soil-tuber mass supplied to the conveyor easily. As shown in Table 4, the maximum field efficiency was 87.82% at 2.5 km/hr and 15° rake angle; whereas the minimum field efficiency was 82.88% at 3.5 km/hr and 10° rake angle combinations. That was at the grand mean and CV of 84.49% and 0.04% respectively.

The main and interaction effects of forward speed and rake angle on the field efficiency of the digger were analyzed statistically and presented in Tables 3 and 4. Analysis of variance (ANOVA) results revealed that rake angle and forward speed had a highly significant effect on field efficiency and also the interaction effect of forward speed and rake angle had a highly significant effect at ($P<0.05$) level of confidence.

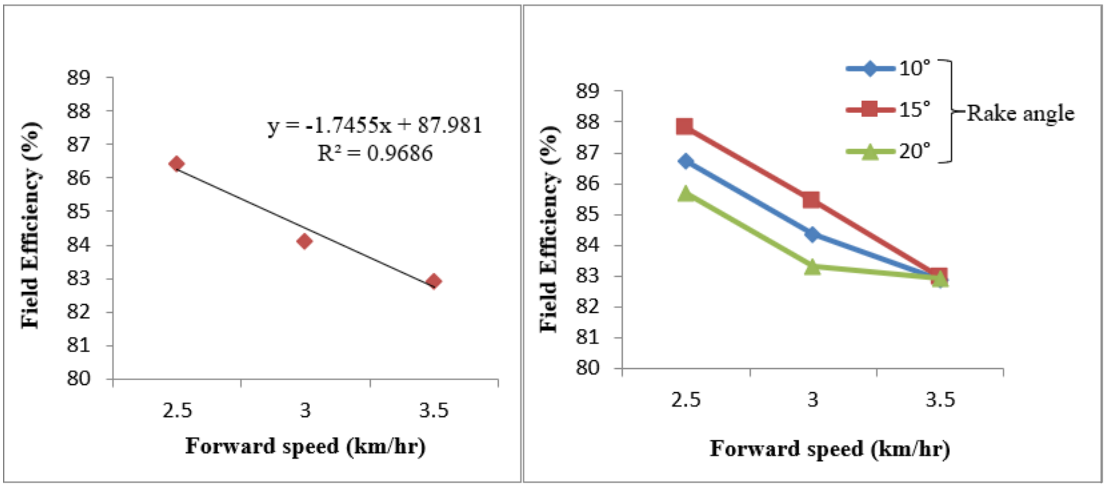

Figure 7: Effect of forward speed and rake angle on field efficiency

Fuel Consumption

Effects of forward speed and rake angle on fuel consumption of the tractor-drawn potato digger are presented in Table 4. From Table 4 and Figure 8, the results revealed that as the forward speed of the digger increased from 2.5 to 3.5 km/hr, the fuel consumption showed increasing values ranging from 1.14 to 2.10 l/hr at a rake angle of 10°. Similarly, the fuel consumption increased from 1.21 to 2.07 l/hr and 1.17 to 2.15 l/hr as the forward speed of the digger increased from 2.5 to 3.5 km/hr at a rake angle of 15° and 20°, respectively. It can also be seen that as the rake angle of the digger increased from 10° to 15°, the fuel consumption increased from 1.14 to 1.17 l/hr at a forward speed of 2.5 km/hr. Similarly, the fuel consumption increased from 1.66 to 1.68 l/hr and 2.07 to 2.15 as the rake angle increased from 15° to 20°, at forward speeds of 3 km/hr and 3.5 km/hr, respectively.

From Table 4, the maximum fuel consumption tractor-drawn potato digger was 2.15 l/hr at 3.5 km/hr and 20° rake angle; whereas the minimum fuel consumption was 1.14 l/hr at 2.5 km/hr and 10° rake angle combinations.

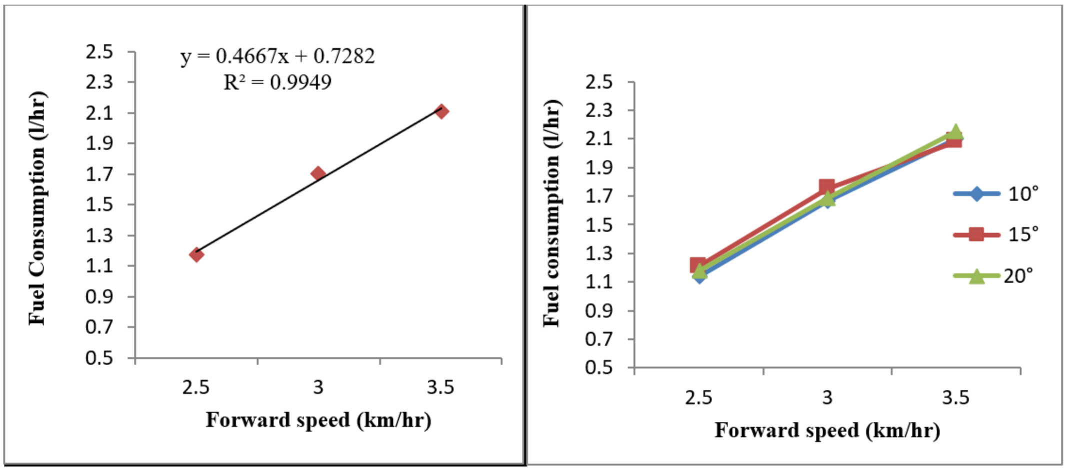

Figure 8: Effect of forward speed and rake angle on fuel consumption of the digger

That was at the grand mean and CV of 1.66 l/hr and 0.04%, respectively. The main and interaction effects of forward speed and rake angle on the fuel consumption of the digger were analyzed statistically and presented in Tables 3 and 4. Analysis of variance (ANOVA) results revealed that rake angle and forward speed had a highly significant effect on fuel consumption whereas the interaction effect of forward speed and rake angle had a highly significant effect at ($P<0.05$) level of confidence.

Cost Analysis

The cost of harvesting potatoes according to traditional methods was compared with the evaluation of the potato digger's prospective operational costs. The total fabrication cost of the potato digger was 42,656.18 ETB. The calculated results of fixed and variable costs were 9.82 and 159.41 ETB/hr, respectively. The cost of operation per hectare for tractor-drawn potato digger and traditional method were 2876 and 6050 ETB/ha, respectively. The cost of operation per hour for tractor-drawn potato diggers and traditional methods was 169.23 and 700 ETB/hr, respectively. The saved cost of harvesting was 52% and the saved in time was 75% compared to traditional potato harvesting.

CONCLUSION

This study was undertaken to develop and evaluate the tractor-drawn potato digger at the farmer's field. The digger was tested at three levels of forward speeds (2.5, 3, and 3.5 km/hr) and three levels of rake angles (10, 15, and 20°). The experiment was replicated three times for the performance parameters of harvesting efficiency, exposing efficiency, percentage of tuber damage, effective field capacity, field efficiency, and fuel consumption. As a result, the following conclusions were drawn from the study: The percentage of exposed potatoes, undug potatoes, and damaged potatoes increased with an increase in the forward speed of the potato digger but the harvesting efficiency decreased with an increase in speed whereas decreased with an increase in the rake angle of the potato digger. However, the harvesting efficiency increased with the increase in the rake angle of the potato digger. The maximum value of harvesting efficiency and minimum value of potato damage 98.21 and 4.69% respectively were obtained at a forward speed of 2.5 km/hr and a 10° rake angle. The maximum effective field capacity of 0.15 ha/hr was obtained at 3.5 km/hr forward speed and 20°rake angle. As the rake angle increased, the effective field capacity also increased. The effective field capacity increased with the increasing forward speed, as a result of more area being covered in less time. The field efficiency of the potato digger is higher when operated at a low forward speed and low rake angle. Fuel consumption increased as the forward speed and rake angle increased. In general, the performance of the potato digger was found to be optimum at a 20° rake angle with 2.5 km/hr forward speeds. Hence, maximum harvesting efficiency of 98.21% was recorded with lower potato damage of 4.32% while the exposing efficiency, undug potato, effective field capacity, field efficiency, and fuel consumption were found to be 91.48%, 1.79%, 0.11 ha/hr, 84.71%, and 1.17 l/hr, respectively. So, the above study revealed that the forward speed of 2.5 km/hr and rake angle of 20° is selected best for the operation of the potato digger in the field. The potato digger performance evaluation revealed that it can be used successfully on the farm for harvesting operations. To make the tractor-drawn potato digger applicable and acceptable among farmers, the following are recommended for further study on the digger:

- Adaptation, modification, and performance test of the potato digger for multi-root crop harvesting operation can be done and
- Demonstration of this digger should be undertaken at a wider farm level.

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