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Performance Evaluation of Tractor Drawn Combined Tillage Implement

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ABSTRACT

Soil tillage is one of the most critical processes in the agricultural production system, requiring the greatest energy and time of any operation. The purpose of this study was to evaluate the performance of a tractor-drawn combined tillage implement. The performance of the implement was evaluated in terms of the draft force, draft power, wheel slip, fuel consumption, mean weight soil diameter, field efficiency, soil inversion, volume of soil tilted, and tillage performance index. The tillage implement is tested at forward speed of 3, 5, and 7 km/hr and depth of operation 10, 15, and 20 cm. The optimum performance was achieved at 20 cm depth and 5 km/h forward speed. Hence, a maximum tillage performance index of 1.202 was recorded with a minimum mean weight diameter of 12.73 mm while the draft, draft power, wheel slip, field efficiency, and fuel consumption were found to be 2289.71 N, 1.87 kW, 8.74%, 84.71%, and 6.16 l/hr, respectively. The analysis of variance (ANOVA) revealed that forward speed and depth of operation had significant effects on draft, draft power, wheel slip, mean weight diameter, field efficiency, tillage performance index, and fuel consumption at a ($P<0.05$) level of significance. The costs of operation of tractor-drawn combined tillage were 1707.43 Birr/hr whereas the break-even point, payback period, and benefit-cost ratio were 1,349.45 hr/yrs, 1.84 yrs, and 4.34, respectively. From the above results, it can be concluded that farmers could use this implement for tillage/seedbed preparation.

Keywords: Pulverization; Tillage; Tillage Performance Index; Wheel Slip; Mean Weight Diameter.

1. Introduction

Tillage is the process of mechanically manipulating soil to make it more conducive to crop cultivation. Soil tillage entails breaking the earth's compact surface to a particular depth and loosening the soil mass to allow crop roots to penetrate and disseminate into the soil (Zhou *et al*., 2020). It is the mechanical manipulation of soil and plant debris to prepare a seedbed for the planting of seeds that will produce grain for human use. Tillage breaks the soil, enhances the release of soil nutrients for crop growth, destroys weeds, and enhances the circulation of water and air within the soil (Reicosky & Allmaras, 2003). Tillage is considered one of the most important processes in agriculture, as it gives suitable conditions for root growth, which in turn supports the growth of plants; it reduces soil resistance, increases the ventilation process, and eliminates weeds (Al-Shamiry *et al*., 2020). Nowadays, conventional tillage practices are very expensive, more time-consuming, and higher number of passes which causes soil compaction. Furthermore; conventional tillage is considered to be one of the low fuel-efficient operations. Digman (2012) mentioned that only 20% of diesel fuel energy is available at the drawbar of the tractor, however, only 4% of that energy is converted into breaking up the soil. Therefore, it is so important to find an early way to get the most out of tillage operation, one way to bypass these problems is the use of combined tillage implements in one field operation. This practice is useful only for those who prefer the use of conventional tillage practices such as the Ethiopian farmers.

Prem *et al.* (2016) defined as combined tillage is the way in which two or more implements operate at the same time to manipulate the soil. In a general sense, combined tillage means integrated management of resources such as time, energy, fuel, labor, soil, and water conservation, on the other hand, increasing yield and better utilization of natural resources. It also contributes to and sustains agriculture production.

Tillage implements work based on two working motions, sliding type and rotating type. Implements like mouldboard plough and cultivators use sliding action to cut the soil. By functioning in a rotational motion, disc ploughs; disc harrows, clod crushers, and rollers cut and pulverize the soil. Because of the soil frictional force and the contact area of the implement, sliding-type implements consume more drafts than rotating-type implements. A negative draft was produced by rotary-type implements. As a result, the combination tillage implements were more energy efficient and saved nearly 50% in cost and 50 up to 55% in time compared with the same single passive tillage implement (Parmar & Gupta, 2016).

In Ethiopia, farmers are using the conventional tillage system which disturbs the soil more; increases soil compaction increases erosion capacity by wind and water. The combined tillage used was also imported from other countries which are too expensive. The implementation did not consider small-scale mechanization, affordable power, high land agriculture, costly, and not scale appropriately. The overall dimensions and weight of the tillage tool were heavy, not easily dismantled, or repaired and it was complicated.

Nowadays there are combined tillage implements in the world that operate soil tilling purposes within a short period in a single pass but they are very expensive for our farmers to import them. Governmental and non-governmental organizations (NGOs) distribute a lot of tractors for the farmers, youths, and the Biro of Agriculture in different ways. But most of them have been distributed with primary and secondary tillage implements and accessories. So, to alleviate this problem Asella Agricultural Engineering Research Centre (AAERC) was developed combined secondary tillage implements for seedbed preparation ultimately for import substitution. Therefore, the objective of this activity is to evaluate the performance of a tractor-drawn combined tillage implement.

1.1. Study Objectives

The following are the objectives of this study:

1) To evaluate the performance of a tractor-drawn combined tillage implement.

2) To quantify the implement's operational efficiency and field capacity.

3) To determine the implement's draft requirement and power efficiency.

4) To assess the quality of tillage achieved by the implement.

5) To analyze the economic viability and cost of operation.

2. Materials and Methods

2.1. Materials

Materials used for the evaluation of combined tillage implements were tractor, digital balance, dynamometer, measuring tape, graduated cylinder, stopwatch, oven dry, and core sampler.

2.2. Methods

2.2.1. Descriptions of the Implement

Combined tillage implement was operated for secondary tillage operations in a single pass to ensure timeliness in seedbed preparation. The implement consists of the following main components: mainframe, cultivator tines, two rollers with pulverizing blades, and three-point linkage system. Mainframe was fabricated from the square pipe having a determined size of 80 × 80 × 4 mm for accommodating cultivator tines, three-point linkage systems, and two rollers with pulverizing blades. All components of the cultivator and roller were assembled and fitted on the frame. Cultivator was fabricated from a rectangular shape made up of MS material with 40 mm width, 600 mm length, 780 mm height, and 103.2 mm radius of curvature was fabricated.

Three-point hitch was fabricated from Ms Flat iron. The overall dimension of the three-point hitch was 1300 mm in length, 760 mm in width, and 850 mm in height. The pulverizing roller was attached to the rear back of the cultivator with spike blades to pulverize the soil to a greater degree. The pulverizing roller consists of a disc, cylinder drum, central shaft, pulverizing members, and mounting link. The pulverizing roller consists of a mild steel roller of 1,900 mm length and 200 mm diameter on which mild steel flat spikes of 40×40×120 mm length were welded in the helical pattern. The overall dimension of the implement was 2150 mm in length, 1550 mm in width, and 1530 mm in height.

2.2.2. Working Principles of the Implement

The implement was to reduce secondary tillage operations to a single pass to ensure timeliness in seedbed preparation. Behind the pulverizing attachment to the cultivator which had having pulverizing roller was an active unit behind the implement and in front cultivator tines were attached as passive units.

Figure 1. Operation during performance evaluation of combined tillage implement

Cultivator tines were used for breaking clods and working the soil to a fine tilth in the preparation of the seedbed at the desired depth of operation and the pulverizing roller was used for cutting, mixing, and clod breaking which ultimately pulverized the soil by impact force. The cutting and clod-breaking action of this unit provides excellent land preparation and also the pulverizing roller cut and pulverizes the soil for seedbed preparation.

2.3. Performance Evaluation Parameters

The following parameters were determined to evaluate the performance of the combined tillage implement.

2.3.1. Soil moisture content

To determine the soil moisture content of the field, soil samples were taken up to a depth of 0 to 25 cm. The samples were collected randomly from five locations of each test plot. These samples were weighed and kept in the oven at 105°C for 24 hours and the moisture content was calculated by using the following formula given 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

2.3.2. Bulk density of soil

Soil samples were taken randomly from the field with the help of a core sampler. The bulk density of soil samples was measured by a core sampler having an inner diameter of 7 cm and a height of 12 cm. The soil samples were collected at a depth level of 0 to 25 cm before the tillage operation. The bulk density was determined by dividing the weight of oven-dried soil (at 105°C for 24 hr) samples by the volume it occupied and calculated by using the following equation given 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)

2.4. Machine Performance

The machine performance parameters such as draft, draft power, tillage performance index (volume of soil handled, cone index, fuel energy), wheel slip, mean weight diameter of the soil aggregate, field capacity, field efficiency, and fuel consumption of the combined tillage implement were determined for the performance evaluation as follows:

2.4.1. Effective Field Capacity

For calculating the effective field capacity, the time taken for actual work and the time used for other activities such as turning, cleaning, adjustment of the machine, and time spent for machine trouble were taken into consideration. The length and width of the plot were measured and the area covered in that time was calculated. It is the actual average rate of coverage by the machine. The total time required to complete the operation was recorded and effective field capacity was calculated as follows (Kepner *et al*., 2005):

$$EFC = \frac{A}{T_p + T_i} \times 100 \qquad (3)$$

Where: EFC = Effective field capacity, ha/hr

A = Actual area covered, ha, T_p = Productive time, hr, T_i =Non-productive time, hr

2.4.2. Theoretical Field Capacity

It depends upon the speed and theoretical width of the implement or it is the rate of field coverage that shall be obtained if implements perform its function 100% of the time at the rated speed and always covers 100% of its rated width. The theoretical field capacity will be calculated as (Kepner *et al*., 2005):

$$TFC = \frac{W \times S}{10} \qquad (4)$$

Where, TFC = Theoretical Field capacity, ha/h

S = Speed of operation, km/hr and W = Theoretical width of implement, m

2.4.3. Field Efficiency

The field efficiency is the ratio of the effective field capacity to the theoretical field capacity, usually measured in terms of percentage. It includes the effect of time lost in the field and of failure to utilize the full width of the machine (Kepner *et al.*, 2005):

$$\eta = \frac{EFC}{TFC} \times 100 \qquad (5)$$

Where: η = Field efficiency (%)

TFC = Theoretical field capacity (ha/h), EFC = Effective field capacity (ha/h)

2.4.4. Draft

The draft was measured by two tractors and dynamometer. The implement was mounted on a tractor (A) and this tractor was pulled by another tractor (B) through a dynamometer. The draft was measured when tractor A was in neutral gear condition but the implement was in operating condition and again when the implement was lifted position. The difference between the two readings gives the draft requirement of the implement (Mehtha *et al*., 2005).

2.4.5. Draft Power

Power required to pull the equipment was calculated only for rota-cultivator and was given by the equation (Mehtha *et al*., 2005):

$$D_p = \frac{D \times S}{3.6} \qquad (6)$$

Where: D_p = Power, kW, D = Draft, kN and S = Speed of travel, km/hr

2.4.6. Wheel slip

Slip in traction device occurs between the surfaces of the device and the medium on which it operates. The distance covered in ten wheel revolutions is recorded with and without load and the values were used to calculate slip using the following expression. It was given by the equation (Mehtha *et al*., 2005):

$$S = \frac{D_O - D_l}{D_O} \times 100 \qquad (7)$$

Where, S = Slip %,

D_O = distance covered in 10 revolutions of the drive wheel at no load in the field, and

D_l = distance covered in 10 revolutions of the drive wheel with load in the field

2.4.7. Mean Weight Diameter

The mean weight diameter (MWD) of the soil aggregates is considered the index of soil pulverization and can be determined by sieve analysis of the soil sample through a set of test sieves. The set of sieves used was a collecting pan or mesh opening of 37.5, 31.5, 26.5, 16, 13.2, and 11.2 mm. Sieving provides a simple means for measuring the range of clod size and relative amount of soil in each size class. The mean weight diameter of soil in mm was determined by using the following equation (Mehtha *et al*., 2005):

$$MWD = \frac{1}{W}\left(A + 2.4B + 3.4C + 4.8D + 6.8E + XF\right) \qquad (8)$$

Where, MMD = Mean weight diameter, mm

W = Total weight of the soil retained on the sieves, kg

A, B, C, D, E & F = Weight of soil on each sieve, kg

X = Mean of measured diameters of soil clods retained on the largest aperture sieve, mm

2.4.8. Fuel Consumption

Fuel consumption has a direct effect on the economics of the combined tillage implement. It was measured by the top-fill method. The fuel tank was filled before the testing at level condition. After completion of the test operation, the amount of fuel required to top fill again is the fuel consumption for the test duration. This observation was used for the computation of fuel consumption in terms of l/ha (Nkakini *et al*., 2010):

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

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

2.4.9. Tillage performance index

The overall performance of a tillage implement was expressed in terms of the tillage performance index (TPI), which is considered to be directly proportional to the volume of soil handled per unit time (Vs), soil inversion (SI) and inversely proportional to fuel energy (Fe) and mass weight diameter (MWD) (Raheman & Behra, 2018):

$$TPI = \frac{V_S}{MWD \times F_e} \qquad (10)$$

2.4.10. Volume of soil handled

As shown in the equation below, the amount of soil handled was estimated by multiplying the effective field capacity by the depth of operation (Ahaneku *et al*., 2011). Therefore, the volume of soil handled per unit of time could be expressed as:

$$V_s = AFC \times T_d \times 1000 \qquad (11)$$

Where, V_s = Volume of soil tilled per unit time, m^3/hr

AFC = Actual field capacity, ha/hr

T_d = Depth of operation, m

2.4.11. Soil inversion

Quantity and quality of work done by the implement were expressed in terms of soil inversion. The soil inversion was determined by calculating the number of weeds collected from an area of 1m×1m before and after the tillage operation carried out by the developed combined tillage implements (Inthiyaz *et al.*, 2020):

$$SI(\%) = \frac{W_2 - W_1}{W_2} \times 100 \qquad (12)$$

Where: SI = indicator for soil inversion

W_2 = no. of weeds before operation per unit area, m^2

W_1 = no. of weeds exposed on the surface after operation, m^2

2.4.12. Fuel energy input to the tractor

The fuel energy input to the tractor to carry out a tillage operation could be expressed as:

$$F_e = FC \times CV \qquad (13)$$

Where: F_e = Fuel energy input, MJ/hr

FC = Fuel consumption, l/hr

CV = Calorific value of diesel, MJ/l

2.5. Experimental Design and Treatment

To evaluate the performance of the combined tillage implement, three levels of forward speed 3, 5, and 7 km/hr and three levels of depth of operation 10, 15, and 20 cm were selected. The experimental design was a randomized complete block design (RCBD) with 3^2 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.

2.6. Statistical Analysis

The results of the performance of the combined tillage implements 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 the selected parameters. The mean values and standard deviation (Mean ± Standard deviation) were used to present the results.

2.7. Cost Analysis

The cost analysis was performed in two steps. The first step is to calculate the cost of the materials and the fabrication. The second step is to calculate the developed combined tillage operating cost. To evaluate the financial viability of the developed combined tillage, two parameters were computed and analyzed thus fixed and variable costs. Fixed costs include depreciation, interest, taxes, shelter, and insurance. Variable costs also called operational costs vary in proportion to the amount of machine used. It includes repair and maintenance, fuel, oil or lubrication, and labor costs. The total fabrication cost of the combined tillage was calculated taking into consideration the materials used and labor charges. The fixed and variable costs for operating the unit per hour were calculated as per the procedure enumerated by IS 9164-1979 test codes and procedures. From the field capacity of the unit, the cost of operation per ha was calculated. The break-even point (BEP), payback period, and benefit-cost ratio of the tractor-drawn combined tillage were estimated.

3. Results and Discussion

The field experiment was conducted at a farmer's field with an area of 20×50 m^2 plot in sandy loam soil. During the ploughing periods of the land by the combined tillage implement, the average moisture content of the soil, bulk density of the soil, speed of operation, theoretical field capacity, actual field capacity, and field efficiency were 18.67%, 1.48 gm/cm^3, 2.87 km/hr, 0.488 ha/hr, 0.418 ha/hr, and 84.88%, respectively as presented in Table 1.

Table 1. Field observation during the tractor-drawn combined tillage implement

S/No	Moisture Content, %	Bulk density, g/cm^3	Speed of operation (km/hr)	Theoretical field capacity (ha/h)	Actual field capacity (ha/h)	Field Efficiency (%)
1	19.71	1.51	2.572	0.405	0.322	79.75
2	18.55	1.46	2.252	0.360	0.315	85.50

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3	19.54	1.54	3.174	0.571	0.514	90.00
4	17.28	1.36	3.001	0.540	0.482	89.25
5	19.26	1.52	2.572	0.405	0.322	79.75
Ava.	**18.67**	**1.48**	**2.873**	**0.488**	**0.418**	**84.88**

3.1. Performance Evaluation of the Implement

Tractor drawn combined tillage implement was tested under field conditions to determine the performance parameters. The parameters selected for the study included three forward speeds (3, 5, and 7 km/hr) and three levels of depth of operation (10, 15, and 20 cm). The effect of forward speeds and depth of operation were studied to evaluate the performance of the combined tillage implement in terms of draft, draft power, wheel slip, mean weight diameter, fuel consumption, field efficiency, tillage performance index, and the results are discussed below.

3.1.1. Draft

The effects of forward speed and depth of operation on the draft of implements are presented in Figure 2 and Table 3. From Table 3, the results showed that as the depth of operation increased from 10 to 20 cm, the draft increased from 1367.07 to 1937.13 N at tractor forward speed of 3 km/hr, and also depth of operation increased from 10 to 20 cm, the draft increased from 1770.21 to 2289.71 N at tractor forward speed of 5 km/hr. Similarly, an increasing trend of the draft was observed from 1367.07 to 1937.13 N and 2206.87 to 2656.69 N as the tractor forward speed increased from 3 to 7 km/hr at depth of operation 10 cm and 20 cm, respectively. Similar trends of an increase in draft with an increase in forward speed on combined tillage have been reported by Prem *et al*., 2016. The main effect of forward speed and depth of operation on draft is summarized in Table 2.

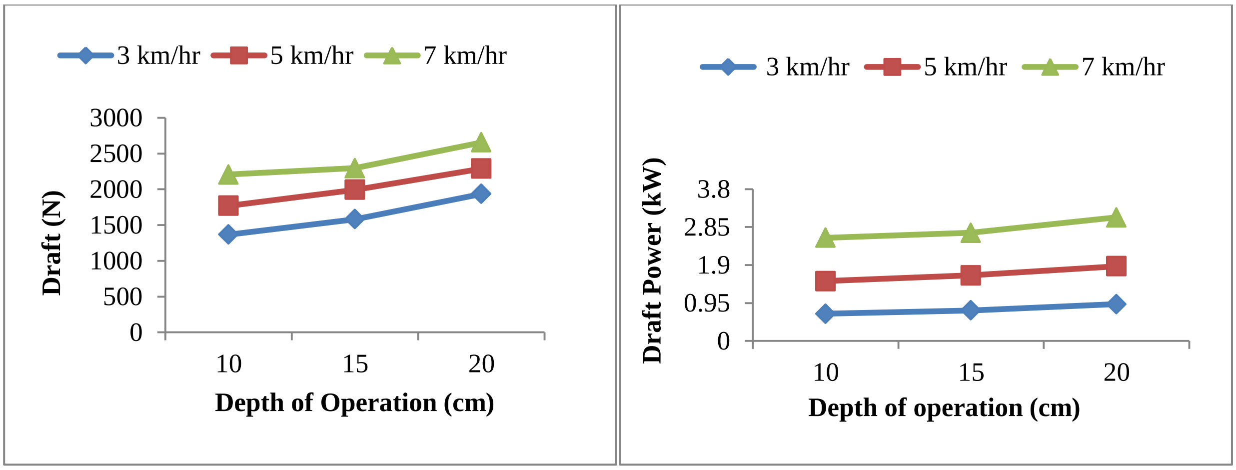

Figure 2. Effect of depth on draft and draft power of combined tillage at different forward speeds

Its results revealed that as the depth of operation increased from 10 to 20cm, the draft increased from 1781.38 to 2294.51 N and forward speed increased from 3 to 7 km/hr, the draft increased from 1628.65 to 2386.51 N. From Table 3, the minimum draft value of 1367.07 N was recorded at a 10 cm depth of operation and 3 km/hr tractor forward speed whereas the maximum draft value of 2656.69 N was obtained at a 20 cm depth of operation and 7 km/hr tractor forward speed. Analysis of variance (ANOVA) revealed that the main effect of forward speed and depth of operation and their interaction had a significant effect on the draft at P< 0.05. Draft increased with increase in depth of operation due to more volume of soil tilted and increase in soil resistance. Draft decreased with decrease in forward speed of the tractor due to the decrease in speed of tractor decreased the accelerating forces which in turn decreased normal loading on soil engaging surfaces thereby decreasing the shear strength of soil.

3.1.2. Draft Power

The effect of depth of operation and tractor forward speed on the draft power of the implement is presented in Figure 2 and Table 3. From Table 3, the results showed that as the depth of operation increased from 10 to 20 cm, the draft power increased from 0.68 to 0.92 kW at forward speed of 3 km/hr, and also the depth of operation increased from 10 to 20 cm, the draft increased from 1.49 to 1.87 kW at forward speed of 5 km/hr. Similarly, an increasing trend of draft power was observed from 2.59 to 3.09 kW at a tractor forward speed of 7 km/hr. The draft power of the combined tillage implement varied from 0.68 to 3.09 kW at depths of operation varied from 10 to 20 cm and tractor forward speed varied from 3 to 7 km/hr. The main effect of forward speed and depth of operation on draft power is presented in Table 2. From Table 2, the results show that as the depth of operation increased from 10 to 20 cm, the draft power increased from 1.59 to 1.96 kW and forward speed increased from 3 to 7 km/hr, the draft power increased from 0.79 to 2.79 kW. Analysis of variance (ANOVA) revealed that the main and interaction effects of depth of operation and forward speed and their interaction effects had a significant effect on the draft power of the pulverizing roller attached to the cultivator at P<0.05. This indicates that the effect of all factors influences on draft power of combined tillage implements. The effects of different depths of operation and forward speed on the draft power of the pulverizing roller attached to the cultivator are presented in Figure 2. It was observed that the draft power of the pulverizing roller attached to the cultivator increased with an increase in the depth of operation and forward speed of the tractor. However, minimum draft power of 0.68 kW was recorded at a 10 cm depth of operation and 3 km/hr tractor forward speed while a maximum draft power of 3.09 kW was recorded at 20 cm depth of operation and 7 km/hr tractor forward speed. Draft power increased with an increase in depth of operation due to more volume of soil handled and an increase in soil résistance. Draft power decreased with the decrease in the forward speed of the tractor due to a decrease in the strength of the soil. The quantity of soil disturbed and distance moved per unit time was also decreased with the decrease in speed of operation which resulted in a decrease in draft power. Similar trends have been reported by Raheman & Behra, (2018).

Table 2. Main effect of forward speed and depth of operation on combined tillage performance

Speed (km/hr)	**D_R (N)**	**D_P (kW)**	**W_S (%)**	**MWD (mm)**	**TPI**	**FC (l/hr)**
3	1628.65 ± 254.47^c	0.79 ± 0.11^c	5.31 ± 1.94^c	12.32 ± 1.44^a	0.741 ± 0.17^b	4.22 ± 0.81^c
5	2018.22 ± 234.19^b	1.67 ± 0.18^b	6.71 ± 1.88^b	11.58 ± 1.04^b	0.984 ± 0.22^a	5.18 ± 0.82^b
7	2386.51 ± 219.15^a	2.79 ± 0.84^a	8.91 ± 1.78^a	11.62 ± 1.36^b	0.600 ± 0.16^c	6.61 ± 1.01^a
Depth of operation (cm)						
10	1781.38 ± 368.04^c	1.59 ± 0.83^c	4.94 ± 1.69^a	12.74 ± 1.84^b	0.563 ± 0.14^c	4.36 ± 0.92^c
15	1957.46 ± 316.49^b	1.70 ± 0.84^b	6.95 ± 1.77^b	11.53 ± 1.62^c	0.803 ± 0.19^b	5.28 ± 1.06^b
20	2294.51 ± 319.69^a	1.96 ± 0.94^a	9.05 ± 1.56^a	13.57 ± 1.87^a	0.958 ± 0.21^a	6.37 ± 1.17^a

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CV (%)	0.70	2.00	1.21	3.28	2.55	2.23
LSD (5%)	14.25	0.04	0.08	0.39	0.019	0.118

Where, DR = Draft, Dp =Draft power, WS = Wheel slip, MWD = Clod mass weight diameter of soil aggregate, TPI= Tillage performance Index, 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.

3.1.3. Wheel slip

The effect of operational parameters of depth of operation and forward speed on wheel slip of tractor with combined tillage implement are presented in Tables 2 and 3. From Table 3, the results showed that as the depth of operation increased from 10 to 20 cm, the wheel slip increased from 3.28 to 7.57% at a forward speed of 3 km/hr, and also the depth of operation increased from 10 to 20 cm, the wheel slip of tractor increased from 4.61 to 8.74% at a forward speed of 5 km/hr. Similarly, an increasing trend of wheel slip was observed from 6.93 to 10.83% at 7 km/hr tractor forward speed in sandy loam soil. The main effect of forward speed and depth of operation on wheel slip is presented in Table 2. From this Table, the results indicated that as the depth of operation increased from 10 to 20cm, the wheel slip increased from 4.94 to 9.05% and forward speed increased from 3 to 7 km/hr, the wheel slip increased from 5.31 to 8.91%. Analysis of variance (ANOVA) revealed that the main and interaction effects of depth of operation and forward speed had a significant effect on wheel slip at a 5% significance level ($P<0.05$). This indicates that the effect of all factors influences on draft power of combined tillage implements. It also observed that wheel slip increased with an increase in the depth of operation and forward speed of the tractor for sandy loam soils. The minimum wheel slip (maximum skid) of 3.28% was recorded at 10 cm depth of operation and 3 km/hr tractor forward speed whereas the maximum wheel slip of 10.83% was observed at 20 cm depth of operation and 7 km/hr tractor forward speed in sandy loam soil. The wheel slip with pulverizing roller attached to the cultivator was minimal at lower speeds may be due to less resistance offered, less volume of soil handled, and lower draft requirement with the decrease in forward speed causing less thrust requirement at the drive wheels to decrease and resulting in less slip. Wheel slip increased with an increase in depth of operation due to more volume of soil handled and higher draft requirement with an increase in depth of operation caused thrust requirement at rear wheels to increase and resulted in more wheel slip and with the presence of moisture in the soil, more resistance was offered to the soil-engaging tool making it difficult to move and resulting in more slip. The results are in agreement with the findings of Singh *et al.* (2016)

3.1.4. Mean weight diameter (*MWD*) of soil aggregates

The effect of operational parameters depth of operation and tractor forward speed on *MWD* of soil aggregates are presented in Tables 2 and 3. From Table 3, the *MWD* pulverizing roller attached to the cultivator varied from 10.51 to 12.72 mm and 10.37 to 11.64 mm at depths of operation 10 to 15 cm at forward speeds of 3 and 5 km/hr, respectively. Similarly, the increasing trend of *MWD* was observed from 10.11 to 11.74 mm at 7 km/hr tractor forward speed in sandy loam soil. The minimum *MWD* of 10.11 mm was obtained at a 10 cm depth of operation and 7 km/hr tractor forward speed whereas the maximum *MWD* of 13.75 mm was obtained at a 20 cm depth of operation and 3 km/hr tractor forward speed. From Table 2, the main effects of depth of operation and tractor forward speed had a significant effect on clod mean weight diameter of soil aggregate at ($P<0.05$), and their interaction of effects depth of operation and tractor forward speed had no significant effect on mean weight diameter of soil aggregate at ($P>0.05$). The effects of depths of operation and forward speed on the *MWD* of soil aggregates are presented in Figure 3. It was observed that the *MWD* increased with an increase in tillage depth or depth of operation from 10 to 20 cm. *MWD* decreased with an increase in the forward speed of the tractor.

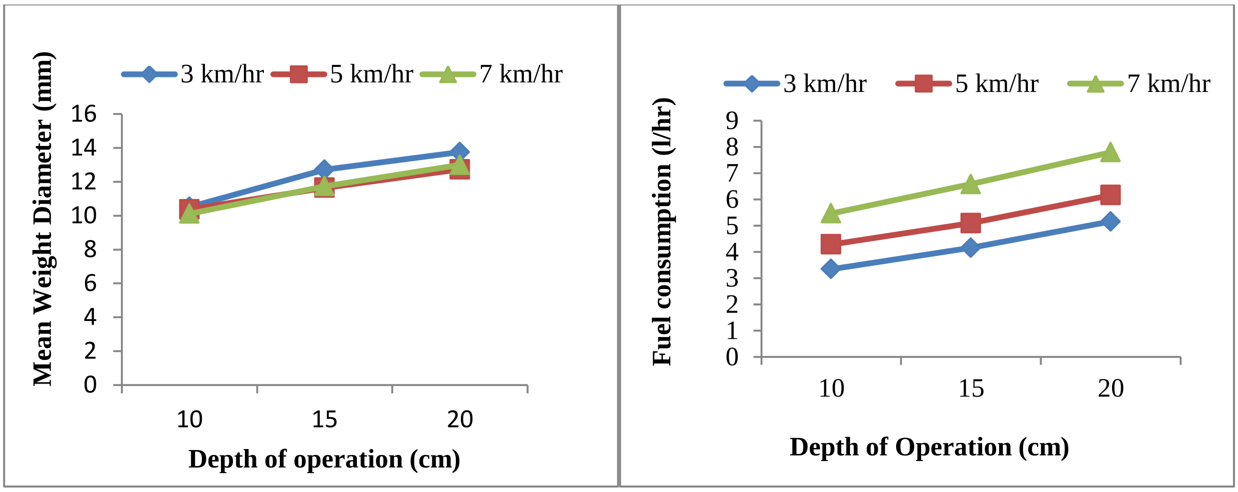

Figure 3. Effect of depth and forward speed on *MWD* of soil aggregates and Fuel consumption

The *MWD* of soil decreased with the decrease in the forward speed of the tractor due to the tilling time of rotor blades at a particular place, which resulted in the decrease in clod size. Other studies have also shown that the *MWD* value increased with an increasing tillage depth (Yassen *et al.* 1992; Esehaghbeygi *et al*. 2020). Increasing the tillage depth increased the *MWD* value due to the higher compaction in the deeper soil layers. Increasing the forward speed decreased the *MWD* value (Figure 3). Increasing the forward speed from 3 to 7 km/hr decreased the *MWD* by 5.68%. Dehghani and Karparvarfard (2017) reported that increasing the forward speed decreased the *MWD* value. This is due to creating high acceleration to the soil particles during their translocation. However, *MWD* decreased with an increase in tractor forward speeds because with the increase in depth, wheel slip increased, so pulverizing roller blade had more tilling time at a particular place resulting in less *MWD*. Hence, increasing the forward speed and decreasing the operating depth reduced the *MWD* of the combined tillage implement. Presence of moisture content in soil tends to increase the aggregate stability of soil particles which requires higher breakup energy to reduce the clod size, Therefore with increase moisture content *MWD* of soil has increased with combined tillage Kepner *et al.*(2005). This observation was in agreement with the result obtained by Prem *et al*. (2016) and Raheman and Behra (2018).

3.1.5. Fuel Consumption

Effects of forward speed and depth of operation on fuel consumption of the tractor-drawn combined tillage are presented in Table 3. From Table 3 and Figure 4, the results revealed that as the depth of operation increases from 10 to 15cm, the fuel consumption showed increasing values ranging from 3.35 to 4.16 l/hr at a tractor forward speed of 3 km/hr. Similarly, as the depth of operation increased 10 to 20 cm the fuel consumption increased from 4.28 to 6.16 l/hr and 5.47 to 7.79 l/hr as the forward speed of the tractor increased from 3 to 7 km/hr, respectively.

From Table 3, the results revealed that as the depth of operation increased from 10 to 20 cm, the fuel consumption increased from 4.36 to 6.37 l/hr. From Table 3, Maximum fuel consumption of combined tillage was 7.79 l/hr at 7 km/hr and 20 cm depth of operation whereas the minimum fuel consumption was 3.35 l/hr at 3 km/hr and 10 cm depth of operation combinations. The main and interaction effects of forward speed and depth of operation on the fuel consumption of the tractor-drawn combined tillage were analyzed statistically and presented in Tables 3 and 4. Analysis of variance (ANOVA) results revealed that both the main and their interaction of depth of operation and forward speed had a significant effect on fuel consumption at $P<0.05$. The effects of different depths of operation and forward speed on fuel consumption of tractors with combined tillage are presented in Figure 3. It was observed that fuel consumption increased with an increase in depth of operation and forward. Fuel consumption increased with an increase in depth of operation due to more volume of soil handled at higher depths and a decrease in forward speed of the tractor due to less volume of soil handled per unit time at lower forward speeds. This observation was in agreement with the result obtained by Makange and Tiwari (2015).

3.1.6. Tillage Performance Index (TPI)

The effect of operational parameters of depth of operation and tractor forward speed on TPI of combined tillage are presented in Tables 3 and 4. The TPI of combined tillage varied from 0.54 to 0.91 at depths of operation varied from 10 to 20 cm at 3 km/hr tractor forward speed. From Table 3, the results revealed that as the depth of operation increases from 10 to 15 cm, the tillage performance index showed increasing values ranging from 0.723 to 1.026 at a tractor forward speed of 5 km/hr. Similarly, as depth of operation increased 10 to 20 cm the tillage performance index increased from 0.421 to 0.763 at the forward speed of 7 km/hr. The main effect of forward speed and depth of operation on the tillage performance index is summarized in Table 2. The results show that as the depth of operation increased from 10 to 20 cm, the tillage performance index increased from 0.563 to 0.958 whereas a tractor forward speed increased from 3 to 7 km/hr, the tillage performance index decreased from 0.741 to 0.60. Analysis of variance results showed that the main and their interaction effect of depth of operation and tractor forward speed had a significant effect on the tillage performance index at $P<0.05$. The effects of different depths of operation and forward speed on the TPI of the pulverizing roller attached to the cultivator are presented in Figure 4. It was observed that TPI increased with an increase in depth of operation till 15 cm with further increase in the depth to 20 cm whereas TPI of combined tillage increased with an increase in tractor forward speed till 5 km/hr with further decrease in forward speed of tractor 7 km/hr. However, the minimum TPI of 0.421 was recorded at 10 cm depth of operation and 7 km/hr tractor forward speed whereas the maximum TPI of 1.202 was found at 20 cm depth of operation and 5 km/hr tractor forward speed. TPI of combined tillage implement increased till 5 km/hr forward speed then decreased with further increase in depth of operation, maybe the volume of soil handled and fuel consumption increased with the increase in depth of operation but the reduction in cone index decreased at 20 cm depth of operation due to increase in *MWD*. Therefore, the pulverizing roller could not operate efficiently beyond 5 km/hr tractor forward speed. TPI of pulverizing roller attached to the cultivator increased with an increase in depth of operation due to an increase in the volume of soil handled, an increase in reduction of cone index with the decrease in *MWD*, and comparatively less fuel energy spent. The volume of soil tilled and fuel energy decreased with the decrease in forward speed but TPI was affected greatly by the reduction of cone index. Therefore, TPI of pulverizing roller attached to the cultivator increased with an increase in forward speed up to 5 km/hr i.e., a decrease in the forward speed of the tractor but greater than 7 km/hr due to a reduction of cone index pulverizing blades got more tilling time at a particular place which increased soil pulverization. Moisture content in soil increased the aggregate stability which decreased the volume of soil handled, decreased the reduction in cone index, and increased the fuel energy. These results are in agreement with Prem *et al.* (2017) and Raheman and Behera (2018).

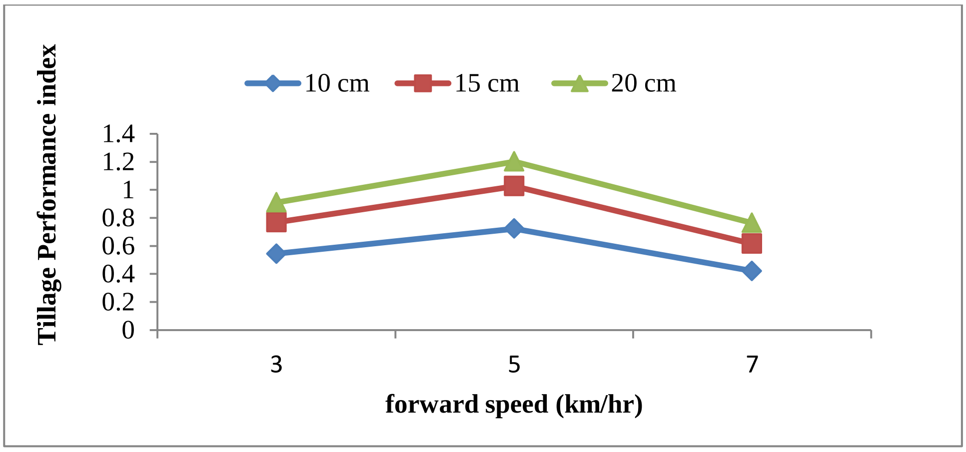

Figure 4. Effect of depth of operation and forward speed on tillage performance index

The combined tillage implement used for tilling operation could be optimized based on the mean weight diameter (*MWD*) of soil and tillage performance index (TPI). The *MWD* of soil is dependent on clod size whereas, TPI is dependent on the volume of soil handled, cone index, and fuel consumption. *MWD* is minimal and TPI is maximal which gives better soil pulverization and efficient performance of combined tillage implement was selected based on optimum depth of operation and tractor forward speed. The operational parameters of the combined tillage implement were optimized based on the draft, draft power, wheel slip, mean weight diameter, fuel consumption, field efficiency, and TPI. The optimum values of tractor-drawn combined tillage found to be at 15cm depth of operation and 5 km/hr tractor forward speed were 1581.73 N of draft, 0.736 kW of draft power, wheel slip of 5.10%, *MWD* of 9.73 mm, fuel consumption of 4.16 l/hr and TPI of 0.768. The maximum field efficiency of 84.88% was recorded at 10 cm depth and 7 km/hr tractor forward speed.

Table 3. Interaction effect of forward speed and depth of operation on performance of tillage implement

Speed (km/hr)	Depth of Operation (cm)	D_R (N)	D_P (kW)	W_S (%)	MWD (mm)	TPI	FC (l/hr)
	10	1367.07±48.79^{h}	0.68±0.04^{i}	3.28 ±0.48^{i}	10.51±0.17^{d}	0.543±0.06^{g}	3.35±0.15^{h}
3	15	1581.73±56.45^{g}	0.76 ±0.06^{h}	5.10±0.61^{g}	12.72±0.19^{b}	0.768 ±0.07^{d}	4.16 ±0.14^{f}
	20	1937.13±69.13^{e}	0.92 ±0.05^{g}	7.57 ±0.77^{d}	13.75±0.19^{a}	0.910±0.09^{c}	5.16 ±0.38^{e}
	10	1770.21±63.18^{f}	1.49 ±0.13^{f}	4.61 ±0.65^{h}	10.37±0.13^{d}	0.723 ±0.06^{e}	4.28 ±0.15^{f}
5	15	1994.72±71.19^{d}	1.64±0.06^{e}	6.77 ±0.66^{f}	11.64±0.25^{c}	1.026±0.07^{b}	5.10 ±0.03^{e}

	20	2289.71±81.71[b]	1.87±0.05[d]	8.74 ±0.74[c]	12.73±0.16[b]	1.202±0.10[a]	6.16 ±0.18[c]
7	10	2206.87±78.80[c]	2.59±0.10[c]	6.93 ±0.72[e]	10.11±0.25[d]	0.421 ±0.07[h]	5.47 ±0.03[d]
	15	2295.95±81.94[b]	2.71±0.13[b]	8.97 ±0.65[b]	11.74±0.66[c]	0.616±0.09[f]	6.58 ±0.05[b]
	20	2656.69±94.80[a]	3.09 ±0.09[a]	10.83 ±0.65[a]	12.99±0.92[b]	0.763±0.11[d]	7.79 ±0.13[a]
CV (%)		0.70	2.00	1.21	3.28	2.55	2.22
LSD (5%)		24.67	0.06	0.15	0.67	0.03	0.21

Where, D_R = Draft, D_p =Draft power, W_S = Wheel slip, MWD = Clod mass mean diameter of soil aggregate, TPI= Tillage performance Index, 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.

3.2. Economic Analysis

The operational cost of tractor-drawn combined tillage was determined as per the procedure enumerated by BIS standard IS 9164-1979 test codes. So, the economic cost of tractor-drawn combined tillage for tilling operation is presented in Table 4. The total fabrication cost of the combined tillage was 295,000 ETB. The calculated results of fixed and variable costs developed combined tillage were 205.025 and 98.33 ETB/hr, respectively. The costs of operation of tractor-drawn combined tillage were calculated as 1707.43 ETB/hr or 4,084.76 ETB/ha. From this table, the calculated break-even point (BEP), payback period, and benefit-cost ratio of the tillage implements were 1,349.45 hr/yrs, 1.84 yrs, and 4.34, respectively.

Table 4. The cost of operation for tractor-drawn combined tillage implement

Initial costs of the tractor		2,500,000 ETB
Initial costs of combined tillage implement		295,000 ETB
Assumption Made		
The expected life of tractor (H)		10 years
Life of implement		8 years
Salvage value (S)		10% of initial cost
Interest rate (I)		12% per annum
Fuel cost (FC)		1 Litre = 78 ETB
Driver charge		500 ETB/day = 62.5 ETB/hr for 8 working hour
Annual use of tractor		1000 hr, for Ethiopian smallholder conditions
Annual use of implement		300 hr
Insurance and tax cost		2% of initial cost
Repair and maintenance cost		10% of the initial cost
Lubrication cost		20% of fuel cost
Cost of the operating tractor		**Costs of the developed combined tillage**
Fixed cost (ETB/hr)		
Depreciation	225.00	110.625
Interest	165.00	64.90

Housing	50.00	29.5
Total fixed costs	515.00	205.05
Variable cost (ETB/hr)		
Repair & maintenance cost	250.00	98.33
Fuel costs	480.48	
Lubrication costs	96.096	
Total variable costs	889.076	
Total operating costs	1404.076	303.36
Total costs of operating the tractor-drawn combined tillage, ETB/hr	1707.43	
Overhead charge, ETB/hr	426.86	
Custom hiring charges, ETB/hr	2,241	
Breakeven point, hr/yr	1,349.45	
Payback period, yrs	1.84	
B-C ratio	4.34	

3.3. Conclusions and Recommendation

Mechanization in agriculture requires appropriate machinery with a reduction of drudgery for increasing cropping intensity, ensuring timely field operations, and effective application of various crop production inputs utilizing different power sources. This helps in increasing the productivity of land to meet the growing demand for food for the increasing population of Ethiopia. Conventional tillage employs many passes over a field with various soil-turning and soil-pulverizing implements. Such conventional tillage operations require high fuel consumption and contribute to the compaction of soil due to several passes of these implements. This study was undertaken to develop tractor-drawn combine tillage at the farmer’s field. Its performance was tested at forward speeds of 3, 5, and 7 km/hr and depth of operation 10, 15, and 20 cm. As a result, the following the findings are summarized as below: Draft and draft power combined tillage implement increased with an increase in depth of operation and it increased with an increase in the forward speed of the tractor for sandy loam of soils. Minimum draft and draft power of 1367.07 N and 0.68 kW were recorded at 10 cm depth of operation and 3 km/hr tractor forward speed, respectively. MWD decreased with an increase in depth of operation till 15 cm and increased at 20 cm depth of operation. Mean weight diameter decreased with the increase in the forward speed of the tractor with the combined tillage. Fuel consumption with combined tillage increased with an increase in depth of operation and forward speed of the tractor. The minimum fuel consumption of 3.35 l/hr was found at 10 cm depth of operation and 3 km/hr forward speed of the tractor. TPI of combined tillage implement increased with an increase in tractor forward speed up to 5 km/hr. The maximum TPI of 1.202 was recorded at 20 cm depth and 5 km/hr tractor forward speed. The combined tillage implement used for tilling operation could be optimized based on the mean weight diameter of soil and tillage performance index (TPI). The MWD of soil is dependent on clod size whereas, TPI is dependent on the volume of soil handled, soil inversion, and fuel consumption. The operational parameters of combined tillage were optimized based on the draft, draft power, wheel slip, mean weight diameter, fuel consumption, field efficiency, and TPI. As a result, the performance of the combined tillage implement was found to be optimum at a 20 cm depth of operation with 5 km/hr forward speeds. Hence, a maximum tillage performance index of 1.202 was recorded with a lower MWD of 12.73 mm while the draft, draft power, wheel slip, field efficiency, and fuel consumption were found to be 2289.71 N, 1.87 kW, 8.74%, 84.88%, and 6.16 l/hr, respectively. So, the above study revealed that the forward speed of 5 km/hr and depth of operation of 20 cm is selected best for the operation of the combined tillage in the field. The tractor-drawn combined tillage performance evaluation revealed that it can be used successfully on the farm for tillage operations. To make the tractor-drawn combined tillage implement applicable and acceptable among farmers, the following are recommended for further study on the combined tillage implement:

1) The developed combined tillage should be tested on different soil types.

2) The empty weight of the pulverizing roller was not suitable for working effectively for clod breaking; it could be filled with sand in the hollow portion of the roller.

3) Adaptation, modification, and performance test of the implement should be done for both tillage operations.

Declarations

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Competing Interests Statement

The authors have declared that no competing financial, professional or personal interests exist.

Consent for publication

All authors contributed to the manuscript and consented to the publication of this research work.

Availability of data and material

Supplementary information is available from the authors upon reasonable request.

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