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## Performance Evaluation of Tractor Drawn Combined Tillage Implement

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### ABSTRACT

Soil tillage is a critical but resource-intensive component of agricultural production. While combined tillage implements aim to improve efficiency, comprehensive assessments that integrate both in-field performance and economic viability remain limited. This study evaluates the mechanical performance and economic feasibility of a tractor-mounted combination tillage implement. Performance was assessed based on draft force, draft power, wheel slip, fuel consumption, mean weight diameter of soil aggregates, field efficiency, soil inversion, volume of disturbed soil, and a tillage performance index. The implement was evaluated at operating depths of 10, 15, and 20 cm and forward speeds of 3, 5, and 7 km/h. The best performance was achieved at an operating depth of 20 cm and a forward speed of 5 km/h. Consequently, a maximum tillage performance index of 1.202 was achieved with a corresponding minimum mean weight diameter of 12.73 mm. Under these optimal conditions, the draft force, draft power, wheel slip, field efficiency, and fuel consumption were 2289.71 N, 1.87 kW, 8.74%, 84.71%, and 6.16 l/hr, respectively. Analysis of variance indicated that both forward speed and operating depth had significant effects ( $P < 0.05$ ) on performance parameters. The operational cost for the tractor-drawn combined tillage implement was calculated at 1707.43 Birr per hour. The economic analysis yielded a break-even point of 1,349.45 hours per year, a payback period of 1.84 years, and a benefit-cost ratio of 4.34. Based on these results, it can be concluded that this implement is mechanically effective and economically viable, making it suitable for implementation by farmers for tillage and seedbed preparation.

### INTRODUCTION

Tillage is the mechanical manipulation of soil to enhance its suitability for crop cultivation. This process involves breaking the compacted soil surface to a specific depth and loosening the soil mass, thereby facilitating root penetration and expansion (Zhou *et al.*, 2020). As a mechanical manipulation of soil and crop residues, its primary function is to prepare a seedbed for sowing. Tillage further serves to release soil nutrients, suppress weeds, and improve the circulation of water and air within the soil (Reicosky & Allmaras, 2003). Tillage is regarded as a fundamental agricultural process, creating optimal conditions for root development and thereby supporting plant growth. It reduces soil resistance, enhances aeration, and suppresses weeds (Al-Shamiry *et al.*, 2020). However, conventional tillage practices are associated with high costs, significant time investment, and the need for multiple passes, which can lead to soil compaction. Furthermore, conventional tillage is considered a fuel-inefficient operation. According to Digman (2012), while just 20% of diesel fuel energy is available at the tractor drawbar, a mere 4% is effectively converted into soil fracturing. This significant energy loss underscores the importance of enhancing tillage efficiency. Utilizing combined tillage implements in a single pass is a strategy to mitigate these losses, which is relevant for agricultural systems employing conventional tillage, like those in Ethiopia. Prem *et al.* (2016) define combined tillage as the simultaneous use of two or more implements for

soil manipulation. Broadly, this practice represents an integrated approach to managing resources including time, energy, fuel, labor, and soil and water conservation; while simultaneously enhancing crop yield and improving the utilization of natural resources. It thereby contributes to the sustainability of agricultural production. Tillage operations employ two primary working motions: sliding and rotating. Sliding action, utilized by implements such as cultivators and moldboard ploughs, cuts through the soil. In contrast, implements like disc ploughs, disc harrows, clod crushers, and rollers function through rotation to fragment and pulverize the soil. Sliding-type implements typically require greater draft force due to increased soil friction and a larger contact area. Conversely, rotating tools can exhibit negative draft, thereby reducing overall resistance. As a result, combined tillage tools reveal greater energy efficiency compared to individual passive implements, resulting in approximate savings of 50% in cost and 50 to 55% in operational time (Parmar & Gupta, 2016).

In Ethiopia, conventional tillage practices disturb the soil significantly, leading to increased soil compaction and greater susceptibility to erosion by wind and water. The combined tillage equipment introduced has been imported from other countries and is prohibitively expensive. Furthermore, its implementation has failed to account for the needs of small-scale mechanization, affordable power sources, or highland agriculture. This machinery is costly, not appropriately scaled for local use, and often

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physically heavy and bulky. The tools are difficult to dismantle, repair, and are overly complex. While modern combined tillage implements exist internationally capable of completing soil preparation quickly in a single pass they remain too expensive for Ethiopian farmers to import. Governmental and non-governmental organizations (NGOs) frequently distribute tractors to farmers, youth, and local Agriculture Bureaus through various programs. However, these are predominantly supplied with only basic primary and secondary tillage attachments 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 the developed tractor-drawn combined tillage implement.

## MATERIALS AND METHODS

### Materials

The equipment and tools utilized during the evaluation of the combined tillage implements included a tractor, a digital balance, a dynamometer, measuring instruments (tape and graduated cylinder), a stopwatch, oven-drying equipment, and a core sampler.

### Methods

#### Descriptions of the Implement

The combined tillage implement was designed to perform secondary tillage operations in a single pass to support timely seedbed preparation. It is comprised of four primary components: the mainframe, cultivator tines, two pulverizing rollers, and the three-point linkage system. The mainframe, constructed from an  $80 \times 80 \times 4$  mm square pipe, serves as the central structure supporting all other elements. Attached to it are the cultivator tines, which were fabricated from a mild steel (MS) plate measuring 40 mm in width, 600 mm in length, and 780 mm in height, with a radius of curvature of 103.2 mm. The three-point hitch, fabricated from MS flat iron, provides the connection to the tractor. It measures 1300 mm in length, 760 mm in width, and 850 mm in height. At the rear, two pulverizing rollers are mounted to finely break up the soil. Each roller consists of a central shaft and a cylinder drum. The drum itself is a mild steel cylinder 1900 mm in length and 200 mm in diameter. To its surface, mild steel spike blades, each measuring  $40 \times 40 \times 120$  mm, are welded in a helical pattern. The implement has overall dimensions of 2150 mm in length, 1550 mm in width, and 1530 mm in height.

#### Working Principles of the Implement

The implement was intended to consolidate secondary tillage into a single pass, ensuring timely seedbed preparation. It functioned through a combination of active and passive soil-engaging units arranged in sequence. Operating from front to rear: Passive cultivator tines: Positioned at the front, these tines first broke and

loosened soil clods, working the soil to a fine tilth at the desired operating depth. Active pulverizing roller: Mounted directly behind the tines, this powered roller subsequently cut, mixed, and further broke the pre-loosened soil. Its primary action was to pulverize the soil through impact force. This sequential action initial loosening by the tines followed by aggressive impact pulverization by the roller provided effective soil cutting and clod reduction, resulting in a well-prepared seedbed in a single operational pass.



**Figure 1:** Operation during performance evaluation of combined tillage implement

#### Performance Evaluation Parameters

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

##### Soil moisture content

To determine the soil moisture content, soil samples were collected from a depth of 0–25 cm. From each test plot, samples were randomly taken from five locations. These samples were weighed, oven-dried at 105 °C for 24 hours, and re-weighed. The moisture content was then calculated using the formula provided by Khura (2008).

$$M = \frac{M_w - M_d}{M_d} \times 100 \quad (6)$$

Where,  $M$  = Moisture content of soil, %

$M_w$  = Weight of wet soil, gm and

$M_d$  = Weight of oven-dry soil, gm

##### Bulk density of soil

The bulk density of the soil was measured using a core sampler with an inner diameter of 7 cm and a height of 12 cm. Soil samples were collected randomly from a depth of 0–25 cm prior to tillage operations. Each sample was oven-dried at 105 °C for 24 hours. Bulk density was then determined by dividing the dry weight of the soil by the known volume of the core sampler, using the equation provided by Khura (2008).

$$\rho_b = M/V \quad (7)$$

Where,  $\rho_b$  = bulk density of soil (g/cm<sup>3</sup>)

$M$  = oven-dry mass of soil (gm), and  $V$  = volume of the core sampler (cm<sup>3</sup>)

### 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:

### Effective Field Capacity

The effective field capacity of the implement was calculated by considering the total area worked and the total time required completing the operation. The total area was determined by measuring the length and width of each plot. The total operational time included both the time spent on active work and the time spent on auxiliary activities, such as turning, adjustments, cleaning, and any machine troubleshooting. Effective field capacity, representing the actual average rate of coverage, was then calculated using the total area worked divided by the total recorded time, as per the method described by Kepner *et al.* (2005).

$$EFC = \frac{A}{T_p + T_i} \times 100 \quad (8)$$

Where: EFC = Effective field capacity, ha/hr

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

### Theoretical Field Capacity

Theoretical field capacity is defined as the maximum potential rate of field coverage, calculated based on the implement's rated operating speed and its full working width. It represents the ideal performance achievable if the machine operates continuously at 100% of its rated speed and utilizes 100% of its rated width, with no time lost to non-working activities. This theoretical value was calculated according to the method provided by Kepner *et al.* (2005).

$$TFC = W \times S / 10 \quad (9)$$

Where, TFC = Theoretical Field capacity, ha/h

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

### Field Efficiency

Field efficiency is the ratio of effective field capacity to theoretical field capacity, expressed as a percentage. This efficiency includes the losses in operating time and incomplete use of the implement's working width during actual field operations (Kepner *et al.*, 2005).

$$\eta = EFC / TFC \times 100 \quad (10)$$

Where:  $\eta$  = Field efficiency (%)

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

### Draft

Draft force was measured using two tractors and a dynamometer. The implement was attached to tractor A, which was then pulled by tractor B via a dynamometer. Measurements were taken first with tractor A in neutral

gear and the implement engaged in operation, and again with the implement in a raised position. The draft requirement of the implement was determined by the difference between these two readings (Mehtha *et al.*, 2005).

### Draft Power

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

$$D_p = D \times S / 3.6 \quad (11)$$

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

### Wheel slip

Slip in a traction device is defined as the movement occurring at the interface between the device's surface and the operating medium. The distance traveled during ten wheel revolutions is measured both with and without a load. These values are then applied in the following formula to calculate slip (Mehtha *et al.*, 2005):

$$S = \frac{D_o - D_l}{D_o} \times 100 \quad (12)$$

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

### 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).

$$MWD = 1 / W (A + 2.4B + 3.4C + 4.8D + 6.8E + XF) \quad (13)$$

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

### Fuel Consumption

Fuel consumption directly influences the economic performance of a combined tillage implement. It was measured using a top-fill method. Initially, the fuel tank was filled to a set level prior to testing. Upon completion of the test operation, the quantity of fuel needed to refill the tank to the same level represented the total fuel consumed during the test. This measurement was used to compute the rate of fuel consumption in liters per hectare (l/ha) (Nkakini *et al.*, 2010).

$$F_c = f_r / A \tag{14}$$

Where:  $F_c$  = fuel consumption (l/ha),  $f_r$  = Re-filled quantity of fuel (l),  $A$  = tilling area (ha)

**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 ( $V_s$ ), soil inversion (SI) and inversely proportional to fuel energy ( $F_e$ ) and mass weight diameter (MWD) (Raheman & Behra, 2018).  $TPI = V_s / MWD \times F_e$  (15)

**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:

$$V_s = AFC \times T_d \times 100 \tag{16}$$

Where,  $V_s$  = Volume of soil tilled per unit time,  $m^3/hr$   
 $AFC$  = Actual field capacity,  $ha/hr$   
 $T_d$  = Depth of operation,  $m$

**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  $1m \times 1m$  before and after the tillage operation carried out by the developed combined tillage implements (Inthiyaz *et al.*, 2020).

$$SI(\%) = (W_2 - W_1) / W_2 \times 100 \tag{17}$$

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,  $m^2$

**Fuel energy input to the tractor**

The fuel energy input to the tractor for performing a tillage operation is given by:

$$F_e = FC \times CV \tag{18}$$

Where:  $F_e$  = Fuel energy input,  $MJ/hr$

$FC$  = Fuel consumption,  $l/hr$

$CV$  = Calorific value of diesel,  $MJ/l$

**Experimental Design and Treatment**

To assess the performance of the combined tillage implement, three forward speeds (3, 5, and 7  $km/hr$ ) and three operating depths (10, 15, and 20  $cm$ ) were chosen. The experiment followed a randomized complete block design (RCBD) with a  $3 \times 3$  factorial structure, each combination replicated three times. This resulted in a total of 27 experimental runs.

**Statistical Analysis**

The performance results of the combined tillage implement were statistically analyzed using Analysis of variance (ANOVA) in R software. Significant differences among treatment means were assessed at a 5% significance level and separated using the least significant difference (LSD) test. The results are presented as mean  $\pm$  standard deviation.

**Cost Analysis**

The cost analysis was conducted in two stages: first, determining the materials and fabrication expenses, and second, calculating the operational cost of the developed combined tillage implement. Financial viability was assessed by computing both fixed and variable costs. Fixed costs such as depreciation, interest, taxes, shelter, and insurance remain constant regardless of use. Variable (operational) costs, which include repair and maintenance, fuel, lubrication, and labor, fluctuate with machine usage. The total fabrication cost was derived from material and labor expenses. Following the IS 9164-1979 test codes and procedures, hourly fixed and variable operating costs were determined. Using the unit's field capacity, the per-hectare operational cost was computed. Finally, the break-even point, payback period, and benefit-cost ratio were estimated to evaluate the economic performance of the tractor-drawn combined tillage implement.

**RESULTS AND DISCUSSION**

The field experiment was carried out on a  $20 \times 50 m^2$  plot of sandy loam soil in a farmer's field. Important operational parameters recorded during ploughing with

**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	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
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

the combined tillage implement are summarized in Table 1. The average soil moisture content was 18.67%, with a bulk density of 1.48 g/cm<sup>3</sup>. The implement operated at a speed of 2.87 km/hr, achieving a theoretical field capacity of 0.488 ha/hr and an actual field capacity of 0.418 ha/hr, resulting in a field efficiency of 84.88%.

### Performance Evaluation of the Implement

A tractor-drawn combined tillage implement was evaluated under field conditions to assess important performance parameters. The study examined three forward speeds (3, 5, and 7 km/hr) and three depths of operation (10, 15, and 20 cm). The influence of these variables was analyzed based on draft force, draft power, wheel slip, mean weight diameter, fuel consumption, field efficiency, and the tillage performance index. The results of this analysis are presented in the following section.

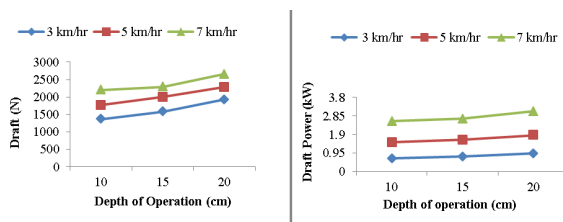
### Draft

The effect of forward speed and operating depth on implement draft is shown in Figure 2 and detailed in Table 3. The data indicate a consistent increase in draft with greater depth. At a forward speed of 3 km/hr, draft rose from 1367.07 N to 1937.13 N as depth increased from 10 cm to 20 cm. A similar trend was observed at 5 km/hr, with draft increasing from 1770.21 N to 2289.71 N over the same depth range. Likewise, draft also increased with higher forward speeds. At a 10 cm depth, draft grew from 1367.07 N to 2206.87 N as speed increased from 3 km/hr to 7 km/hr. At a 20 cm depth, the corresponding increase was from 1937.13 N to 2656.69 N. This pattern of rising draft with increased speed aligns with findings reported by Prem *et al.* (2016). The main effects, summarized in Table 2, further confirm these trends. On average, draft increased from 1781.38 N to 2294.51 N as operating depth was raised from 10 cm to 20 cm. Similarly, increasing forward speed from 3 km/hr to 7 km/hr resulted in an average draft increase from 1628.65 N 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.

### 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 resistance. 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).



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

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

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

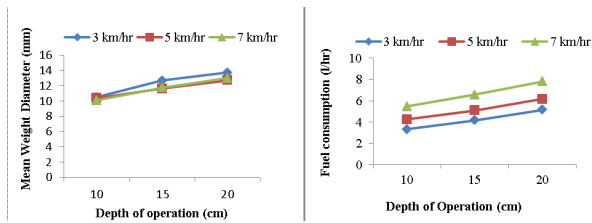
### Wheel slip

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)

### 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 mean weight diameter of soil exhibited a clear inverse relationship with forward speed, decreasing as speed increased. This occurs because slower forward speeds allow rotor blades more tilling time at a given point, resulting in greater soil breakup and smaller clod sizes. As shown in Figure 3, increasing the forward speed from 3 to 7 km/hr reduced the MWD by 5.68%. This trend aligns with findings by Dehghani and Karparvarfard (2017), who attributed the decrease in MWD at higher speeds to the greater acceleration imparted to soil particles during displacement. Conversely, MWD increased with greater tillage depth. This is likely due to the higher compaction found in deeper soil layers, which yields larger clods. This observed positive correlation between tillage depth and MWD is consistent with earlier research by Yassen *et al.* (1992) and Eshaghbeygi *et al.* (2020). 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).

### Fuel Consumption

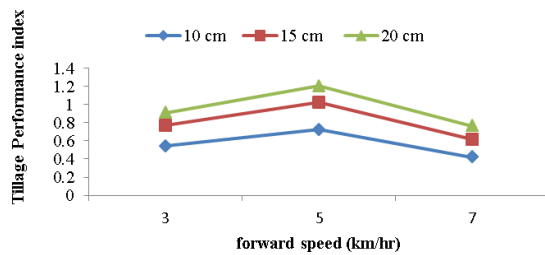
The effects of forward speed and operating depth on the fuel consumption of the tractor-drawn combined tillage implement are presented in Table 3 and Figure 4. The results indicate a clear trend: fuel consumption increased with both greater operating depth and higher forward speed. Specifically, fuel consumption rose from 4.36 to 6.37 l/hr as the depth increased from 10 to 20 cm. concurrently, increasing the forward speed from 3 to 7 km/hr also raised fuel consumption. 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).

### 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



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

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).

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 <sub>R</sub> (N)	D <sub>P</sub> (kW)	W <sub>S</sub> (%)	MWD (mm)	TPI	FC (l/hr)
3	10	1367.07±48.79 <sup>h</sup>	0.68±0.04 <sup>i</sup>	3.28 ±0.48 <sup>i</sup>	10.51±0.17 <sup>d</sup>	0.543±0.06 <sup>g</sup>	3.35±0.15 <sup>h</sup>
	15	1581.73±56.45 <sup>g</sup>	0.76 ±0.06 <sup>h</sup>	5.10±0.61 <sup>g</sup>	12.72±0.19 <sup>b</sup>	0.768 ±0.07 <sup>d</sup>	4.16 ±0.14 <sup>f</sup>
	20	1937.13±69.13 <sup>c</sup>	0.92 ±0.05 <sup>g</sup>	7.57 ±0.77 <sup>d</sup>	13.75±0.19 <sup>a</sup>	0.910±0.09 <sup>c</sup>	5.16 ±0.38 <sup>c</sup>
5	10	1770.21±63.18 <sup>f</sup>	1.49 ±0.13 <sup>f</sup>	4.61 ±0.65 <sup>h</sup>	10.37±0.13 <sup>d</sup>	0.723 ±0.06 <sup>c</sup>	4.28 ±0.15 <sup>f</sup>
	15	1994.72±71.19 <sup>d</sup>	1.64±0.06 <sup>c</sup>	6.77 ±0.66 <sup>f</sup>	11.64±0.25 <sup>c</sup>	1.026±0.07 <sup>b</sup>	5.10 ±0.03 <sup>c</sup>
	20	2289.71±81.71 <sup>b</sup>	1.87±0.05 <sup>d</sup>	8.74 ±0.74 <sup>c</sup>	12.73±0.16 <sup>b</sup>	1.202±0.10 <sup>a</sup>	6.16 ±0.18 <sup>c</sup>
7	10	2206.87±78.80 <sup>c</sup>	2.59±0.10 <sup>c</sup>	6.93 ±0.72 <sup>c</sup>	10.11±0.25 <sup>d</sup>	0.421 ±0.07 <sup>h</sup>	5.47 ±0.03 <sup>d</sup>
	15	2295.95±81.94 <sup>b</sup>	2.71±0.13 <sup>b</sup>	8.97 ±0.65 <sup>b</sup>	11.74±0.66 <sup>c</sup>	0.616±0.09 <sup>f</sup>	6.58 ±0.05 <sup>b</sup>
	20	2656.69±94.80 <sup>a</sup>	3.09 ±0.09 <sup>a</sup>	10.83 ±0.65 <sup>a</sup>	12.99±0.92 <sup>b</sup>	0.763±0.11 <sup>d</sup>	7.79 ±0.13 <sup>a</sup>
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<sub>R</sub> = Draft, D<sub>P</sub> = Draft power, W<sub>S</sub> = 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.

**Economic Analysis**

The operational cost for the tractor-drawn combined tillage implement was calculated according to the BIS standard IS 9164-1979 test codes. The economic analysis is summarized in Table 4.

The total fabrication cost of the implement was 295,000 ETB. The calculated fixed and variable operating costs were 205.025 ETB/hr and 98.33 ETB/hr, respectively, yielding a total operational cost of 1707.43 ETB/hr, or 4,084.76 ETB per hectare. Based on this analysis, the

implement's break-even point was 1,349.45 hours per year, with a payback period of 1.84 years and a benefit-cost ratio of 4.34.

**Conclusions and Recommendation**

Agricultural mechanization relies on suitable machinery to reduce labor intensity, enhance cropping intensity, ensure timely field operations, and enable the precise application of crop inputs using diverse power sources. This approach is essential for increasing land productivity to meet the rising food demands of Ethiopia's growing population. Conventional tillage, in contrast, typically involves multiple passes over a field using various soil-turning and pulverizing implements. This method not only demands higher fuel consumption but also

contributes to soil compaction 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

**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	
<b>Assumption Made</b>		
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	
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	
<b>Cost of the operating tractor</b>	<b>Costs of the developed combined tillage</b>	
<b>Fixed cost (ETB/hr)</b>		
Depreciation	225.00	110.625
Interest	165.00	64.90
Housing	50.00	29.5
Total fixed costs	515.00	205.05
<b>Variable cost (ETB/hr)</b>		
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	

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 3 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: The combined tillage should be tested on different soil types, 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. Adaptation, modification, and performance test of the implement should be done for both tillage operations.

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