Design, development and performance evaluation of tractor drawn tie ridger

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Abstract: At present in Ethiopia, tie-ridging operation is conducted using human and draft animal as power sources which is labor intensive, tedious, and time-consuming. Its field capacity and efficiency were limited. To solve the aforementioned problem, present study was aimed to design, develop and evaluate the performance of a tractor-drawn tie ridger capable of tie ridging at desired depth and spacing. The tractor-drawn tie ridger was developed using locally available materials and consists of the mainframe, central driving wheel, tie ridger, furrow opener, and shank. The performances of tractor-drawn tie ridger were evaluated in the laboratory and field, by considering independent parameters (soil type and condition, drawbar pull, working width, forward speed and depth of operation) and dependent parameters (field efficiency, fuel consumption, slippage of tractor wheels and draft force required). In a laboratory test, the machine was checked for its specifications and operations. The average theoretical field capacity, effective field capacity and field efficiency of the machine were 0.94 ha hr^{-1}, 0.67 ha hr^{-1} and 71.24% respectively. The maximum draft required for the implement is 1,135.23 N. The 40 hp tractor was used to drive this implement. The average depth and width of tie ridge were observed at 22.92 cm and 34.29 cm respectively. The cost of fabrication of the tie ridger was estimated to be approximately about 19,683.45 birr. Test results in-field evaluation of the tie ridger indicated that it could form tie ridges of 2.78 m × 34.29 cm size. Per hour, cost of operation of tie-ridger is 220.12birrhr^{-1}. The developed tie ridger was used effectively to promote sustainable agriculture by conserving soil moisture and improving water use efficiency, leading to increased crop productivity.
Keywords: design, tie ridger, field efficiency, performance evaluation, economics.

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1 Introduction

Agriculture in most parts of Ethiopia depends on the vagaries of the rainy season. The rainfall, in the large areas of it, is insufficient and extremely uncertain. The average annual rainfall in the area is 768 mm, which is erratic and uneven in distribution. As water is the most important input for crop production, the insufficiency and uncertainty of rainfall often results in partial or complete failure of crops and leads to periodic inadequacies and droughts. The mean minimum and mean maximum temperature of the area is 12.6°C and 28.5°C respectively. Such condition naturally makes the economic life of the cultivators in these regions extremely difficult and insecure. Water is often the most limiting factor in dryland agricultural production. In the Ethiopian highland, agricultural productivity is

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low due to low soil fertility. The problem is directly related to periodic low soil moisture due to erratic and poorly distributed rainfall, severe soil erosion, and runoff loss of water (Heluf and Yohannes, 2002; Chimdessa et al., 2019).

The furrow diking practice is known by many names including tied ridges, furrow damming, basin tillage, basin listing, and micro basin tillage. Furrow diking is a soil and water conservation practice, which is very adaptable to dryland crop production. It is most often used on gently sloping terrain in arid and semi-arid areas where crops are grown under water deficit conditions (Jones and Baumhardt, 2003). The most extensive soil loss rates were estimated in croplands and bare land cover, with a mean soil loss rate of 37.60 t ha^{-1} y^{-1} and 15.78 t ha^{-1} y^{-1}, respectively (Woldemariam and Harka, 2020). The annual rate of soil loss in the country is higher than the annual rate of soil formation rate. Annually, Ethiopia losses over 1.5 billion tons of topsoil from the highlands to erosion which could have added about 1.5 million tons of grain to the country's harvest (Braimoh and Vlek, 2008). This indicates that soil erosion is a very serious threat to the food security of people and requires urgent management intervention.

Moisture conservation at the farm level is the current important issue in the world today for sustainable crop production. Ahmed et al. (2018) reported in the current on-farm trial, the effect of selected in-situ soil and water conservation measure (tied ridge) was compared with traditional practices in terms of maize productivity parameters like grain yield, biomass production, and soil moisture conservation. The tied ridges showed 35.8% and 27.8% grain yield and biomass production advantage over traditional practice respectively. The low crop productivity in the country particularly in the study area is directly related to periodic low soil moisture due to erratic and poorly distributed rainfall, which could result in low soil fertility. The study indicated that the average soil moisture content during critical growth stages was as low as 12%, far below the optimal range of 20%-25% required for most crops. This periodic low soil moisture is directly related to erratic and poorly distributed rainfall, with annual precipitation recorded at only 400-600 mm, contributing to reduced soil fertility and low crop productivity. The tie ridger's use significantly improved ridge formation, reduced soil erosion, and enhanced water retention in furrows. This calls to design effective and efficient in-situ soil moisture conservation strategies that have a better role in sustaining crop production.

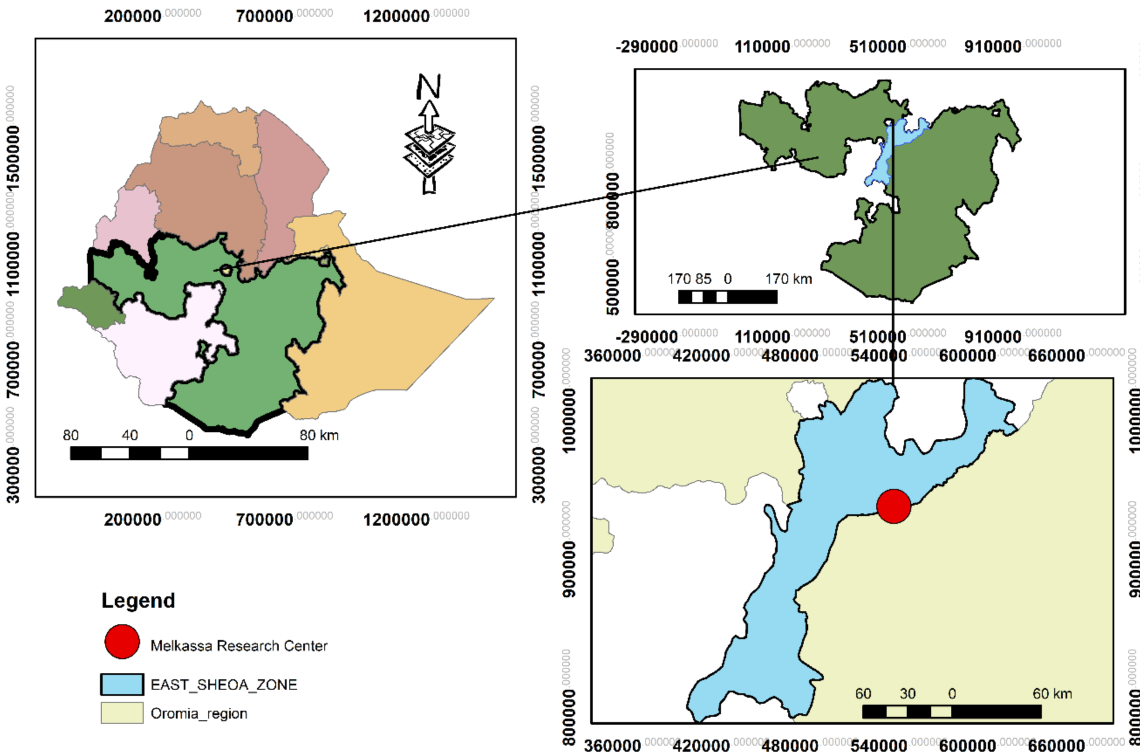
The use of tied ridges is very effective in soil water conservation and results in 50-100 percent grain and 80 percent straw yield increase is obtained compared to the traditional method of planting in the flat seedbed in many semi-arid areas of Ethiopia (Georgis, 2015). It is widely adopted in many semi-arid areas. Tie ridging involves creating ridges that are 20-30 cm high and commonly spaced 75 cm apart, before, either during or after planting. The effectiveness of tie ridging depends on field conditions. The conditions identified for the fields where tie-ridging is likely to be beneficial are: - slope <7%; soil type:- sandy loam or finer, soil depth (effective rooting depth) >60 cm, rainfall amount for the growing season <650 mm, or little rainfall during grain filling (Brhane et al., 2005).

Despite its laborious and time-consuming nature (Araya and Stroosnijder, 2010), tied ridging is a proven practice to conserve soil moisture in semi-arid areas (Biazin and Sterk, 2013). In tied ridging, sometimes called tied-furrows, ridge furrows are blocked with earth ties spaced on fixed intervals to form a series of micro-basins in the field (Biazin and Sterk, 2013). Tied-ridging increase soil water in the root zone by 24% and by at least 13% which brought a 44% yield increase of barley (Araya and Stroosnijder, 2010) as compared to traditional tillage in rain season. The objective of this paper was to design, develop and evaluate the performance of tractor-drawn tie ridger.

2 Materials and methods

2.1 The study area description

The study site is located in Oromia Regional State, Adama Woreda, In East Sha Zone, near the town of Awash-Melkassa, 117 km East of Addis Ababa and 17 km southeast of Adama city at Melkassa Agricultural Research Center (MARC). It's found at an elevation of 1560 m above sea level and lies between 8°24'0" to 8°30'12"N, 39°21'0" to 39°35'14"E. The average annual rainfall in the area is 768 mm, which is erratic and uneven in distribution. The agro-ecology is termed as Kolla (Warm, semi-arid lowlands). The dominant soil type in the area is sandy loam. Fabrication of prototype and any adjustment or maintenance also conducted in Agricultural Engineering Research workshop, which was found in Melkasa Agricultural Research center.



Drawn by Wobi Abdisa

Figure 1 Study area description map

2.2 Material selection

The selection of the materials was based on durability, cost, availability, strength and rigidity, weight, and friction. The selected materials were strong, stiff, and wear-resistant and serve the purpose and operating requirements of the tie ridger parts. It was readily shaped, welded, and easily machine-able. The structure of the power unit was simple and which made operation, maintenance and repair easy. The following materials listed in the Table 1and Table 2 were selected based on the ductility characteristics; function and strength requirements; and aforementioned properties of the metal.

2.3 Power unit selection

Chinese made 404 model 40 horse power YTO tractor was selected as a motive power for designed tie ridger. The tractor had weight of 19 kN with 270 mm minimum ground clearance. The overall dimension (length, width and height), wheel base and wheel track were, 3727 × 1630 × 2400 mm^3, 1965 mm and 1250/ 1300 -1600mm respectively. Number of transmission gears are 8/4 and ground speed range (kM hr^{-1}) was 2.49-32.59/ 3.69-11.25. The tire being used by tractor was designated as 7.5-16/ 11.2-28. The hydraulic lifting capacity was 6.62 kN at 610mm at lifting height.

Table 1 Tools, materials and machine needed for the fabrication of the tie ridger

S.N N	Machine /tool name	Purpose
1	Drills machine	Hole/cell making
2	Lathe machine	Threading /cutting /finishing /shaping /machining.
3	Grinding machine	Grinding /cutting tool
4	Cutting blade	Cut flat bar
5	Electric welding machine	Welding
6	Steel tape	Measurement of linear distance
7	Vernier calipers	Measurement of outer diameter and inner diameter
8	Center punch	Hole marking
9	Choke	Marking
10	Hammer	Used to strike an object
11	Chisel	Cutting
12	Spanner	Tighten nut and bolt
13	Screwdriver	Tighten screw

Table 2 Different components part, functions, and material

S.N	Components	Specification	Material
1	Ground wheel	Wheel diameter 680 mm and 6 mm thick	Mild steel flat
2	Frame	Total length and width were 2,160 mm and 1,550 mm respectively	MS square pipe 70× 50 × 3 mm
3	Shaft for central driving wheel	30 mm diameter and 1000 mm length	Round mild steel
4	Tyne type of furrow opener	Adjustable row to row spacing, 40 × 150 ×10 mm	Flat iron
5	Tie Ridger	MS. flat 250 mm having depth, 300 top widths, 100 bottom width and 6mm thick	Mild steel flat bar
6	Three-point hitch system		Mild steel bar
7	Ball-bearing	Diameter 30 mm	

Figure 2 Ridger development in work shop

2.4 Conceptual design

The tractor-drawn tie-ridger was developed basically to cope up with the problems of low moisture stress in drought-prone areas. The functional components of the machine consist of the mainframe, shaft, shank, furrow wing, bearing, hub, spoke and wheel. The selection of materials for the construction depends on - strength, availability, durability, weight, resistance to corrosion.

The tractor drawbar horsepower (DBHP), draught available (D_f) and the number of the row (n) was calculated by Equation 1 (Sharma and Mukesh, 2010).

2.4.1 Design of mainframe

The mainframe, with low weight, strength, and reliability, was made from square pipe material. Other parts of the ridge, like the central driving wheel, furrow wing, bearings, etc. were attached to the mainframe. Besides, three-point linkage attachments were provided to the mainframe for attaching to the power source. The consideration has been given while selecting the material for the frame to be light in weight and strong enough to withstand the imposed load during field operation.

2.4.2 Design of tine

It is assumed that the draught force on the furrow opener is 50 to 100 kgf/tine and acting and a height of h/3 from the bottom of the furrow opener where the *h* is the total length of the furrow opener and tine. The standard will be set with a bending design to ensure easy operation and proper balance of the machine. The maximum height of the furrow opener tine is set at 20 cm, as recommended by Bosai et al. (1987). Taking into account the available draft force (measured in kgf) that a tractor exerts on the tip of the furrow openers, which have a length of 42 cm, the calculation is based on Equation 2 from Bosai et al. (1987).

$$DBHP = \frac{D_f \times v}{270} \quad (1)$$

Where: *DBHP, Kw;* D_f = Draft force, kg; V = Speed, km hr^{-1}.

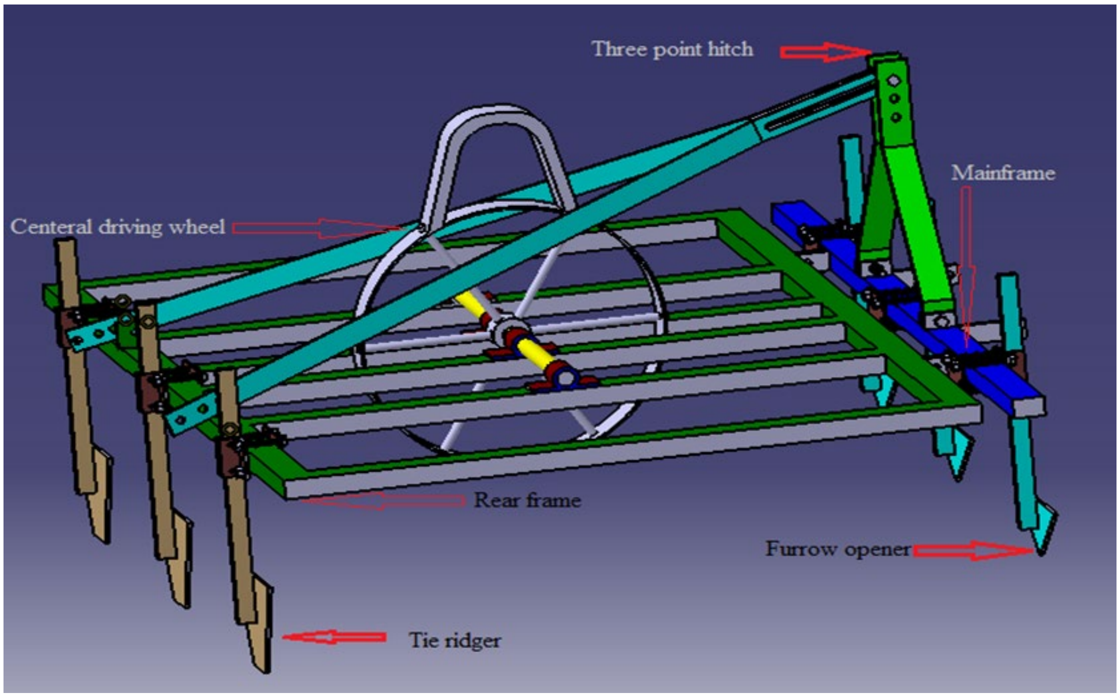


Figure 3 Conceptual design of tractor drawn tie ridger

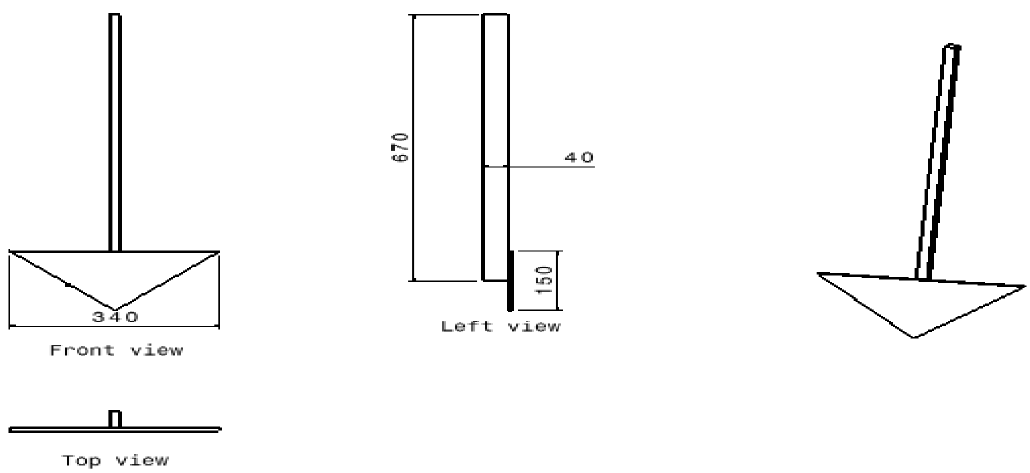


Figure 4 Tine farrow opener

Draft on tine was estimated using the following equation (Sharma and Mukesh, 2010):

$$D_e = A \times S_r \times Fos \quad (2)$$

Where: A = Cross-sectional area of the furrow, cm2; S_r= Soil resistance, kg; FOS = Factor of safety; D_e= Theoretical draft on one tine, kg cm-2.

2.4.3 Estimation of force required to drive the tie ridger

The total weight of the prototype tie ridger was determined using the thickness, area, volume and density of mild steel and taking 2% margins for the weights of welding bolts and nuts.

A rolling resistance force (*F*), which was assumed to act horizontally at the wheel and ground interface or ground and wheel contact patch was estimated using Equation 3.

$$F = (C_R + i) \times N \tag{3}$$

$$F = \left[\sqrt{\frac{Z}{d}} + i\right] \times N$$

Where: F= rolling resistance force, N; *CR* = Coefficient of rolling resistance; *d* = Wheel diameter, m; *z* = Maximum wheel sinkage depth (on a soft surface *z* ≈ *0.05d*), m; *N* = Weight of the tie ridger on the wheel, kN; *i* = Gradient of the ground (let *i* = 5%).

2.4.4 Torque on the ground wheel

Torque on the ground wheel estimated by using Equation 4.

$$T = F(\frac{d}{2}) \tag{4}$$

Where: *T* = Torque, N m; *F* = Rolling resistance force, N; *d* = Diameter of the ground wheel, m.

2.4.5 Power requirement of the tie ridger

The power requirement of the tie ridger was given by using Equation 5

$$P = T \times N_w \tag{5}$$

Where: *P*= Power requirement of the tie ridger, w, *Nw*= Wheel revolution, rpm.

2.4.6 Shaft design

The design of the wheel shaft was based on ductile material (mild steel) whose strength is controlled by maximum shear stress. The wheel shaft diameter was needed to determine the load-carrying capacity of the shaft. The shaft is expected to be subjected to both torsion and bending moments. This may be due to the rotational effect of the shaft during the forward motion of the machine.

For a solid shaft with little or no axial load, the diameter of the shaft is determined as reported by Khurmi and Gupta (2005).

$$d^3 = \frac{16}{\pi s_S} \times \sqrt{(K_b M_b)^2 + (K_t M_t)^2} \tag{6}$$

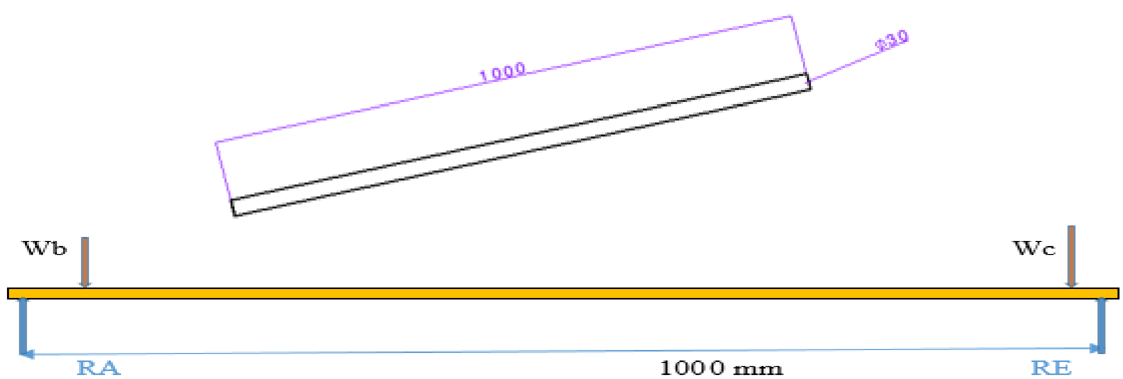


Figure 5 Wheel shaft

Where: d^3= Diameter of the shaft, m; S_s = Allowable stress, MN m^{-2}; K_b = Combined shock and fatigue factor applied to bending moment; M_t = Torsional moment, Nm; M_b = Bending moment, NM Mt; K_t = Combined shock and fatigue factors applied to torsional moments. For rotating shafts, when the load is suddenly applied with minor shock, Khurmi and Gupta (2005) recommended that values of K_b = 1.2 to 2.0 and K_t= 1.0 to 1.50 be used. Furthermore, it was noted that for shaft without key way, the allowable stress (*Ss*) must be 55 MN m^{-2}, and for the shaft, with the key way, the allowable stress (*Ss*) should not exceed 40 MN m^{-2}.

Torsional moment (M_t) on the shaft was calculated using equation below.

$$M_t = \frac{P \times 60}{2\pi N} \tag{7}$$

Where: *P* = Power required to drive the machine, kW; *N* = Speed of the shaft, rpm; *V* = Forward speed, m s^{-1}.

The maximum bending moment on the shaft was determined by the following Equation 8.

$$M_b = \sqrt{M_v^2 + M_h^2} \quad (8)$$

Where: M_b=Maximum bending moment, N m; M_v=Vertical bending momentum, N m; M_h = Horizontal bending momentum, N m.

2.4.7 Wheel design

The ground wheel diameter was selected based on the trial-and-error method depending on the height of the machine above the ground surface. Therefore, the diameter of the ground wheel was selected to be 68 cm. The young's modulus of the mild Steel plate and Poisson ratio were 205 GPa and 0.30, respectively.

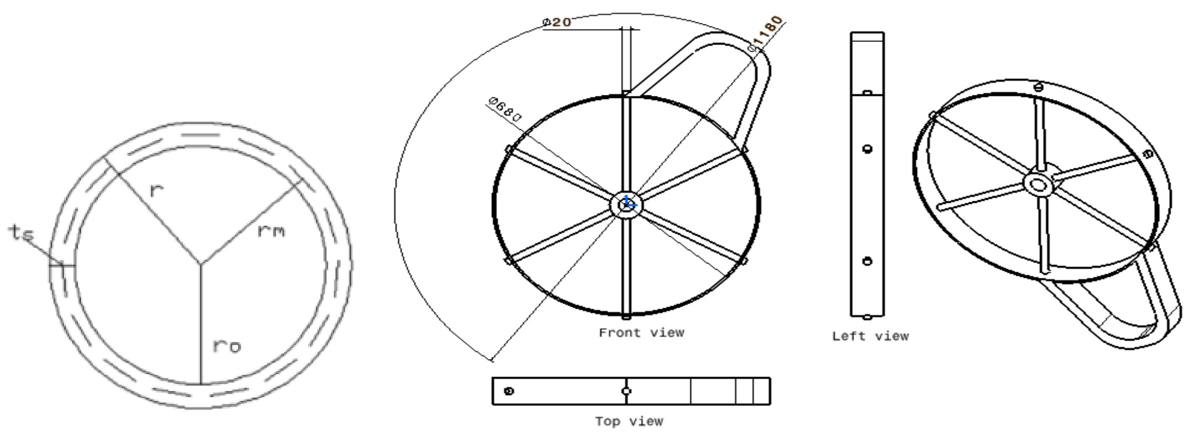


Figure 6 Three dimensional and cross-section views of the wheel

The wheel of the tie ridger was made from mild steel sheet metal whose maximum shear strength, **τ**max, is 80 MPa. Reinforcing bars were used to strengthen the wheels. For the simplicity of the analysis, it was assumed that the stress occurs on the wheel was pure torsion. Therefore, the formula used in the analysis was the one that estimates the sheer amount in "welded closed thin wall, *t*<<<*d*", as shown below Equation 9.

$$\tau = \frac{T}{2A_m \times t_s} \quad (9)$$

$$\tau = \frac{T}{2\pi(r - 0.5t_s)^2 \times t_s}$$

Where: T = The torque produced by the wheel, Nm; A_m = The area of the wheel calculated based on the mean diameter of the wheel, m^2; r = The outer radius of the wheel (m); r= The inner radius of the wheel, m; r_m= The mean radius of the wheel (m); t_s= The thickness of the wall/wheel, m; Comparing this shear stress with the maximum allowable shear stress of the metal; $\tau <<< \tau_{max}$, indicated the wheel was safe.

The angle of twist can be estimated using the Equation 10 below

$$\theta = (\frac{TL_m}{4GA_m^2 t})L \quad (10)$$

Where: L = Length or width of the wheel, m; T = Torque produced by the wheel, N m; L_m = The length of the median line of the wheel, m; t=wheel thickness, m; θ = The angle of twist, radian); G = Modulus of rigidity, Nm^{-2}.

The angle of twist produced by the wheel is negligible since the torque is small. The width of the wheel specified in the design was 8 cm and this had to be checked whether the width selected would allow the wheels to rotate on the surface of the ground without sinkage or not.

2.5 Test of tie ridger

According to the design, the tie ridger was fabricated in Melkassa Agricultural Research Center workshop and tested on a rectangular farmland of 3200 m2 area having a sandy loam soil texture with moisture content of 10.23% in dry basis. Field capacity and efficiency were determined using relevant parameters that included effective operation time, turning time and time losses due to obstructions on the field.

Figure 7 Field test of tie ridger machine

2.5.1 Working speed

The working speed was estimated using the Equation 11 below.

$$V = \frac{D}{ta} \quad (11)$$

Where: V = Working speed, m s-1; D = Distance of run, m; ta = Average time of each pass, s.

2.5.2 Field efficiency

The field efficiency was evaluated from Equation 12.

$$\varepsilon = \frac{T_e}{T_c} \times 100 \quad (12)$$

Where: Ɛ = Field efficiency, %; Te = Effective operating time, min; Tt = Total time, min (effective operating time + time lost for turning).

3 Results and discussion

2.5.3 Effective field capacity

The effective field capacity was suggested by Equation 13.

$$Effective\ field\ capacity(hah^{-1}) = \frac{Actual\ area, ha}{Time\ taken\ to\ cover\ test\ area, h} \quad (13)$$

The Table 3 shows that the moisture content at 5 different places was found to be 9.15%, 9.51%, 10.49%, 10.32% and 11.68% respectively. The average moisture content of the experimental field was 10.23%. The bulk density of soil was measured by a core sampler. Bulk density of soil was found to be 1.143 g cm^{-3}, 1.108 g cm^{-3}, 1.166 g cm^{-3}, 1.129 g cm^{-3} and 1.122 g cm^{-3}, respectively (Table 3). The average bulk density of experimented plot was found 1.134 g cm^{-3}.

Table 3 Moisture content and bulk density of soil

Observation	Weight of soil sample (g)	Weight of soil after oven dried (g)	Soil moisture content (d.b%)	Volume of core sampler (cm^3)	Bulk density (gcm^{-3})
1	613	561.6	9.15	491	1.143
2	596.3	544.5	9.51	491	1.108
3	632.7	572.6	10.49	491	1.166
4	612.1	554.8	10.32	491	1.129
5	615.7	551.3	11.68	491	1.122
Average	613.96	556.96	10.23	491	1.134
S.D	5.1786	4.2806	0.3930		0.00883

Table 4 Mean of measured performance evaluation of tie ridger during field test

SN	Parameters	Operating speed, km hr^{-1}		
		3.6	4.3	5.0
1	Fuel consumption, L hr^{-1}	5.93	6.48	6.75
2	Draft requirement, kg	101.57	108.20	115.84
3	Power requirement, hp	1.35	1.59	2.09
4	Wheel slip, %	4.17	4.93	5.99
5	Theoretical field capacity, ha hr^{-1}	0.79	0.93	1.1
6	Effective field capacity, ha hr^{-1}	0.58	0.66	0.77
7	Field efficiency, %	72.78	70.96	70.00

Table 5 Test results of performance evaluation of tractor-drawn tie ridger

Sr. no	Particulars	Values			
		Trial I	Trial II	Trial III	Average
1	Total area covered, m^2	3200	3200	3200	3200
2	Operation time, hr	0.388	0.35	0.33	0.36
3	Time lost, hr	0.16	0.15	0.15	0.15
4	Effective working width, m	1.73	1.70	1.68	1.70
5	Length of tie ridge, m	2.88	2.76	2.72	2.78
6	Width of tie ridge, cm	35.88	33.77	33.22	34.29
7	Depth of tie ridge, cm	21.22	23.55	24	22.92
8	Distance between successive tie ridge, cm	48.33	51.55	52.66	50.84

The distance between two successive tie-ridges was observed to be 48.33, 51.55 and 52.66 cm for the 1st, 2nd and 3rd trials, respectively. The average distance between two successive tie-ridges was 50.84 cm. Thus, the basins of an average size of 2.78 m × 34.29 cm were constructed by this tie-ridger.

The analysis of variance (ANOVA) revealed that tie ridger forward speed had a significant effect ($p< 0.05$) on length of tie ridging whereas, it had no significant effect ($p > 0.05$) on depth, distance between successive and width of tie ridging.

Table 6 Draft and power measurement

Operation speed (km hr^{-1})	Draft (kg)			Power (hp)		
	Load condition	Unload condition	Net draft	Load condition	Unload condition	Net power
3.6	339.68	238.11	101.57	4.52	3.17	1.35
4.3	358.12	249.92	108.20	5.70	3.98	1.72
5.0	369.42	253.58	115.84	6.84	4.69	2.15
Mean	355.74	247.20	108.53	5.68	3.94	1.74
SD	7.07	3.8	3.27	0.54	0.35	0.19
CV	1.98	1.53	3.0	9.50	8.88	10.91

The higher the CV, the less the precision of the experiment for a determined parameter. There was a good correlation between draft and operating speed in all trials, with a high coefficient of determination.

Table 7 Theoretical field capacity, effective field capacity and field efficiency

Speed (km hr^{-1})	Total time required (s)	Theoretical field capacity (ha h^{-1})	Effective field capacity (ha h^{-1})	Field efficiency (%)
3.6	1,986	0.79	0.58	72.78
4.3	1,745	0.93	0.66	70.96
5.0	1,496	1.1	0.77	70.00
Mean	1,742.33	0.94	0.67	71.24
SD	200.05	0.073	0.044	0.66
CV	11.4	7.76	6.6	0.93

Both the theoretical field capacity and effective field capacity were increased as the speed increase. Field efficiency test is presented in Table 7. The field efficiency was varied from 70.00% to 72.78% at the three speeds. It shows that the average field efficiency to cover 1 ha area was 71.24% and average effective field capacity of tractor-drawn tie ridger was 0.67 ha hr^{-1}.

Table 8 Cost summary

No.	Cost variables	Summary
A	Raw materials cost	12,656.6 ETB
B	Machine wastages 2.5%	316.41 ETB
C	Machine cost	1,964 ETB
D	Labor cost	500 ETB
E	Overhead cost 5% (C+D)	123.02 ETB
F	Profit 10% (A+B+C+D+E)	1,556.02 ETB
G	Sell tax 15%	2,567.40 ETB
	Selling price	19,683.45 ETB

The estimated cost of the one unit of tractor-drawn tie ridger was determined as 19,683.45 ETB.

4 Conclusion

The tractor-drawn tie ridger was developed for tie ridging operation suitable for medium (model) farmers and its performance was evaluated. The machine was powered by 40 hp YTO tractor. The tie ridger consists of the mainframe, shaft, shank, furrow wing, bearing, hub, spokes and central driving wheel. The field-testing of tractor-drawn tie ridger was carried out at the field of MARC. The field was well prepared which was 25 cm depth, firm, fine structure, smooth and level, relatively free of surface trash. In the field test, a tractor-drawn tie ridger was operated at 3rd gear with speed of 3.6, 4.3 and 5.0 km hr^{-1}.

The tie-ridger was developed and fabricated with care so; that the components were free from cracks and visual defects. The welded joint was not porous. The anti-corrosive and rust preventive paint was applied to each components. The mainframe was made strong enough to support all components fixed on it.

The following conclusions are made from the study.

1. Under normal moisture content (10.23%) the average wheel slip was observed to be 5.03% (tractor operated at 3rd gear).

2. The tie ridger can be used to form the tie-ridged basin of 2.78 m × 34.29 cm in size in the prepared field.

3. It formed an average of 34.29 cm width and 22.92 cm depth.

4. The average distance between two successive tie-ridges was 50.84 cm.

5. The implement was attached easily to the tractor with the help of a three-point linkage.

6. The average field efficiency (%) and effective field capacity ($hahr^{-1}$) were 71.24 and 0.67, respectively.

7. The average draft of 1,063.59 N was required for operating the implement.

8. The average fuel consumption for the tie-ridger was about 4.78 lit hac^{-1}.

9. The average cost of operation was about 220.12 $ETBhr^{-1}$.

10. The cost of fabrication of the tie ridger was estimated at approximately 19,683.45 ETB.

Conflict of interest

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

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