

Conceptual design of a multi-crop inter-row cultivator including development and performance evaluation of prototype

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Abstract: The emergence of herbicide-resistant weeds, environmental impact and increasing demand for chemical-free foods made chemical method of weed control less attractive and hence gave rise to the importance of mechanical weeding method. The main objective of this study was to design, develop and test a two wheel tractor (2WT) drawn multi-crops inter-row cultivator. While designing and in material selection, premium was given to crop parameters such as row to row spacing, plant height and branching pattern; soil parameters such as soil penetration resistance, soil bulk density and soil moisture content, and machine-soil parameters. Consideration was given to strength, durability, portability, simplicity and techno-economic status of the smallholder farmers and artisans who are the intended users and mass producers respectively. The design computations and graphic of the functional units and components of the machine were achieved using the CATIA software package and Solid Work 2013. The machine was constructed and tested at Melkassa Agricultural Research Center (MARC) fabrication workshop and tested at the center's experimental farm using a 11.19 kw, 2WT. Results revealed that the average weeding indexes were 84.27%, 92.12% and 88.31% for maize, soybean and sorghum respectively while the average mechanical damage were 4.27%, 3.65% and 4.25% for maize, soybean and sorghum respectively. The results of the test showed that the machine performed satisfactorily. With a production cost of ETB 11,196.80 (USD 279.92), the machine can be easily afforded by the smallholder and low income farmers who are the intended users.

Key words: design, multi-crop cultivator, two wheel tractor (2WT), weed control

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1 Introduction

Competition between crops and weeds is still a serious challenge to crop production worldwide

because weeds compete with crops for nutrients, light, space and water. Therefore effective weed control is necessary and important to achieve maximum productivity and profitability. Chavan et al. (2015) observed that weeds compete keenly with crops for essential nutrients and manual weeding as well as animal-drawn weeders further lead to damage of main crop. In the same development, more than 33% of the cost incurred in cultivation is diverted to weeding

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operations thereby reducing farmers' profits. Rajashekar and Mohan (2015) reported that delay in weeding operation affects the crop yield and result in 40%-60% loss in grain quality and in many cases cause complete crop failure. Hand hoe weeding is very difficult and tedious as it tends to perpetuate human drudgery, risk and misery.

Cultivation implements can destroy weeds by completely or partially burying the weeds, uprooting and breaking the weed root contact with the soil but there are limitations using this method. This due to the fact that weed control can only be done during the early crop stages because limited tractor and cultivator ground clearance and machine-plant contact may potentially damage the crop foliage at later growth stages (Cloutier et al., 2007). In spite of these limitations, a wide range of cultivation implements can be used for mechanical inter-row weeding with inter-row cultivators being the most common machine in that category. This implement consists of cultivating tools mounted on a toolbar that sweep to move soil, bury, cut or uproot the weeds.

Herbicide-based weed control offers very high labour productivity with stable yields but its environmental viability at the smallholder level cannot be guaranteed. Its use requires good discipline and technical awareness from farmers. The traditional method of hand cultivators is time consuming while human-operated cultivators cannot be used for a long time because they require muscle power. Though various types of mechanical cultivators have been developed, most of them are meant to be powered by the conventional four wheel tractors which cannot be afforded by smallholder farmers. In order to overcome these problems, two wheel tractor (2WT) drawn multi-crop inter row cultivator is being proposed for smallholder farmers in maize, sorghum and soybean cultivation.

Tajuddin (2006) developed an engine operated blade harrow for weeding operation. It was noticed that as the blade angle increased weeding efficiency is also increased. Draught of the blade harrow increased with increase in depth of operation.

However, the rate of increase of the unit draft was found to be decreasing with increasing depth of operation. Karkal (2013) designed and developed a self-propelled cultivator having 4 hp petrol-start-kerosene-run engine, power transmission system, sweep-type weeding blades and cage wheel as its main components. The rated engine speed of 3600 rpm was reduced to 23 rpm of the cage wheel by using chain and sprocket mechanism in three steps to run the machine.

Therefore, the objective of this study was to design, develop and conduct performance evaluations of 2WT drawn multi-crop inter row cultivator. The machine would control weeds, improve the soil conditions by making the soil loose, improve infiltration of rain or surface water and maintain ridges or beds on which the crop is grown. Adoption of the machine is expected to increase production and crop productivity by reducing tedious weeding work in terms of labour and time required. In addition, the 2WT will be available for different agricultural operations such as postharvest hauling.

2 Design of machine elements

2.1 Design considerations

While designing the multi-crop cultivator, the basic design considerations included the following: (i) the machine should be suitable for operation with a power tiller 11.19 KW 2WT; (ii) the machine should be strong, durable, portable and light in weight so that it can be transported easily from one terrace to another by the prime mover; (iii) the machine should be easily fabricated using Ethiopian artisans and technicians; (iv) the costs of the machine should be within the purchasing capacity of smallholder farmers; and (v) It should be adjustable to cultivation of different crops including maize, sorghum and soybean.

2.2 Design computations

2.2.1 Drawbar horse power and drawbar pull

Drawbar horse power is calculated by the equation given by Alvi and Pandya (2001) as the

$$DBHP = 60 \% \times BHP \quad (1)$$

Where $DBHP$ is draw bar horse power (hp) and BHP is brake horse power (hp). With BHP for a single-axle tractor being 11 Kw, hence, $DBHP$ is 6.6 Kw. Therefore, drawbar pull is calculated using the by equation given by Sharma and Mukesh (2010) and stated below as:

$$BHP = \frac{F \times V}{270} \quad (2)$$

Given that $DBHP$ is 6.6 Kw ($270 \text{ kg km hr}^{-1}$) and speed of the 2WT is 2.5 km hr^{-1} (Sharma and Mukesh, 2010), therefore from Equation 2, drawbar pull is 486N.

2.2.2 Determination of width of implement

The width of the implement is calculated from the expression given by Equation 3 (Sharma and Mukesh, 2010) as follows:

$$W_i = \frac{D_t}{D_u \times d_c} \quad (3)$$

Where, W_i is width of implement (cm), D_t is total draft (N), D_u is unit draft (N cm^{-2}), and d_c is depth of cultivation (cm). Given that D_t is 486 kgf, D_u for heavy clay soil is 0.75 kgf cm^{-2} (Dubey, 2003), and d_c for maize and sorghum field is 7 cm while that of soybean is 6 cm (Marta and Ivica, 2014) hence, W_i is 92.57 cm (for sorghum and maize) and 108 cm (for soybean). However, the row to row spacing between crops ranges between 40 cm to 45 cm (FAO, 1983), therefore a row to row distance of 45 cm is selected.

2.2.3 Determination of width and number of cutting blade

The cutting width of the sweep type is determined by using expression given by Sharma and Mukesh (2008) in Equation 4 following the recommended spacing of duck-foot tines for cultivation of sorghum and maize by FAO (1983).

$$S_c = Z_f + Z_p \quad (4)$$

Where, S_c , Z_f and Z_p are row to row spacing of crop (cm), effective soil failure zone (cm) and soil protective zone (cm) respectively. Substituting S_c as 75 cm (for sorghum and maize) and 45 cm (for soybean), Z_p as 10 cm (for sorghum and maize) and 6 cm (for soybean) into Equation 4 as recommended by FAO (1983) and given that the protection zone was

provided on both sides of crops, hence, Z_f is 55 cm (for sorghum and maize) and 33 cm (for soybean) as shown in Figure 1.

The effective cutting width of sweep is calculated by using Equation 5 as stated by Sharma and Mukesh (2008).

$$Z_f = W_s + 2d_c \tan \Phi \quad (5)$$

Where, W_s is effective cutting width (cm) and is Φ is angle of internal friction which ranges between 10° to 30° depending up on type of soil (Sharma and Mukesh, 2008). Substituting the values Z_f and d_c as stated earlier and Φ as 20° for heavy clay soil, hence, W_s (cutting width of one blade) is 50 cm (for sorghum and maize) and 29 cm (for soybean).

Therefore, number of blades needed on the cultivator is determined by the expression below:

$$N_b = \frac{W_i}{W_s} \quad (6)$$

Where, N_b is number of blades while W_i and W_s including their values are as defined earlier for sorghum and maize and for soybean. Substituting the values gives N_b as 1.85 (indicating that 2 rows are cultivated in one sweep for sorghum and maize) and 3.72 (indicating that 4 rows are cultivated in one sweep for soybean).

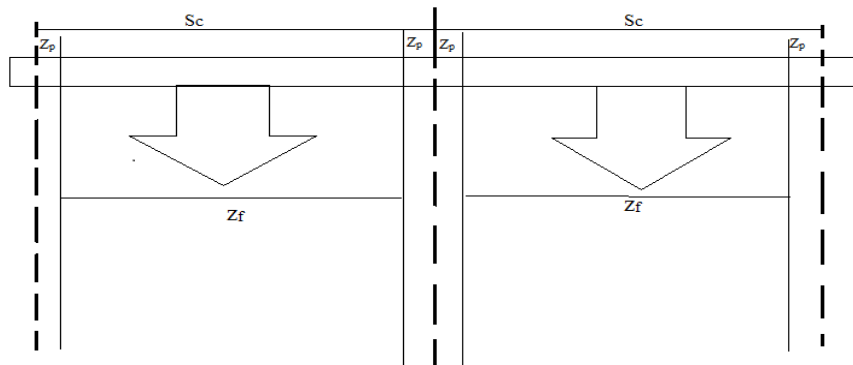
According to Sharma and Mukesh (2008), providing a small full sweep on the back and front with 15 cm width duck foot cultivator is favourable good for more soil disturbance as well as uprooting the weed between rows of crops. However, there must be overlap of sweep between the blades to avoid uncultivated soil gap. Therefore, widths of full sweep of 18 cm are selected instead of 15 cm in order to ensure to overlapping.

2.2.4 Design of main frame

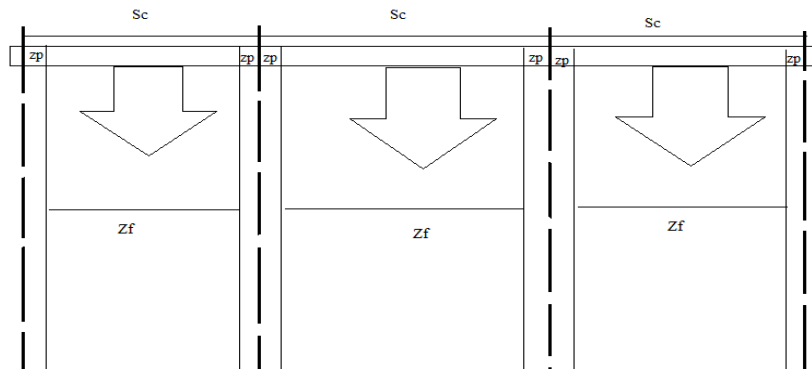
The main frame is subjected to torsion and bending due to induced draft through attachments to the shank and power tiller and the design was based on the stresses produced on the frame. While designing the main frame and in material selection, consideration was given to lightweight (to minimize cost) and strength to withstand the imposed loading during cultivation, and offer resistance against

bending and twisting. The shank was attached to the frame in such a way that load was distributed at the

back and front of the frame to minimize bending and twisting of the frame (Figure 2).



(a) 2 rows for sorghum and maize



(b) 3 rows for soybean

Figure 1 Row Cultivator with full sweep tyne profile

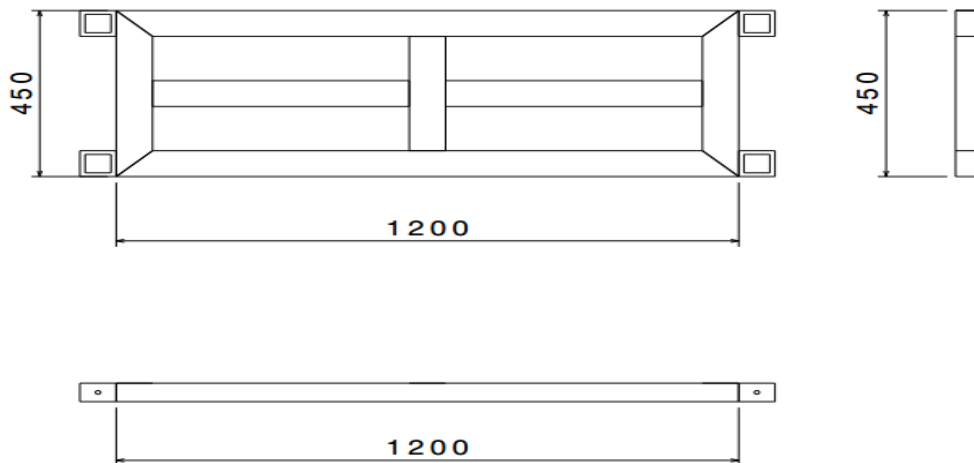
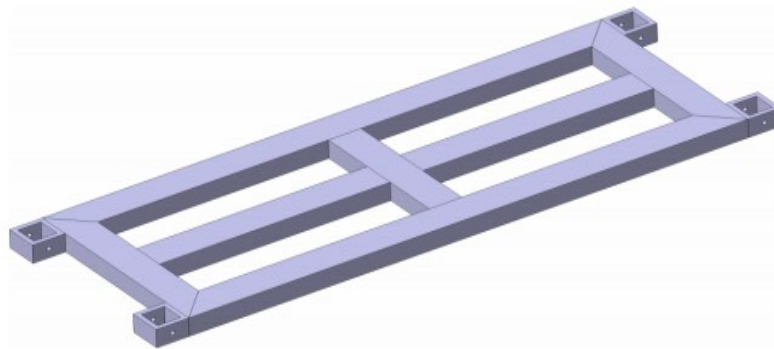


Figure 2 Frame Profile with views

The total draft was determined using the equation given by Bosoi et al., (1987) and Singh (2000) and expressed below:

$$D_t = k \times n \times a \times b \quad (7)$$

Where: k is specific soil resistance for heavy clay (kg cm^{-2}), n is number of rows, a is depth of cultivation (cm), and b is width of implements (cm). From the equation, total drafts for two-row crops ($k = 0.75 \text{ kg cm}^{-2}$, $n = 2$, $a = 7 \text{ cm}$, $b = 45 \text{ cm}$) and three-row crops ($k = 0.75 \text{ kg cm}^{-2}$, $n = 3$, $a = 6 \text{ cm}$, $b = 29 \text{ cm}$) are 1417.5 kgf and 1174.5 kgf respectively, given that the factor of safety is 3 in both cases. Therefore, to ensure safety of the structure, the design is based on the maximum draft of 1417.5 kgf. With a ground clearance of 61.5 cm, torque on the frame bar is 80949.375 kgf cm.

In addition to the torque, bending moment would also be produced with the bar being considered as a simple supported beam on the frame. The maximum bending moment is calculated below as follows:

$$M_{max} = \frac{W \times l}{4} \quad (8)$$

Where: M_{max} is maximum bending moment (Nm), W is total weight (N) and l is total length (m)

With W being total weight on the frame (50.9 kg) and l as total length of frame (130 cm), the frame is subjected to a maximum bending moment of 1654.25 kg cm.

The equivalent torque due to torsional and bending moments is determined by using Equation 10 below as given by Khurmi and Gupta (2005)

$$T_e = \sqrt{M_{max}^2 + T^2} \quad (9)$$

Given that M_{max} and T are 1654.25 kg cm and 80949.375 kgf cm respectively, the equivalent torque, T_e , was determined to be 80966.27 kgf cm. The maximum shear stress developed at the center of the frame where draft is applied was obtained by the equations given by Khurmi and Gupta (2005) as follows:

$$\frac{F_s}{R} = \frac{T_e}{I} \quad (10)$$

$$I = \frac{d^4}{9.6} \quad (11)$$

Where: F_s is shear stress at any section (N cm^{-2}), R is distance of the section from neutral axis (cm), T_e is equivalent torque (N cm), I is polar moment of inertia (cm^4) and d is width of section of the frame (cm). Substituting R as 22.5 cm and T_e as $80966.27 \times 9.8 \text{ N cm}$ into the Equations 11 and 12, then, F_s and d were determined to be 1120 kg cm^{-1} and 45.23 cm respectively and the width of section 50 mm is therefore selected. Thus a mild steel angle iron of section $50 \text{ mm} \times 50 \text{ mm} \times 2 \text{ mm}$ was selected for the construction of the frame.

2.2.5 Sweep blade design and blade angle

While designing the sweep blade, the factors taken into consideration included row to row spacing, depth of cut, crop protection zones, effective soil failure zone and angle of internal friction according to Sharma and Mukesh (2008). The shape and operating characteristics of the sweep blade are governed by the apex angle, the sharpness and the radius of curvature for inversion of soil. The apex angle was calculated by Equation 13 as given by Sharma and Mukesh (2008) as:

$$\theta = 90^\circ - \Phi_w \quad (12)$$

Where θ and Φ_w are apex angle and angle of friction between weeds and cutting edge respectively in degree. According to Sharma and Mukesh (2008), Φ_w varies between 30° - 56° but, in this design, Φ_w was taken as 45° . Hence, θ is and the blade angle (2θ) is 90° (Figure 3).

2.2.6 Design of duck foot type shank

The duck foot type shank (Figure 4) was designed to have proper fixing on frame of the cultivator with a unit draft being assumed and width of the sweep, depth of cut and factor of safety being considered according to Sharma and Mukesh (2008). The radius of curvature of the shank was determined from Equation 14 below as expressed by Shrivastava and Jha (2011) and Das (2003).

$$R = \frac{h_o - l_1 \sin \Phi_w}{\cos \Phi_w} \quad (13)$$

Where R , h_o and l_1 are radius of curvature, height of shank from its tips to be bent portion and length of

the part at which blade is laid respectively in mm; and Φ_w is load angle in degree. Substituting h_o and l_l as 160 mm, 120 mm and Φ_w 45° respectively; hence, R was determined to be 106.27 mm. This is in agreement with Shrivastava and Jha (2011) and Das (2003).

The radius of curvature should be ≤ 120 mm.

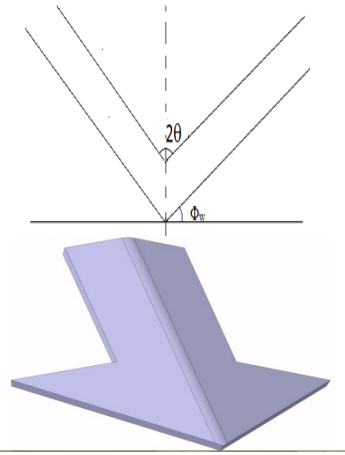


Figure 3 Sweep blade showing blade angle

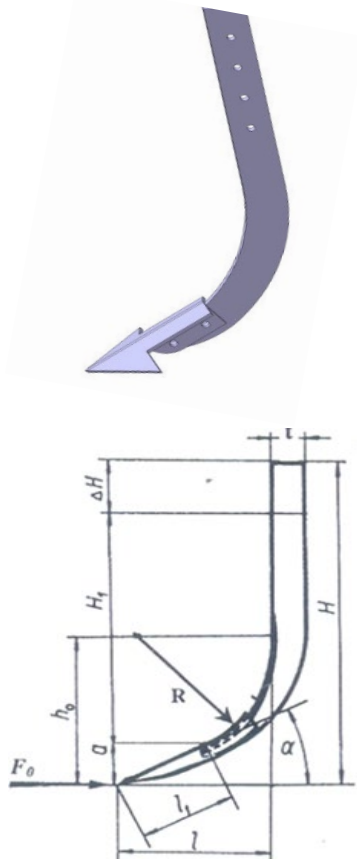


Figure 4 Dimensions of the shank

Where,

t , thickness of shank (mm); k_o , soil resistance (kg cm^{-2});

ΔH , length of the upper part of shank (mm);

b_l , width of shank (mm);

H , height of shank from the tip of blade to the frame (mm);

H_l , shank height from the frame to the top end of the breast (mm);

h_o , height from bottom up to straight part (mm);

l_l , length of the part at which blade is laid (mm);

R , radius of curvature (mm);

α , angle the shank from the ground (degree);

F_o , direction of resistance of force on the shank (N cm^{-2}).

The height of the shank was determined using the equation given by Shrivastava and Jha (2011) and Das (2003) as

$$H = d + H_l + \Delta H \tag{14}$$

Where: H , d , H_l and ΔH are height of shank from the tip of blade to the frame (overall length of shank), maximum working depth, shank height from the frame to the top end of the breast and length of the upper part of tine serving for fastening respectively in mm. Given that d , H_l and ΔH are 65 mm, 50 mm and 500 mm respectively, hence, H is 615 mm.

During the operation, the effective draft force acts at the tip of the tool and generates a bending stress at the bent thereby causing bending of the shank. Hence, the shank was designed based on maximum bending moment; thus the maximum draft on the row cultivators with full sweep shank is expressed as follows (Dubey, 2003):

$$D_e = K_o \times W_i \times d \tag{15}$$

Where: D_e is draft force, kgf; W_i is width of implement attached on shank, cm; d is depth of cultivation, cm; and K_o is specific soil resistance, kg cm^{-2} . Substituting values of K_o , W_i and d as 0.75 kg cm^{-2} , 18 cm and 6.5 cm into Equation 16 gives D_e as 87.75 kgf and the maximum draft ($D_m = 2D_e$) is 175.5 kgf. The shank can be taken as a cantilever and, according to Kurtz et al. (1984), the maximum bending moment for a cantilever occurred at fixed point on the frame. Hence, the bending moment was determined by the expression given below as follows:

$$M_b = D_m \times H \tag{16}$$

Substituting D_m and H as 175.5 kgf and 61.5 cm respectively into Equation 17 gives M_b as **5,528.25 kgf cm**.

The section modulus of the shank was computed from the classical flexure formula (Seely and Smith, 1952; Timoshenko and YOUNGH, 1964) as given by the expression below:

$$Z = \frac{M_b}{\sigma_b} \tag{17}$$

Where: Z is section modulus (cm^3); M_b is bending moment (kgf cm); and σ_b is bending stress, (kgf cm^{-2}). A mild steel flat bar was used for the design of shanks and, according to Senger (2002), the bending stress for mild steel is 1000 kgf cm^{-2} . Substituting the values of M_b and σ_b into Equation 18 gives Z as 5.52825 cm^3 . The section modulus of the shank can also be calculated using the formula (Seely and Smith, 1952; Timoshenko and YOUNGH, 1964) below as follows:

$$Z = \frac{1}{6} \times t \times b^2 \tag{18}$$

Where: t and b are thickness of shank and width of shank respectively (mm) and Z is section modulus (cm^3). Substituting Z and b as 5.528 cm^3 and 50 mm respectively in Equation 19 gives t as 13.28 mm . Therefore, considering factory of safety and availability of standard size of material, a mild steel material of cross-section $b \times t = 50 \text{ mm} \times 10 \text{ mm}$ was selected for the construction of shank.

This section would fail at a point at which maximum deflection occurs and that deflection can be determined by using the equation (Seely and Smith, 1952; Timoshenko and YOUNGH, 1964) below as follows:

$$Y_{max} = \frac{D_m \times L^3}{3EI} \tag{19}$$

Where: Y_{max} is the deflection due to loading (mm); D =Draft force, 175.5 kgf; L =Length of shank, 615 mm; E = Modulus of elasticity, $2 \times 10^4 \text{ kgf mm}^{-2}$ for mild steel (Norton, 2005); I = Moment of inertia, mm^4

$$I = \frac{t \times b^3}{12} \tag{20}$$

Where: t =thickness of shank, 10 mm; and b =width of the shank, 50 mm. Substituting the values of the parameters of Equations 20 and 21 gives I as 104166.66 mm^4 and Y_{max} as 0.653 mm. Therefore, a minute deflection of 0.653 shows that the design of the shank is safe.



Figure 5 Shank in an attachment position with the blade
2.2.7 Design of wheel

The wheels were used for movement as well as controlling the depth cultivation during operation. The width of the wheel depends on types of soil and wheel sinkage of soil (Figure 6) with the rolling resistance: being assumed to act horizontally at the wheel and ground interface.

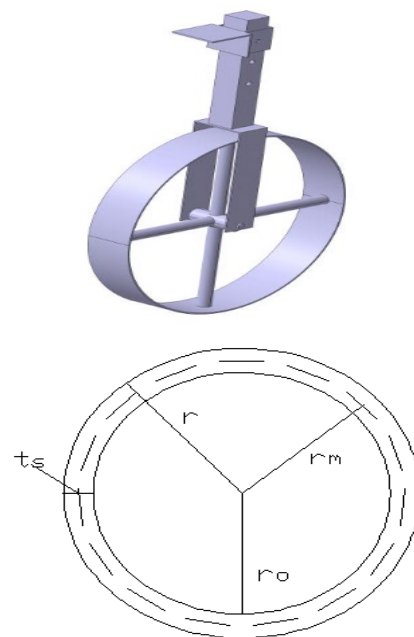


Figure 6 Wheel and wheel cross-section front view

The rolling resistance, coefficient of rolling resistance and vertical load supported by each wheel were estimated by the Equations 22, 23 and 24 respectively, assuming static equilibrium, as follows (Kumar et al., 2015):

$$RR = P \times C_{RR} \tag{21}$$

$$C_{RR} = \sqrt{\frac{z}{d} + i} \quad (22)$$

$$P = \frac{W_t - W_s}{2} \quad (23)$$

Where: RR=rolling resistance, N; P=vertical load supported by each wheel, N; C_{RR} =coefficient of rolling resistance; d=wheel diameter, m; Z=sinkage, cm; i=gradient - maximum slope where 2WT operate; W_t = total weight of machine, N; and W_s = weight of stand, N. Substituting d, z, i, W_t and W_s as 10 cm, 0.5 cm, 0.05, 747.33 N and 01.04 kg respectively into the equations; hence, P, C_{RR} and RR are 328.14, 0.3 and 98.44 N respectively.

The torque, shear stress, area of the ground wheel and median radius of the wheel were calculated by Equations 25, 26, 27 and 28 respectively (Sharma and Mukesh, 2010) as follows:

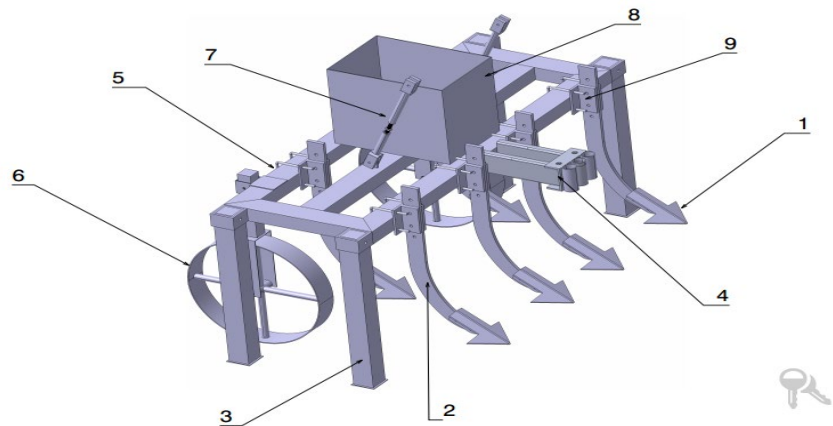
$$T = RR \times \left(\frac{d}{2}\right) \quad (24)$$

$$\tau_w = \frac{T}{2 A_m t_w} \quad (25)$$

$$A_m = \pi \times r_m^2 \quad (26)$$

$$r_m = r - \frac{t_w}{2} \quad (27)$$

Where: T=torque produced by the wheel, Nm; A_m =area of the wheel calculated based on the median diameter of the wheel, m^2 ; t_w = thickness of the wheel wall, m; r_m =median radius of the wheel, m; τ_w =shear stress on the ground wheel, MPa; and r=outer radius of the wheel, m. Substituting t_w and r as 0.003 m and 0.1 m respectively; hence, r_m , A_m , τ_w and T are 0.0985 m, 0.03 m^2 , **54.66 Pa** and 9.84 Nm respectively. Therefore, since τ_w (54.66 MPa) \llll τ_{max} (80 MPa), the ground wheels are safe for operation. The depth controlling wheel was made from a mild steel sheet of 3 mm thickness For the purpose of the analysis, it was assumed that the stress that occurred on the wheel was purely torsional. Therefore, the formula used in the analysis was the one that estimates the shear amount in “welded closed thin wall ($t \lll d$)”, as stated Richard and Keith (2011).



Legend=1-blade; 2-shank; 3-stand of body; 4-hitch to 2WT; 5-frame; 6-wheel; 7-adustable implement link; 8-ballast box; 9-shank attachment on frame

Figure 7 CATIA Drawing of the 2WT Drawn Cultivator

3 Construction and assembly of the machine

Fabrication and assembly of the machine was carried out at Melkassa Agricultural Research Center (MARC) in the Agricultural Engineering Research Workshop. The study site was located 17 km away south of Adama and 117 km from Addis Ababa city at Melkassa Agricultural Research Center (MARC). It's found at an elevation of 1560 m above sea level with point locations of 8° 24' 0" N latitude and 39°

20' 0" E longitude. The average annual rainfall ranges between 500 mm to 800 mm which is erratic and uneven in distribution. The site has a mean maximum temperature of 30.5⁰ C and mean minimum temperature of 12.6⁰ C. sandy loam soil textures are the dominant soils of the area.

Based on the design specifications and machine drawing (using CATIA software), different parts of the cultivator were fabricated and assembled in the workshop of MARC. The frame was made of MS

angle iron of dimensions 50 × 70 × 20 mm. The size of frame was 1300 mm length and 450 mm width. The blade was fabricated from MS sheet metal of 4 mm thickness while the shank was made from MS of dimensions 615 × 50 × 10 mm height, width and thickness respectively.

Hitching link of the cultivator to the 2WT was made a U-channel bar having designed the hitching mechanism considering the way it is hitched to the 2WT and easy manoeuvrability. Two slotted links were attached to the frame to protect the side

movement of the cultivator frame. Two wheels, each of 200 mm diameter, 70 mm width and 3 mm thickness were fabricated for controlling the depth and for transporting the cultivator. After the fabrication and assembly (Figure 7), the machine was tested in the laboratory to ensure proper functioning of different components and ease of operation and adjustment. Different parts such as nuts, bolts, welding joints and others were checked and rectified as appropriate.

Table 1 Materials for the construction of the machine and their costs

No	Type of material	Standard size	Unit cost (ETB)	Material used	Total cost (ETB)
1	Angle iron	(50 × 70 × 6000) mm	310	4970 mm	356.78
2	Angle iron	(60 × 60 × 6000) mm	300	2400 mm	225.00
3	Sheet metal 4mm	(6 × 1000 × 2000) mm	1850	60000 mm ²	55.5
4	Sheet metal	(4 × 1000 × 2000) mm	1570	194400 mm ²	252.60
5	Sheet metal	(2 × 1000 × 2000) mm	1500	2512 mm ²	18.84
6	U- channel	(10 × 150 × 6000)	650	560 mm	60.66
7	Round bar	∅10 × 6000 mm	250	4800 mm	300.00
8	Circular hollow pipe	∅30 × 6000 mm	725	1600 mm	193.33
9	Metal bolt and nut	M-10 × 30	25	12 psc	300.00
10	Metal bolt and nut	M-16 × 80	35	2 psc	70.00
11	Nut	M – 10	10	24 psc	240.00
	Washer	M -10 ∅	3	24 psc	72.00
12	Electrode	∅ 2.5	250	2 packs	500.00
13	Flat mild steel	(10 × 100 × 6000) mm	300	3600 mm ²	280.00
14	Flat mild steel	(8 × 40 × 6000) mm	275	2400 mm	110.00
15	Paint		160	2 gallons	320.00
Total					3654.71

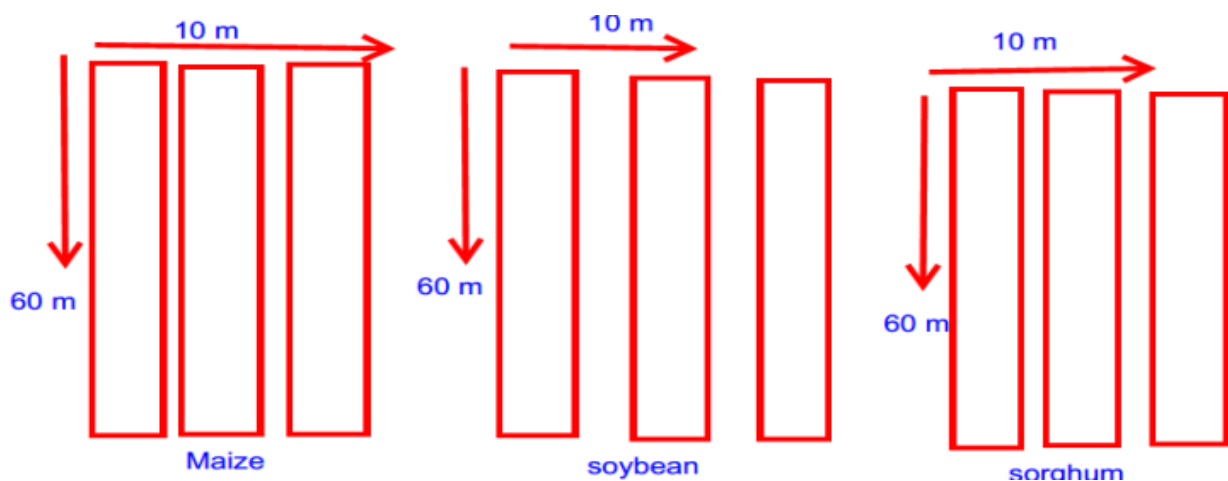


Figure 8 Experimental design and layout

4 Materials and methods

4.1 Experimental design

A Randomized Complete Block Design experiment (Figure 8) was used to evaluate three forward speeds (1.4, 2 and 2.5 km h⁻¹) of the machine on maize, sorghum and soybean fields. Each

experimental trial was replicated three times making a total number of 27 experimental trials that were carried out.

4.2 Experimental procedure

Performance evaluation of the cultivator was carried out at MARC experimental field which was laid out as shown in Figure 8 above. Three plots each

of size 60 m × 10 m, three different crops (maize, soybean, sorghum) and two different weed populations (high and low) were selected for field testing of the machine. Each plot was divided into three sub-plots each of 10 m × 20 m for sample collection. Five soil samples were taken randomly from each sub-plot at 5, 10 and 15 cm depths to determine the bulk density and moisture content before operation. Crop population and number of weed for each crop (1 m×1 m) were counted randomly at five places for each field in order to determine the weeding index and mechanical damage. The machine was set into operation as shown in Figure 9 below.

4.3 Soil parameters

The soil properties relevant to the design of multi-crop inter row cultivators drawn by 2WT were



Figure 9 Penetrometer for measurement of cone index

4.3.2 Bulk density of soil

The soil samples were collected at different depth before and after each pass of the implement. The sample initially weighed before placing it into an oven for 24 hours at 105°C. After drying, weight of samples was again measured. The soil Bulk density was calculated using the relationship (Javadi and Hajjahamad, 2006).

$$\text{Bulk density} = \frac{\text{mass of the soil}}{\text{volume of soil}}$$

identified as soil type, moisture content, bulk density and cone index.

4.3.1 Moisture content

The draft is dependent on soil moisture to great extent. The soil samples from required depths from the test site were taken using a soil augur. The moisture content of the soil profile and at different depths 5, 10, and 15 cm were collected. The collected soil samples were weighted initially and then kept in an oven for 24 hours at 105°C for obtaining dry weight of the soil. Moisture content of soils on percentage wet basis was calculated as follows by using equation (Javadi and Hajjahamad, 2006).

$$MC = \frac{Ww - Wd}{Wd} \times 100\% \quad (28)$$

Where: Mc=Moisture content, (% db), Ww=Wet mass of soil, g, Wd=Dry mass of soil, g.

$$\rho = \frac{M}{V} = \frac{4M}{\pi D^2 L} \quad (29)$$

Where: ρ =Bulk density, g cm⁻³, M=Mass contained in soil sample of oven dry soil, g, V=Volume of cylinder sampler, cm³, D=Diameter of cylinder sampler, cm, L=Height of cylinder sampler, cm.

4.3.3 Soil penetration resistance

Soil penetration resistance (PR) is an indication of soil hardness. Soil Penetration resistance was

measured by Pushing a hand-held analog cone tipped penetrometer CP40 II at different locations within implement operated plots with in close proximity, where soil cores for bulk density were extracted. Cone index was measured by cone penetrometer, the bottom portion of cone penetrometer was conical in

shape having an apex angle of 30° and the cone base area of 332 mm². The readings were taken at a depth interval of 5, 10 and 15 cm.

$$\text{Cone index}(CI) = \frac{\text{penetration resistance of soil}}{\text{based area of cone}} \quad (30)$$



Figure 10 Pictorial view of the 2WT drawn cultivator

4.3 Performance indicators and measurements

4.3.1 Draft and power requirements

Draft force was measured with the dynamometer attached to the front of the tractor on which the implement was mounted. An auxiliary tractor was used to pull the 2WT with the implement mounted through a distance with the tractor being in neutral gear position while the implement was in the operating position and the draft was measured and recorded. On the same field, with the implement lifted off the ground, it was moved through the same distance the draft was measured and recorded as well. The difference in the draft force measured in both condition is the draft force of the implement. Then, the cultivator was set in operation using the three operational speeds and the data obtained was recorded from the dynamometer. Then, the 2WT-drawn cultivator was operated at the recommended speeds of 1.4 km h⁻¹, 2.0 km h⁻¹ and 2.5 km h⁻¹ on the plots. The tractor (another power source) was used for pulling the walking tractor (2WT). The analog type dynamometer was attached in between walking

tractor and pulling tractor. Pull the walking tractor with the help of tractor and note the readings (unloaded condition). The cultivator was attached to the 2WT and pulled with the aid of the auxiliary tractor in the loaded condition, the reading was noted and the procedure was repeated three times.

The draft required to pull cultivator was calculated using the equation given by Rangapara (2014) as follows:

$$D_R = D_L - D_U \quad (31)$$

Where: D_R , D_L and D_U are draft required to pull the cultivator, draft required to pull the 2WT in loaded condition (with cultivator) and draft required to pull 2WT in unloaded condition (without cultivator), respectively in Kgf.

The power required for the pulling operation was calculated using the equation given by Rangapara (2014) and stated below as:

$$P_P = \frac{D_R \times S}{75} \quad (32)$$

Where: P_P is the power required for the pulling operation (Kw) and S is the forward speed of the implement (m s⁻¹).

4.3.2 Weeding index

The total numbers of plants were counted in an area of one square meter by a quadrat of 1m² (1 m × 1 m) from randomly chosen places in each plot, before and after every weeding operation, to observe plant damage percentage. Samples were collected in quadrant method (1 m × 1 m) by random selection of spots by a square quadrant of square meter area. Weeding Index is the ratio of the numbers of weeds removed by the cultivator to the number of weeds present in a unit area before weeding operation, expressed as a percentage. It is calculated using the equation given by Tajuddin (2006) as follows:

$$WI = \frac{W_1 - W_2}{W_1} \times 100 \% \quad (33)$$

Where: *WI* is weeding index in percentage, *W₁* is number of weeds present per unit area before weeding operation and *W₂* is number of weeds counted on the same unit area after weeding operation.

4.3.3 Mechanical damage

Mechanical damage was calculated as the ratio of the number of plants damaged after operation in a unit area to the number of plants present before operation in the same unit area. It is mathematically expressed by Yadav and Pund (2007) as:

$$MD = \frac{N_t - N_e}{N_t} \times 100 \quad (34)$$

Where: *MD* is mechanical damaged in % and *N_t* and *N_e* are total number of plants per unit area before the operation and total number of plants damaged in the same unit area after operation.

4.3.4 Theoretical field capacity

The theoretical field capacity of the machine is the rate of field coverage that would be obtained if the machine were performing its function 100% of the time at the rated forward speed and always covered 100% of its rated width. It was determined using the equation below (Kepner et al., 1972) as follows.

$$TFC = \frac{W \times V}{10} \quad (35)$$

Where: *TFC* is theoretical field capacity (ha hr⁻¹), *W* is width of cut (m) and *V* is speed of operation (km hr⁻¹).

4.3.5 Effective field capacity

The effective field capacity is the actual average rate of coverage by the machine, based upon the total operation set time. It is a function of the rated width of the machine, the percentage of rated width actually utilized], speed of operation and the amount of field time lost during the operations. It was calculated using the equation below (Kepner et al., 1972) as follows:

$$EFC = \frac{A}{T_p + T_l} \quad (36)$$

Where: *EFC* is effective field capacity in ha hr⁻¹, *A* is actual area covered in ha and *T_p* and *T_l* are productive time and non-productive time respectively in hr.

4.3.6 Field efficiency

Field efficiency is the ratio of effective field capacity to the theoretical field capacity and it is the effect of time lost in the field and the failure of the machine to utilize its full width. It was calculated using the equation below (Kepner et al., 1972) as follows:

$$\eta = \frac{EFC}{TFC} \times 100 \quad (37)$$

Where: *η* is the field efficiency in % and *TFC* and *EFC* are as defined earlier.

4.4 Data analysis

The data obtained from the tests were statistically analysed using the analysis of variance (ANOVA) following the procedure appropriate for the design of the experiment (Gomez and Gomez, 1984). The treatment means that were significantly different at 5% levels of significance were compared using least significant difference (LSD 5%) test.

5 Results and discussion

5.1 Soil physical properties

The average soil moisture content at 5 different places at different depth were taken from the field was found to be 17.54%, 23.04%, 23.32% in dry basis at 5,10 and 15 cm respectively and 14.74%, 18.62%, 20.47%, in wet basis at 5, 10 and 15 cm respectively. The average bulk density of soil was

found to be 0.5358, 0.4504 and 0.2302 g cm⁻³ at 5, 10, and 15cm depth respectively on dry mass basis. The average penetration resistance at different depth levels tested were 572.214, 493.8757 and 441.475 N cm⁻² at 0-5, 5-10, and 10-15cm respectively. ANOVA showed that the depth has significant effect on penetration resistance at 5% level of significance.

5.1 Weeding index and mechanical damage

As shown in Table 2, the average weeding indexes of the machine were 84.27%, 92.12% and 88.31% for the maize, soybean and sorghum fields respectively. The above results show that for same field conditions weeding index varies with weed density. It was also shown from the table that the average mechanical damage was 4.27%, 3.64% and 4.25% on maize, soybean and sorghum fields respectively. During the operation of the machine, it

was observed that some crops were damaged because they grew out of alignment with the row.

5.2 Draft and power requirement

As shown in Table 3 below, the average draft requirement increased with increase in operation speeds with values 86.33, 94.66 and 102 kgf on 1.4, 2.0 and 2.5 km h⁻¹ speed, respectively. ANOVA showed that the speed of 2WT has significant ($p < 0.05$) effect on draft needed for the operation. The power requirements were found maximum for speed at 2.5 km hr⁻¹ and minimum 1.4 km hr⁻¹ with values of 2.5 Kw and 1.9 Kw respectively. The table show that power requirement increased with increase in speed. ANOVA showed that the speed of 2WT has no significant ($p > 0.05$) effect on power needed for the operation.

Table 2 Weeding index and mechanical damage on maize, soybean and sorghum fields*

Crop	Weeding index (%)	Mechanical damage (%)
Maize	84.27±1.88	4.27±4.40
Soybean	92.12±3.66	3.64±3.69
Sorghum	88.31±5.55	4.25±3.95

Note: *Each value is the mean of 5 replicates ± standard deviation

Table 3 Effect of speed of operation on draft and power requirements

Operation speed (km h ⁻¹)	Draft requirement (kgf)			Power requirement (hp)		
	Loaded condition	Unloaded condition	Net draft	Loaded condition	Unloaded condition	Net power
1.4	181.00±	93.30±	86.33±	3.33±	1.72±	1.61±
2.0	191.66±	97.00±	94.66±	5.11±	2.58±	2.53±
2.5	205.00±	103.00±	102.00±	6.68±	3.43±	3.39±

Note: *Each value is the mean of 3 replicates ± standard deviation with the three crop fields being replicates in each case

Table 4 Field capacity and field efficiency of the machine on maize, soybean and sorghum

Field	Operation Time (min)			Field Size (ha)	TFC (ha hr ⁻¹)	EFC (ha hr ⁻¹)	FE (%)
	T _p	T _i	T _t				
Maize	22.0	4.5	26.5	0.06	0.18	0.14	75.75
Soybean	18.5	3.5	22.0	0.06	0.18	0.16	88.88
Sorghum	21.5	5.0	25.5	0.06	0.18	0.14	76.98

5.3 Field capacity and field efficiency

The theoretical field capacity, effective field capacity and field efficiency of the machine on the maize, soybean and sorghum fields are as shown in Table 4 below. The test was based 2 km hr⁻¹ as the average speed of the 2WT, 0.9 m as the working width of the machine for all the three crop fields and 600 m² as the size of plot for each crop field. The effective field capacity of the machine was 0.14, 0.16 and 0.14 for maize, soybean and sorghum fields

respectively while the field efficiency were 75.75%, 88.88% and 76.98% respectively.

6 Conclusion

In this study, a multi-crop inter row cultivator suitable for smallholder farmers in the rural communities was designed, developed and evaluated for its performance with a 11Kw diesel engine 2WT. In designing and material selection, consideration was given to strength, durability, portability, simplicity

and techno-economic status of the smallholder farmers and artisans who are the intended users and mass producers respectively. Test results showed that the machine performed with average weeding indexes of 84.27%, 92.12% and 88.31% on maize, soybean and sorghum fields respectively while the average mechanical damage to the crops were 4.27%, 3.65% 4.25% respectively. The average draft requirements were 86.33, 94.66, 102.00 kgf at 1.4, 2.0 and 2.5 km hr⁻¹ respectively while the average power requirements were 1.61, 2.53, 3.39 hp at 1.4, 2.0 and 2.5 km hr⁻¹ respectively for maize, soybean and sorghum fields respectively. Based on the average operational speed of 2.0 km hr⁻¹, the effective field capacity was 0.14, 0.16 and 0.14 ha hr⁻¹ for maize, soybean and sorghum fields respectively while the theoretical field capacity was 0.18 km hr⁻¹. With this satisfactory performance of the machine and an estimated production cost of ETB 11,196.80 (USD 279.92), the machine is within the reach of smallholder farmers and can be scaled up for commercial application.

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