Development and performance evaluation of tractor-drawn broad bed maker

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Abstract: Agriculture in Ethiopia is predominantly characterized by subsistence farming, where smallholder farmers primarily produce for household consumption. In Ethiopia, over 80% of the population is engaged in agriculture, with a significant portion cultivating crops on Vertisol-dominated landscapes. Vertisols, which constitute approximately 16% of Ethiopia's highland areas, pose considerable challenges due to their poor drainage, leading to waterlogging and reduced workability. Farmers have traditionally relied on rudimentary methods, such as delayed planting and manually constructed broad beds, which fail to fully exploit the agricultural potential of these soils. This study focuses on the development and performance evaluation of a tractor-drawn broad-bed maker (BBM) to enhance land productivity on Vertisols. The research involved designing, fabricating, and assembling key components, including an adjustable ridger, shanks, frame, three-point hitch links, and a bed leveller. Performance tests were conducted to optimize operational parameters, including speed and tillage depth. The findings revealed that the optimal bed formation occurred at a speed of 2.9 km h^{-1} and a tillage depth of 20 cm. However, to reduce draft requirements, the recommended operating conditions were established at 2.3 km h^{-1} and a depth of 15 cm. Under these conditions, the developed BBM achieved an average bed height of 23.6 cm and a top width of 124.3 cm, with draft force ranging between 265.91 and 388.03 kgf. The field efficiency was determined to be 72.9%, with a wheel slippage of 6.35% and a fuel consumption rate of 3.44 l ha^{-1}. The total cost of owning the tractor-operated BBM was 23,479.08 Ethiopian birr (144.66 USD). The study demonstrates that the developed BBM significantly improves field efficiency and operational effectiveness compared to traditional methods, making it a viable solution for mechanizing Vertisol management in Ethiopian agriculture.

Keywords: broad-bed maker (BBM), Vertisol, draft force, waterlogging, field performance

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1 Introduction

Agriculture in Africa, particularly in Ethiopia, is dominated by subsistence farming, in which a family produces only to feed themselves (Geffersa, 2023). Further, such farming is the main source of employment; that is, most of the population is involved directly or indirectly, including 75% of the population in Sub-

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Saharan Africa (SSA) countries and 80% in Ethiopia (World Bank, 2023).

Ethiopia has 50 million hectares of land in the highlands which cover about 62% of the highlands of East Africa. Of this area, 16% are estimated to be Vertisols, and almost the same amount has `vertic` properties (Debele and Deressa, 2016). This soil is generally found at the bottom of the landscape with a slope of no more than 8% which makes it attractive from an agricultural point of view.

A significant challenge faced by Ethiopian farmers was the management of Vertisol-dominated landscapes. These soils, despite their high fertility, suffer from poor drainage and waterlogging, severely limiting agricultural productivity (Debele, 2016). Traditional water management techniques such as late planting, soil burning, and rudimentary drainage systems remain inefficient and labor-intensive (Tefera et al., 2024). The "*maresha*" plow and oxen-powered implements, commonly used for soil preparation, fail to provide adequate furrow depth and consistency (Mekuria and Gebremariam, 2022). Besides, manual bed-making method requires 16-17 human labor to make a bed for 1 ha field, and it is a time-consuming operation (Farm Radio International, 2025). Addressing these inefficiencies is critical for optimizing land use and improving crop yields in Vertisol-dominated regions.

A tractor-operated broad bed maker (TBBM) offers an innovative approach to addressing these challenges. By enhancing land preparation efficiency and minimizing manual labor, TBBMs facilitate timely operations while improving soil drainage. Compared to conventional methods, TBBMs offer greater precision in furrow and bed formation, promoting better soil aeration and increased agricultural productivity.

In Ethiopia, access and use of tractor powered broad bed makers remain limited. However, few broad bed makers (BBMs) that were initially developed by research institutions have demonstrated potential in enhancing drainage and increasing yields. Studies on adoption pathways followed by farmers in the on-farm research sites showed that the weight of TBBMs exceeded the power capacity of available tractors or animals in mixed farming systems, making operation difficult (Fetene et al., 2024). In addition, BBMs were often less effective in excessively wet soils, where they fail to create proper channels and adequately cover seeds, affecting germination and crop uniformity (Ayele and Jabbar, 2022).

It was the above limitations of the available broad bed makers that led to the conclusion that a better tractor drawn broad bed maker should be developed for the farmers. The objective of this study was therefore to develop and evaluate the performance of a tractor drawn broad bed maker so that the overall efficiency of Vertisol management can be improved.

2 Materials and methods

2.1 Study area

The study was conducted in the Oromia region, East Shoa Zone, near the town of Melkassa at the Melkassa Agricultural Research Centre. The centre is located approximately 117 km southeast of Addis Ababa, Ethiopia. The study site lies within the central Rift Valley at a latitude of 8°24’ N, a longitude of 39°21’ E, and an elevation of 1,466 meters above mean sea level. The area is characterized by a semi-arid climate and dominated by sandy loam soil.

2.2 Flow chart of the process

Figure 2 illustrates the overall methodology used in this study for designing and evaluating the biomass briquetting machine (BBM). The process includes studying the physical properties of vertisols, selecting suitable materials, designing and analyzing components using CAD tools, and assembling the prototype. The system is then tested and evaluated, with redesign carried out, if necessary, followed by performance assessment, data collection, analysis, and final documentation.

2.3 Structure and working principle of the broad bed maker

The prototype broad bed maker was built at Melkassa agricultural research center workshop. It consists of furrow openers, bed former, frame, ridger and three-point hitch. The prototype was connected to a small horsepower tractor through the three-point hitch linkages. The frame is vertically connected to the shanks/tyne on one side, and the hitches on the other by bolts and nuts. By raising and lowering the hydraulic lever, the plow bottoms are easily engaged to the soil. The depth was adjusted by setting the tractor's hydraulic systems. The wings of the plow could be adjusted as per the furrow width requirements and the plow bottoms could also be connected to the frame, with bolts and nuts fastened on plates.

The detailed view of the developed tractor operated bed maker is presented at Figure 3. The details of the components, their specifications and the material required are presented in Table 1.

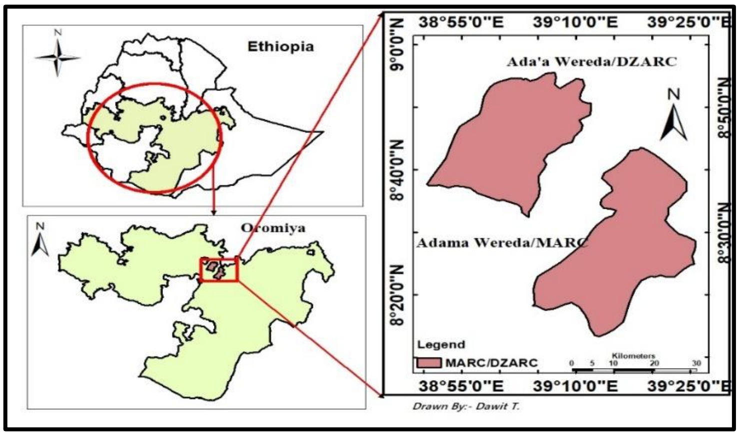


Figure 1 Map of the study area

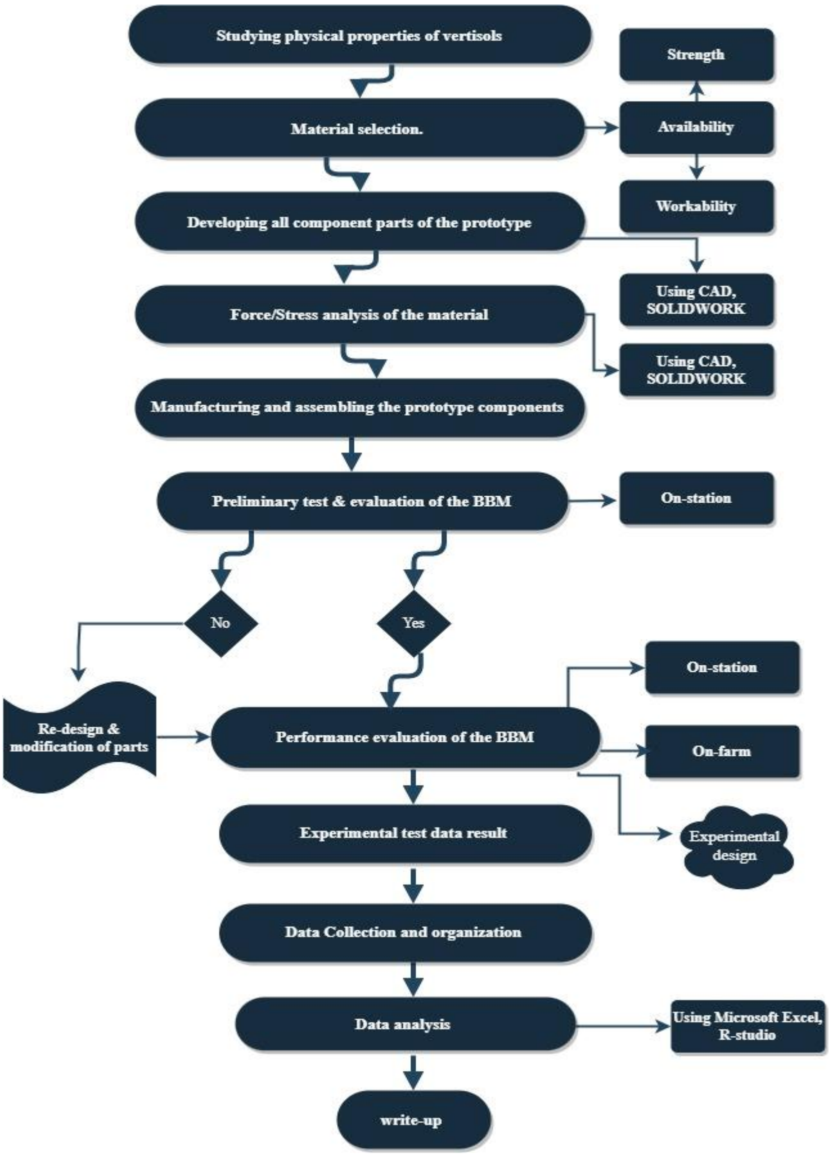
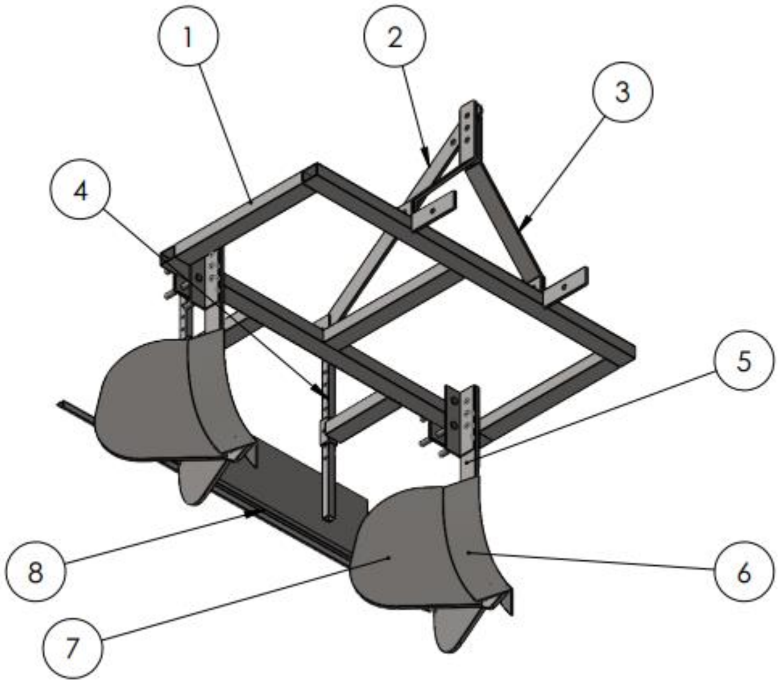


Figure 2 Procedures of the study



1-main frame; 2-top link; 3-side link; 4-leveler holder; 5-tyne; 6-furrow opener; 7-ridger wing; 8-bed leveler

Figure 3 Structure sketch of tractor drawn broad bed maker: machine main scheme

Table 1 Description of the broad-bed maker components and specifications

Component	Specifications and Descriptions
Name of implement	Broad-bed maker (BBM)
Power source	Tractor (100 hp)
Overall dimensions	
Length, mm	1280
Width, mm	1500
Height, mm	1483
Hitch	
System	Three-point hitch (Cat – II for 100 hp tractor); Extended out from main frame
Material of fabrication	Hitch – MS flat bar (70 mm × 12 mm) Hitch base – MS rectangular hollow section (70 mm × 50 mm × 5 mm)
Dimension	ASAE S217.12 (ISO 730)
Frame	
Material of fabrication	Mild steel rectangular hollow section (70 mm × 50 mm × 5 mm)
Dimension (length × width)	1500 mm x 600 mm
Tines and furrow opener	
Type	Shoe type
Furrow opener	Wing – MS sheet metal (500 mm × 500mm × 4 mm)
Tines	MS flat (70 mm × 30 mm); length 700 mm rectangular cross section
No. of furrow opener	2
Bed former	Mild steel sheet, 1500 mm × 600 mm × 3 mm Angle iron, 30 mm × 30 mm ×3 mm, SHS, 30 mm × 30 mm × 3 mm

2.4 Design consideration

The following parameters were considered during development and manufacturing of the prototype for small and medium sized tractors.

-Agronomical requirements;

-Physical and economic considerations

2.4.1 Agronomical requirements

The machine was developed by keeping in mind the various agronomical requirement of the most widely grown cereal crops in Vertisol dominated areas of Ethiopia.

-Type of crop: Tef and Wheat.

-Suitable for planting method: Either broadcasting or row planting/ drilling (row to row distance of both crops is 20 cm).

-Condition of field: well-prepared field or after harrowing and levelling is done.

-Type of soil: Vertisol (heavy black clay soil).

2.4.2 Physical and economic considerations

The following points were considered during the design of the machines.

-The machine should be simple in design and easy to operate.

-The cost of the machine should be within the range of the farmers.

-It should be easily repairable by the farmer or village artisans.

-The total power requirement should not exceed the power available from available

-Small-size HP tractors (75 KW).

-Drawbar horsepower (DBHP): 60% of BHP of tractor.

-Speed of operation: 1st, 3rd, and 4th at high gear of tractor.

2.5 Physical properties of soil

Soil samples from different parts of experimental plots were collected randomly at depths between 10 and 20 m, using a soil auger. The samples were used to determine the soil textural classification, bulk density, and moisture content. The composite soil samples were put in polyethylene bags and taken to the soil laboratory for analysis.

2.5.1 Moisture content

The soil moisture content was studied to understand the draft, workability, power transmission of the machine during operation, and wheel slippage. The gravimetric method (that is oven dry method) was used to determine the soil moisture content. Wet soil was weighed and put into an aluminium pan and placed inside an oven at 105°C. The moisture content of the soil was calculated by formula. (Mohsenin, 1986; BSWM, 2024). The percentage of water in a soil sample was calculated as follows.

$$\text{Soil moisture content} = \frac{M_i - M_f}{M_i} \times 100 \qquad (1)$$

Where

M_i=weight of wet soil sample, kg;

M_f = weight of oven-dry soil sample, kg.

The experiment was replicated for three samples from different parts of the field, and the mean value was calculated.

2.5.2 Bulk density

The bulk density of the soil for the sowing in black cotton soil was considered in the range from 1.51 to 1.63 Mg m^{-3} (FAO, 2022). It was calculated using the formula reported by IERE (2024).

The bulk density of the soil was calculated using the following formula,

$$\text{Bulk density} = \frac{\text{dry weight of bulk sample}}{\text{volume of soil core}} \qquad (2)$$

2.6 Material description of broad bed maker

Mild steel was used throughout the production process of the prototype due to its abundance in the workshop and mechanical properties. The use of mild steel reduced the weight and cost of the implement in addition to retaining the required strength, and durability.

2.6.1 Stopwatch

A stopwatch, measuring a minimum of one-tenth of a second and a maximum of 12 hours was used to record the travel speed and time required to cover the measured area during the test.

2.6.2 Metallic and steel tape

A metallic tape of 50 m and steel tape of 3 m was used for measuring and marking the layout of the test plot. A steel tape was also used for measuring the depth of broad bed making.

2.6.3 Measuring cylinder

A one-liter capacity measuring cylinder with 100 ml graduations was used to measure the fuel consumption of the tractor at the time of field operation.

2.6.4 Dynamometer

A hydraulic pull-type dynamometer of 500 kg capacity was used to measure the draft required to operate the implement in the field.

2.6.5 Weight balance

An electronic weight balance of 1 kg capacity was used to measure the weight of wet and dry soil for the determination of moisture content and bulk density of the soil.

2.6.6 Electric oven

An electric oven was used for drying the soil samples, for the determination of moisture content and bulk density of the soil.

2.7 Operating parameter

2.7.1 Speed of operation

To calculate the traveling speed, two poles were placed approximately 50 m apart in the middle of the test run. Similarly, on the opposite side, two additional poles were positioned 50 m apart, mirroring the placement of the first two. Together, the four poles marked the corners of a rectangle. The speed was calculated from the time required for the machine to travel the 50 m distance between two poles. The average of such readings was taken to calculate the traveling speed of the machine. Similarly, reported the forward speed of operation was calculated by observing the distance travelled with the time taken and calculated by the following formula (Shukla et al., 2021; FAO, 2023).

$$S = \frac{L}{t} \qquad (3)$$

Where,

S = forward speed of the machine, m s^{-1};

L = distance travelled, m;

t = time taken, s.

2.7.2 Width of coverage

The width of coverage was determined by measuring the width of the bed formed by the machine during operation with the help of measuring tape as shown in Figure 4.

Figure 4 Measurement of the width of bed

2.7.3 Measurement of tractor wheel slip

The tractor drive wheel slip was measured considering the relative movement of the wheel in the direction of travel for a given distance under load and at no-load conditions was determined as follows, by Kumar et al. (2021) and Tiwari and Patel (2020).

$$\text{Slip}(\%) = \frac{OL-NL}{OL} \times 100 \qquad (4)$$

Where,

OL = number of rotations of the rear wheel with the load;

NL = number of rotations of rear-wheel at no load.

2.8 Performance evaluation parameters

2.8.1 Draft of the implement

Draft measurement was done with the help of a digital dynamometer with a load cell. The tractor along with dynamometer (D) was positioned in front of the test tractor (T). The dynamometer was connected to the front axle of the tractor with wire rope and clamps, and the dynamometer was kept horizontal during the field trial and the implement was attached to the tractor. The draft of implement was recorded in the field. For no-load reading, the implement was lifted, and the draft was recorded. Similarly, draft reading was recorded while the machine was in operation. Throughout the dynamometer reading, the test tractor was kept in a neutral position. The readings were noted after each run. The results of the draft requirement of implements were calculated by the following formula (Kumar et al., 2021; Singh et al., 2020).

Draft of implement=with load draft-without load draft （5).

Figure 5 Measurement of the draft of the broad-bed maker using a dynamometer

2.8.2 Fuel consumption

To measure the fuel consumption, the tractor was positioned on levelled ground and the fuel tank of the tractor was filled up to the top of the tank. Then the tractor started carrying out the bed making operation. After completion of the operation, the tractor was placed at a levelled ground and then the tank was again refilled with fuel to maintain the original level of fuel. The quantity of fuel required to make up the original level as before was measured by measuring cylinder and recorded as the actual fuel consumption.

Figure 6 Measurement of fuel consumption

2.8.3 Field capacity and field efficiency determination

The Field efficiency (FE) was calculated based on the effective field capacity (EFC) and theoretical field capacity (TFC). The EFC was determined as ability of bed-maker to make bed under the actual field condition, and the TFC was obtained from the width of machine and multiplied with the average forward speed (FS) during the field work (ASABE, 2020). The FE, TFC and EFC were calculated using Equation 6-8 (ASABE, 2020).

$$FE = \frac{EFC}{TFC} \tag{6}$$

Where,

FE = field efficiency (%);

EFC = effective field capacity (ha h^{-1});

TFC = theoretical field capacity (ha h^{-1}).

$$TFC = \frac{W\,x\,S}{10} \tag{7}$$

Where,

W = width of machine (m);

S = speed of machine (km h^{-1}).

$$EFC = \frac{A}{T} \tag{8}$$

Where,

A = the worked area (ha);

T = working time (h).

which represents time spent in performing the operation from the beginning to the end.

2.9 Experimental design

The experiment was conducted using a split-plot factorial design. Three levels of operating speed and three levels of furrow depth represented the main plot and the sub plot factors, respectively. The experimental design was laid as 3×3 having three replications. As a result, a total test run of 27 (i.e, 3×3×3=36) was used. Analysis of variance (ANOVA) of different performance data was performed using Statistix-8 software. A confidence interval of 95% was utilized to indicate a level of significance. The analysis was done based on the design of experiments (Gomez and Gomez, 1984; Shi et al., 2022).

3 Results and discussion

Table 2 gives preliminary observations of the experimental field condition prior to conducting the field test.

Table 2 Preliminary observations during operation

Particular	Observation
Date of operation	April, 2022
Field condition	
Topography	Flat
Soil moisture content, % (D.B.)	6.63
Bulk density, g cm^{-3}	1.73
Type of soil	Vertisol, black cotton soil
Size of each plot, m^2	50 x 6
Land	Roughly levelled (harrowed field)

3.1 Physical properties of soil

From the results obtained from Table 2, it can be confirmed that the moisture content, bulk density and penetration resistance of the soil were 6.63%, 1.73 g cm^{-3} and 4547 kPa, respectively.

3.2 Optimization of machine parameters under dynamic conditions

The optimization tests of the tractor operated broad-bed maker were conducted in an experimental test plot. These tests were conducted to optimize the speed and depth of operation with respect to the height and top width of the seed beds and draft of the bed maker. The selected operational speeds were 1.9, 2.3 and 2.9 km h^{-1} and the depths were varied at 10, 15 and 20 cm respectively. The average values of the measured parameters were found out and are given in Table 3.

Table 3 Optimization of machine parameters under dynamic conditions

S.N	Treatment	Speed of operation (km h^{-1})	Depth of operation (cm)	Height of bed (cm)	Top width of bed (cm)	Draft of Implement (kg f)
1	S1D1	1.9	10	19.5	126.0	287.56
2	S1D2	1.9	15	22.5	125.1	318.42
3	S1D3	1.9	20	23.1	124.4	320.20
4	S2D1	2.3	10	20.5	125.2	326.31
5	S2D2	2.3	15	22.9	124.8	338.59
6	S2D3	2.3	20	23.5	124.1	365.04
7	S3D1	2.9	10	22.1	122.5	372.82
8	S3D2	2.9	15	23.4	121.8	375.16
9	S3D3	2.9	20	26.0	121.0	388.03
10	S1D1	1.9	10	20.1	125.8	286.46

S.N	Treatment	Speed of operation (km h^{-1})	Depth of operation (cm)	Height of bed (cm)	Top width of bed (cm)	Draft of Implement (kg f)
11	S1D2	1.9	15	22.3	125.0	328.37
12	S1D3	1.9	20	23.4	124.8	315.80
13	S2D1	2.3	10	20.8	125.0	324.67
14	S2D2	2.3	15	23.0	124.3	337.39
15	S2D3	2.3	20	23.3	124.0	364.87
16	S3D1	2.9	10	22.5	122.0	360.98
17	S3D2	2.9	15	23.8	121.2	372.93
18	S3D3	2.9	20	25.8	120.9	387.74
19	S1D1	1.9	10	20.3	125.4	265.91
20	S1D2	1.9	15	23.3	125.0	321.43
21	S1D3	1.9	20	21.0	125.0	322.47
22	S2D1	2.3	10	23.7	124.8	324.63
23	S2D2	2.3	15	22.8	124.1	349.48
24	S2D3	2.3	20	23.6	124.3	374.36
25	S3D1	2.9	10	22.1	122.2	370.11
26	S3D2	2.9	15	23.9	121.0	379.52
27	S3D3	2.9	20	26.1	120.5	388.03

3.3 Performance evaluation of the BBM

3.3.1 Speed and depth of operation

ANOVA results of the effects of speed and depth of operation on the top width of the bed has been shown in Table 4.

The analysis results indicated that depth of operation and forward speed of operation had significant effect on the top width of the bed ($p<0.05$). In the contrary, the combined effect of depth and forward speed of operation on top width of bed was found non-significant ($p>0.05$).

Table 4 Effect of speed and depth of operation on top width of bed

Source	DF	SS	MS	F	P
REP(A)	2	0.4022	0.2011		
Depth of operation(B)	2	5.6467	2.8233	30.43	0.0038
Error AXB	4	0.3711	0.0928		
Speed of operation(C)	2	70.6156	35.3078	698.40	0.0000
BXC	4	0.2644	0.0661	1.31	0.3219
Error AXBXC	12	0.6067	0.0506		
Total	26	77.9067			

Note: C.V = 0.18, DF = Degree of freedom, SS = Sum of squares, MS = Mean sum of squares, F = F-statistic, P = P-value

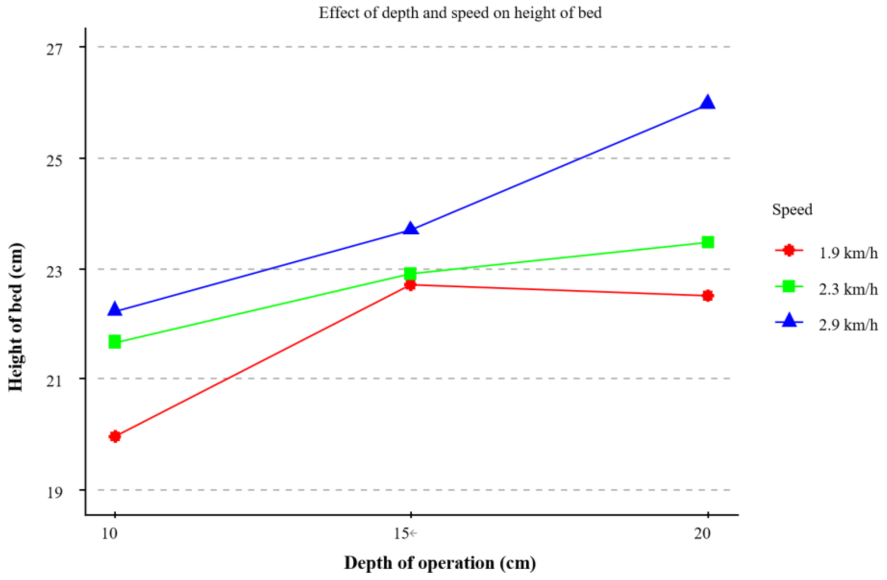


Figure 7 Effect of speed and depth of operation on the top width of bed

The maximum top width, 126 cm, was achieved at a speed and depth of operations of 1.9 km h^{-1} and 10 cm, respectively. As the speed increased from 1.9 to 2.3 km h^{-1}, the top width of bed decreased. Also at the combinations, the top width of the bed formed was found out to decrease when the height of bed and operational speed increased. Hence, it is concluded that for getting maximum top width of the bed, the two parameters, speed and depth of operation, shall necessarily be at minimum possible levels and vice versa.

3.3.2 Height of the bed

The analysis of variance for the height of the bed with respect to different speed and depth of the operation is given in Table 5. From the table, it is evident that the effect of treatment combinations of speed and depth of operation were not significant ($P < 0.05$). As the depth of operation and forward speed of operation increase, the height of the bed also increases. The maximum height, 26.1 cm, was achieved at a depth and speed of operations of 20 cm and 2.9 km h^{-1} respectively. In contrary, the minimum height of the bed, was recorded at the lowest values of speed and depth of operations.

The achieved maximum height may be because of buildup of soil particles by more effective depth of operation. Hence, to achieve a maximum height, it is recommended to fix the speed of operation at 2.9 km h^{-1}. According to the ANOVA, the depth of operation is significant at five percent level.

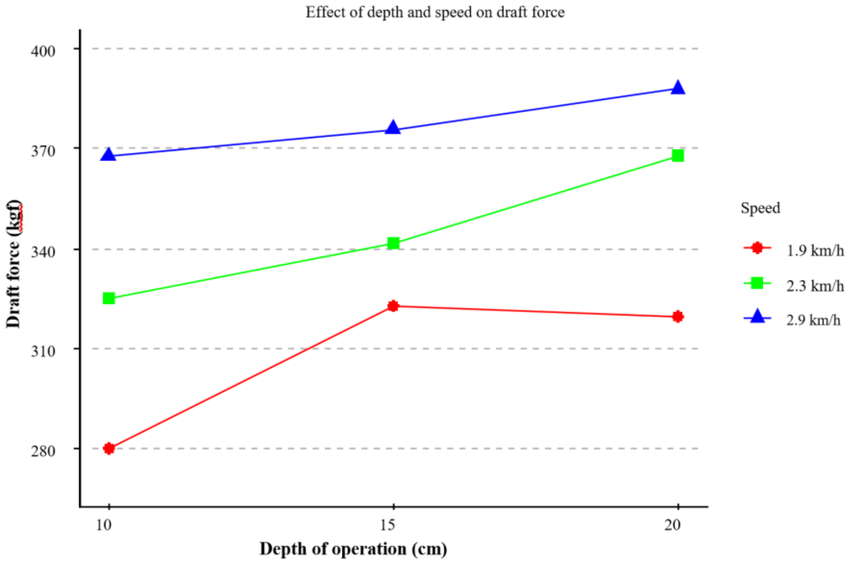


Figure 8 Effect of speed and depth of operation on the height of bed

Table 5 analysis of variance for the height of the bed with respect to different speed and depth of the operation

Source	DF	SS	MS	F	P
REP(A)	2	0.6067	0.3033		
Depth of operation(B)	2	33.8422	16.9211	21.21	0.0074
Error AXB	4	3.1911	0.7978		
Speed of operation(C)	2	22.8356	11.4178	19.20	0.0002
BXC	4	6.3956	1.5989	2.69	0.0825
Error AXBXC	12	7.1356	0.5946		
Total	26	74.0067			

Note: C.V = 3.38, DF = Degree of freedom, SS = Sum of squares, MS = Mean sum of squares, F = F-statistic, P = P-value

3.3.3 Draft of the implement

The analysis of variance for the best treatment combination yielding minimum draft of the implement with respect to operating speed and depth of operation are presented in Table 6. From the Table, it is inferred that the effect of treatment combinations of speed and depth of operations are significant ($P<0.05$).

As it is shown in Table 3 and Figure 9, the draft of the machine increased with an increase in operating speed and depth of operation. The maximum draft, 388.03 kg f, was achieved at a speed of operation of 2.9 km h^{-1} and a depth of operation of 20 cm. The minimum draft was 265.91 kg f at a speed of operation 1.9 km h^{-1} and depth of operation 10 cm. As speed and depth of operation increased volume of the soil mass per unit time through the bed maker was increased and therefore soil resistance was also increased which resulted in higher value of draft. The tractor requires more power at higher speeds to overcome more resistance developed at tractor and working place.

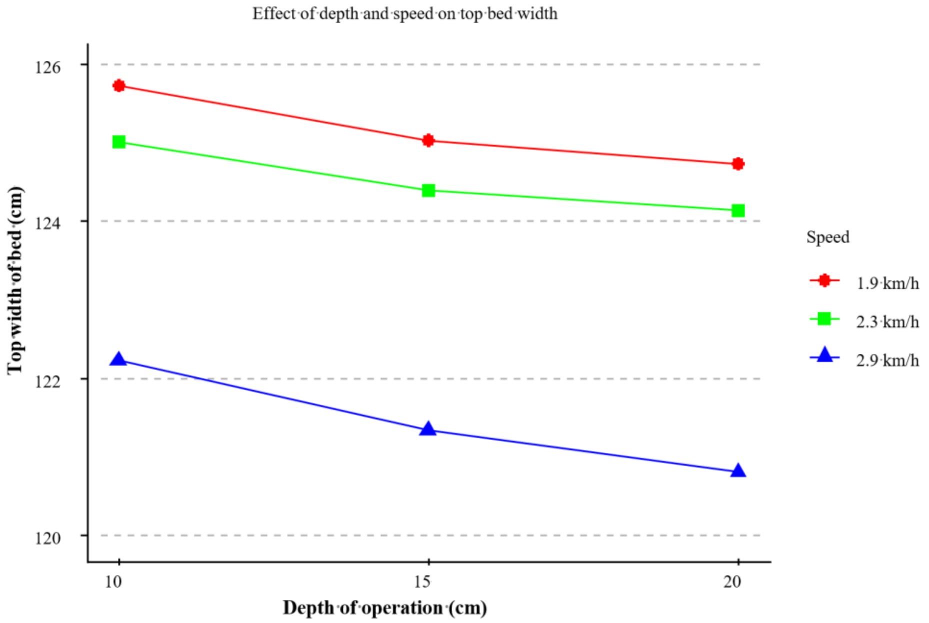


Figure 9 Effect of speed and depth of operation on the draft

Table 6 Analysis of variance for the draft

Source	DF	SS	MS	F	P
REP(A)	2	17.1	8.5		
Depth of operation(B)	2	5411.9	2705.9	53.80	0.0013
Error AXB	4	201.2	50.3		
Speed of operation(C)	2	22003.1	11001.5	327.37	0.0000
BXC	4	1400.6	350.2	10.42	0.0007
Error AXBXC	12	403.3	33.6		
Total	26	29437.1			

Note: C.V = 1.69, DF = Degree of freedom, SS = Sum of squares, MS = Mean sum of squares, F = F-statistic, P = P-value

It was also observed that the draft increased as the height of bed increased. This phenomenon is shown in the Table 3. The draft was maximum when the height of the bed formed was 26.1 cm. The maximum draft was achieved at a speed and depth of 2.9 km h^{-1} and 20 cm respectively.

The draft should be as minimum as possible to increase the field efficiency of the tractor operated bed former. As it is depicted in the graph, lower speeds of operations, 1.9 km h^{-1} and 2.3 km h^{-1} were considered better for much reduced draft. However, at the speed of operation of 1.9 km h^{-1}, the height of bed formed was very less which was not to the desired level for better leaching effect. Hence the speed of operation should be optimized at 2.3 km h^{-1}. Under these conditions, it is concluded that the optimum speed of operation is 2.3 km h^{-1} and depth of operation is 15 cm.

The reduced draft was achieved at intermediate levels of speed and depth of operation. This analysis was further treated by means of LSD All-Pairwise Comparisons Test of draft for depth and speed to find the most suitable combination of the operation. The test method reviewed sixteen subgroups of treatment (homogeneous groups), thus seven for the top width of the bed, five for the draft of the implement, and four for the height of the bed. Treatment combination S3D2 and S2D2 are in comparation from their average. Among these treatments, a speed of operation of 2.3 km h^{-1} and depth of operation of 15 cm was chosen as the most suitable combination. At those values of speed and depth, a reduced draft was achieved.

3.3.4 Wheel slippage

The data regarding the effect of different operational speed and depth on the wheel slippage are presented in Table 7. The mean wheel slippage of the tractor operated broad-bed maker was found as 6.36 percent. This may be due to the higher loading effect in broad-bed maker.

3.3.5 Fuel consumption

The data stated the effect of operating speed and depth of tractor on the fuel consumption were determined for the area of 300 m^2 and are presented in Table 8. From field data collected, the average fuel consumption was measured as 3.44 l ha^{-1}.

Table 7 Determination of wheel slippage

Trial number	Operational Speed (km hr^{-1}) and depth (cm)	Wheel revolutions at 50m distance covered		
		With load, rev.	Without load, rev.	Slip (%)
1	S1D1	9.25	9.00	9.52
2	S2D1	9.25	8.75	2.44
3	S3D1	9.50	8.5	10.52
4	S1D2	9.50	9.25	2.63
5	S2D2	9.75	9.25	5.12
6	S3D2	10.00	9.50	5.50
7	S1D3	9.50	9.00	5.00
8	S2D3	10.00	9.25	7.50
9	S3D3	10.5	9.50	9.50
	Mean	9.69	9.11	6.36
	SD	0.41	0.33	3.02
	CV (%)	4.23	3.66	47.49

Table 8 Fuel Consumption

Plot	Fuel Consumption	
	fuel consumption to cover 300m^2 (L)	fuel consumption (l ha^{-1})
1	0.15	5.00
2	0.09	3.00
3	0.07	2.33
Mean	0.31	3.44

Fuel consumed by broad-bed maker per unit area (l ha^{-1}) decreased as speed and depth of the operation increased.

3.3.6 Height and top width of the bed formed

The average height and top width of the broad-bed obtained with the broad-bed maker were 23.6 cm and 124.3 cm respectively. The results indicated that the height and top width obtained with the developed broad-bed maker are agreeable with the agronomic requirements of the proposed crop.

3.3.7 Time and labour requirement

The data concerning the effect of different speed and depth on the time to cover 1 ha area are presented in Table 9. Time consumed by the broad-bed maker per unit area (ha) decreased as speed of operation increased and depth of operation decreased.

Table 9 Time and labour requirements

Plot	Time and labour requirement		
	time to cover 300m^2 (sec.)	time to cover 1ha (h)	Number of labours
1	429	3.97	2
2	473	4.37	2
3	403	3.73	2
Mean	435	4.02	

The broad-bed maker requires two persons for manipulation and operation of bed making activity on the prepared land. The first person for operating the tractor and another person for adjusting the size of bed former as per the agronomic requirement of the crop.

3.3.8 Determination of field efficiency

The data concerning the effect of different parameter on the theoretical field capacity, effective field capacity and field efficiency to cover 1 ha area are presented in Table 10. The data of average effect of different speed on the theoretical field capacity, effective field capacity and field efficiency to cover 1 ha area are presented in Table 10.

Table 10 Theoretical field capacity, effective field capacity and field efficiency

Plot	Total time required to cover 300 m^2		Total time required to cover 1ha	Theoretical field capacity (ha h^{-1})	Effective Field Capacity (ha h^{-1})	Field Efficiency (%)
	In (sec.)	In (hr.)	In (hr.)			
1	429	0.119	3.97	0.285	0.252	88.42
2	473	0.13	4.37	0.345	0.231	67
3	403	0.112	3.73	0.435	0.267	62
Mean	435	0.12	4.02	0.355	0.25	72.5

Field efficiency of the broad-bed maker was determined using the Equation 8. The theoretical and actual field capacities of the broad-bed maker were respectively as 0.355 and 0.25 ha h^{-1}. Hence, the field efficiency of the broad-bed maker was 72.9 percent.

3.4 Cost economics

The broad-bed maker requires two individuals to operate effectively on prepared land. One skilled labourer operates the tractor, while the second person adjusts the bed former as needed to match the agronomic requirements.

The operational cost was analysed for the developed tractor operated broad-bed maker. Depreciation cost was calculated based on straight-line method. Operational cost for the machine along with tractor was calculated based on the assumptions made according to present day economic condition. The developed BBM was found to be operated at the cost of 379.40 Ethiopian birr (ETB) (2.68 USD) per hour. This is equivalent to 1,254.21 ETB (8.86 USD) per hectare. Considering the custom hiring cost as 20.1% more than the operation cost (Abiy et al., 2021), the actual operational cost was found to be 455.66 ETB (3.22 USD) per hour, i.e., 1,506.31 ETB (10.64 USD) per hectare. In case of providing custom hiring, the payback period of implement was found to be 1.54 years if implement works for 200 hours per year with operation cost of 76.26 ETB (0.54 USD) per hour. The cost of operation was calculated for the one who owns the tractor and machine. This operation cost could be comparatively higher when one hires both the tractor and machine. Moreover, the actual cost of operation changes periodically as the variable cost such as fuel and operator cost changes. The developed broad-bed maker demonstrated higher bed-making efficiency, reduced capital costs, and optimized resource utilization, collectively justifying its operational cost.

3.5 Cost estimation

The unit cost of a tractor drawn broad-bed maker was determined by calculating the cost of different components and their fabrication cost and summarized in Table 11.

Table 11 Cost Summary

No	**Cost variables**	Summary (in ETB)	Summary (in USD)
A	Raw material cost	14,421.28	101.87
B	Material wastage 2.5% of A	360.5	2.55
C	Production cost (machine + labour cost)	3,598.75	4.23
D	Overhead cost 5% of C	180	1.27
E	Profit 10% of (A+B+C+D)	1,856.05	13.11
F	Sells tax 15% of (A+B+C+D+E)	3,062.5	21.63
	Selling price	**23,479.08**	**144.66**

The result showed that the developed tractor drawn broad-bed maker worked satisfactory and therefore proposed its use for the bed making using 100 hp (74.57 kW) tractor.

4 Conclusion and discussion

The performance evaluation of the developed tractor-operated broad-bed maker (BBM) demonstrated its effectiveness in optimizing bed formation under different speed and depth conditions. The results indicated that both speed and depth significantly affected the bed dimensions, draft force, and overall field efficiency. The maximum bed height (26.1 cm) was obtained at 2.9 km h^{-1} and 20 cm depth, whereas the highest top width (126 cm) was recorded at 1.9 km h^{-1} and 10 cm depth. The inverse relationship between speed and top width suggests that lower speeds allow for better soil displacement, leading to wider beds, while higher speeds result in narrower formations due to increased soil resistance and displacement force.

The ANOVA revealed that both speed and depth had a significant effect on bed width and draft force ($p < 0.05$), confirming their critical role in machine performance. Draft force increased with both speed and depth, reaching a maximum of 388.03 kg f at 2.9 km h^{-1} and 20 cm depth. This increase can be attributed to the greater volume of soil being moved per unit time, which raises soil resistance and power requirements. Consequently, lower operational speeds (1.9 km h^{-1} and 2.3 km h^{-1}) resulted in reduced draft values, improving tractor efficiency.

Furthermore, the BBM exhibited an average field efficiency of 72.5%, which is considered suitable for mechanized agricultural operations. Fuel consumption was recorded at an average of 3.44 l ha^{-1}, demonstrating the machine's operational cost-effectiveness. Additionally, wheel slippage was maintained at 6.36%, which indicates stable traction and minimal energy losses during operation.

From an economic perspective, the BBM was found to have an operational cost of 1,254.21 ETB (8.86 USD) per hectare, with a payback period of 1.54 years when used for custom hiring. The reduced cost of bed-making and efficient utilization of resources further justifies the viability of the developed BBM for widespread adoption in vertisol-dominated regions.

Generally, the results suggest that the BBM can enhance soil and water management, particularly in Vertisol areas, by facilitating efficient seedbed preparation. Given its potential benefits, further research should focus on adapting the machine for different soil types, improving its structural durability, and promoting widespread adoption through farmer training and government support programs.

By integrating mechanized broad-bed technology into agricultural systems, farmers can achieve greater efficiency, lower production costs, and improved crop yields, contributing to sustainable and climate-resilient farming practices.

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