Development of a Reciprocating Weeding Machine for Cottage Crop Production

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ORIGINAL RESEARCH ARTICLE

Abstract- Weeding is currently still carried out manually in Nigeria and some of the African countries. This is despite the efforts that have been made to develop different types of weeding machines in Nigeria with different drive mechanisms, features and designs. Up to this point, no model or design have been commercialized but they remain in the prototype stage partly due to sophistication, poor quality and low efficiency. In this study, a prototype of motorised weeding machine, actuated by a reciprocating mechanism was designed and fabricated for use on most subsistent crops' plots. The reciprocation prevented the need to move the blades back and front as this action is automatically achieved in one process. The design features included 20° rake angle of the cutting blade, a working depth of 2.54cm and 28cm width of cut. Dimensions and the thickness of blades were designed according to the principles of general soil mechanics. Other machine elements were designed following PSG TECH procedures. After fabrication and assembly, the machine was tested on a 10m ×10m plot planted with maize and test result indicated a functional efficiency of 98%, quality performance efficiency of 82.7% and field capacity of 0.036m²/s as against 0.01m²/s with manual weeding. The material for the construction was sourced from locally available materials. The weeding machine has an effective cutting width of 27.5 cm and a production cost of NGN 175, 000.00.

Keywords- Cutting blade, machine design, PSG TECH procedures, reciprocating mechanism, soil -machine conditions, weeding,

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1 INTRODUCTION

Weeds are one of the leading causes of agricultural product loss. They compete for crucial nutrients with crops. In agriculture, physically weeding out undesired plants, as well as employing animal-drawn equipment, is a tough task that can result in crop damage. Weed growth among crops is quite common in Nigerian soils, especially during rainy seasons when soil moisture is high and plant growth conditions are high.

Weeds' stronger competitiveness compared to crops poses a severe danger to agriculture, resulting in lower crop yields, poor crop quality, the harbouring of plant pests and diseases, higher irrigation costs, livestock injuries, and a drop in land values. Weed Science of America (2019) reported that 50 to 70% of yield reduction is caused by poor weed control. Therefore, in order to improve crop production, weed control is a necessity. The methods employed in controlling weeds include biological, chemical, manual, laser weeding system and mechanical weeding. Manual weeding is most practised in Africa particularly in Nigeria where about 75% of the population is engaged in farming (Rodenburg et al, 2021]. This method is labour intensive and its one of the major problems of farming in Nigeria (Rodenburg et al, 2021; Thoskar, 2021).

Mechanical weed management is particularly effective because it reduces the drudgery of physical weeding, kills the weeds, and maintains the soil top loose, allowing for aeration and water intake. Weeding mechanically could help to retain removed weeds for manure/mulch purposes unlike chemical weeding which dries up the weed. Although tractor mounted weeders are very effective but they are expensive and could be difficult for the local farmers to afford. Chemical weeding is more common in industrialized countries than mechanical weeding (Pariona, 2017), however the problem of environmental deterioration, as well as the negative effects of chemical weeding on farmers' health and pollution (Buchanan et al, 2009), has caused the globe to reconsider the use of mechanical weeders.

A lot of efforts have been made in the past to develop weeders in Nigeria, many of the efforts have not been adopted by the end users i.e. the farmers (Ademosun, 1990; Manuwa et al, 2009; Ajewole & Elegbeleye, 2014; Olukunle, 2010; Fayose et al, 2018). This may be partly due to sophistication, poor quality and low efficiency. As part of the efforts to improve on the existing mechanical weeders, the design, fabrication and preliminary testing of a low-profile weeder whose cutting blade is actuated by the ground wheel traction through a reciprocating mechanism is described in this paper.

2 DESCRIPTION AND DESIGN CONSIDERATIONS OF THE WEEDER

2.1 DESCRIPTION OF THE MACHINE

The main frame, speed decreasing gear, wheels, reciprocating arms, blades, shafts, coupler and IC Engine are the major components of the weeder. The IC engine is coupled to a gear reducer that stepped down its speed at ratio 1 to 15. The crank shaft installed on the gear reducer

connects the connecting rod which drives the blade. This brings about the reciprocation of the blade carriage, which drives the blades. The blades, made of hard spring steel, are three in number and are arranged in such manner as to allow for an effective cutting width of 28cm, spreading a little beyond the width of the machine frame which is 27cm wide. The blades are replaceable when worn. The main frame and the blade carriage/gang where were of mils steel. The gang is equipped with four rollers to provide frictionless movement of the blades during operation. Length of the crank mechanisms comply with the conditions of four bar parallel crank mechanism (Europeana, 2013).

The reciprocation prevents the need to move the blades back and front as this action is automatically achieved in one process. The handle is of variable height to make weeding convenient for all operators irrespective of their heights. During the design and material selection stages, consideration was given to techno-economic status of the small-scale farmers in the rural communities who are the intended users of the machine. This machine is very simple to operate with little or no technical-know-how, neither does it constitute environmental hazards and could harvest the weeded material and retain them for manure/mulch purposes. Crops are produced on a minimum (25 cm × 25 cm) row spacing in this arrangement. The blades were designed with a 3cm cut overlap each row. All components of the weeder are made to be easily replaceable.

2.2 DESIGN CONSIDERATIONS
Cutting blades, crank shaft, reciprocating mechanism, steering shaft length, and sprocket and chain were all critical components to design for the mechanical weeder from a design standpoint. The factors considered and adapted for the effective design of the mechanical weeder include the following:

2.2.1 The Draft Requirement of the Blade
The draft requirement for the blade could be influenced by the following four factors according to Shahgholi et al (2019): soil/soil parameters, soil/metal parameters, implement shape and speed.

(a) Soil/soil parameters: From Coulomb's law, it is apparent that minimizing the normal load in frictional soils and the area in cohesive soils would minimize the soil shear strength and hence, the draft force. Vibrations can reduce the apparent normal load in frictional soils. Hence a reciprocating mechanism is utilized in this project to generate vibration.
(b) Soil/Metal parameters: Removing the rust from a tine by grinding can reduce angle of soil/interface friction.
(c) The blade's shape: The tine rake angle has a very large effect on the draft. The draft increases slowly from rake angles 10º to 50º. According to Godwin (2007), the rake angle of the cutting blade, should be greater than zero so as to achieve weed cutting below the soil surface and good disturbance of both sparsely and densely distributed weeds, but it should be as low as possible to minimize draught. Therefore, a rake angle of 20º was selected.

(d) Increased forward speed: speed increases draft with most implements, hence in this design, and from a work study, a speed of 1m/s was selected.

2.2.2 Type of cutting blade
The control of shallow weeds can be best achieved by cutting below them and lifting them onto the surface, and for this, a wide tine type of tool would seem to be the most appropriate. (Shahgholi et al 2019).

2.2.3 Soil condition
The soil conditions under which the machine will be adapted are cultivated medium soil to light soils. The soil is assumed to be stump free without stones and tough roots.

3 DESIGN ANALYSIS
The major design features are the cutting blades, reciprocating mechanism and the transmission system.

3.1 DESIGN ANALYSIS OF SOIL CUTTING BLADE
3.1.1 Design of cutting force and power requirement of blade
The draft requirement for the blade was determined according to the general soil mechanics equation as reported in Krishna et al., (2013). This equation (Eq 1) considers different soil properties as well as tool geometry to determine the soil force per unit width of the cutting blade. A wide tine model was selected for this blade according to Godwin & O'Dogherty (2007) where depth/width ratio < 5. A pre-design weeding operation was carried out to determine the appropriate rake angle. Rake angle of cutting blade $\alpha = 20°$.

According to Ademosun (1990), typical parameters of agricultural soils on which a metallic soil engaging implement can be applied are:
Angle of soil/interface friction δ, = 10º
Cohesion, c = 10-15kN/m²
Adhesion, $C\alpha$ = 3.5 kN/m²
Soil unit weight, δ = 17.3 kg/m³
Surcharge pressure, σ = 0
Maximum working depth of machine = 2.54 cm
Designed cutting width: 28cm, for three blades, each blade being 10 cm wide and the selected speed of operation = 1.5 m/s

The blades were designed on the basis of drag/forces acting on it (Godwin, 2007). The expression for the actual soil factor, N, is shown in equation 1 as applied in Krishna et al (2013).

$$N = N_{\delta=0} \frac{[N_{\delta=\phi}]^{\frac{\delta}{\phi}}}{[N_{\delta=0}]} \qquad (1)$$

Where N_δ is the soil weight factor.
The actual soil weight, cohesion and adhesion factors were estimated as 1.41, 1.86 and 0 respectively. The soil force per unit width of blade is estimated as shown in equation 2.

$$F_u = \sigma b^2 N_\sigma + C_0 b N_C \qquad (2)$$

Where Fu is soil force per unit width, kN/m

$N\sigma$ is the adhesion factor.
Nc is the cohesion factor
$F_u = 0.488 \, kNm^{-1}$

The draft per unit width of blade D_u is estimated as shown in equation 3:

$$D_u = F_u \sin(\alpha + \delta) + b \, C_\alpha \cot\alpha \tag{3}$$
$D_u = 1.1423 \, kNm^{-1}$
Total Draught = $D_U = 1.1423 kNm^{-1} \times$ width of blades, = 0.33 kN
Power requirement = Force × velocity. Assuming a velocity of 1.5 m/s and a factor of safety 2.5, then the required power for blades cutting = 1.3 kW

3.1.2. Design of the Cutting Blade

The design of blades would help to determine the thickness of the blade that would prevent it from bending during operation. From the soil model, when $\delta = 0$, then $m = 3.40$ then when $\delta = \phi = 30^0, m = 3.45$. where m is the soil rupture distance ratio. Applying similar analysis as applied for soil factor, the actual soil rupture distance ratio is 3.4165.

Therefore, the actual weed rupture distance, f, is $8.68cm$. Considering the soil directly on top of the cutting blade in Figure 1, from point 0, the centroid of the section OBCD, $\bar{X}$ is given by equation 4, according to Khurmi & Khurmi (2006).
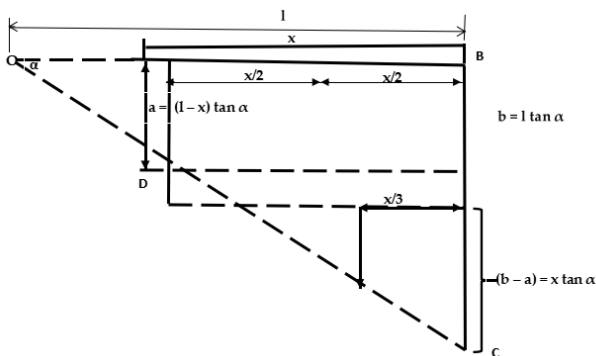

Fig. 1: Analysis of the centroid of the tine.

$$\frac{x}{2}(a + b)\bar{X} = ax.\frac{x}{2} + \frac{1}{2}(b - a) x \times \frac{x}{3} \tag{4}$$

$i.e.$ $\bar{X} = \dfrac{(2a + b)x}{3(a + b)}$

$\bar{X} = \dfrac{(2(l - x) \tan\alpha + l \tan\alpha)x}{3(l - x) \tan\alpha + l \tan\alpha)}$

$\bar{X} = \dfrac{(3l - 2x)x}{3(2l - x)}$

If the load intensities at points 0 and A are respectively w_0 and w_a, the average load intensity over the length $l = \dfrac{W_0}{2}$

Then, the total vertical force on the blade, v_t, is given by
$V_t = \dfrac{W_0 l}{2}, \therefore W_0 = \dfrac{2V_t}{l}$
Also, the average load intensity over the length x:

$$= \frac{W_0 + W_a}{2}$$
Since $\dfrac{W_a}{L - x} = \dfrac{W_0}{L}$
$i.e.$ $W_a = \dfrac{W_0(l - x)}{l}$
Therefore,
the average load intensity over the length x $= \dfrac{2W_0 l - W_0 x}{2l}$

Total load acting over the length x $= \dfrac{(2W_0 l - W_0 x)x}{2l}$
$i.e.$ The shearing force at point A $= \dfrac{-W_0 x(2l - x)}{2l}$
The bending moment at point A $= \dfrac{-W_0 x(2l - x)(x - (3l - 2x)x)}{6l(2l - x)}$

$$= \frac{-f x^2 (3l - x)}{6l}$$
At $X = 1$, the bending moment at point A $= \dfrac{-Fl^2}{3} = \dfrac{2}{3}V_t l$
$i.e.$ The bending moment for the blade of length L is given as $M_b = \dfrac{2}{3}V_t \cos\alpha L$
The total vertical force on the blade in equation 5
$$V_t = W(F_u \cos(\alpha + \delta) + b c_\alpha \tag{5}$$
$V_t = 4.914 \times 10^{-2} KN$.
Hence, the bending moment for the blade, M_b, is calculated as shown in equation 6
$$M_b = \frac{2}{3}V_t \cos\alpha L \tag{6}$$
$M_b = 9.51 \times 10^{-3} KNm^{-1}$.
From bending stress equation in equation 7,
$$I = \frac{M_b h}{2\sigma} = \frac{W h^3}{12} \tag{7}$$
$$h = \left(\frac{12 M_b}{2\sigma w}\right)^{0.5}$$
where, w is the width of the blade.
h is the thickness of the blade.
σ is the normal stress.
Therefore, the actual thickness of the blade as shown in equation 8 is:
$$h = c \left(\frac{12 M_b}{2\sigma w}\right)^{0.5} \tag{8}$$
Where c is the factor of safety.
Thickness of blade, $h = 2.88mm$.

3.3 DESIGN OF THE TRANSMISSION SYSTEM

The transmission system consists of the crankshaft, and the axles. The axle rotates with the wheels. A speed reducing gear with ratio 20:1 which transmit power from the electric motor is installed at the centre of the crankshaft and this transmits motion to the cranks at its two ends. The cranks provide the reciprocating motion that drives the cutting blades. The components of the transmission system are designed based on the procedures of the design data by PSG Tech. (2016) and Hall et al (2017).

The resultant bending moment and torsional moments of the axle were determined to be 36.8Nm and 25.13 Nm respectively. The diameter of the axle was calculated to be 18 mm. The resultant bending moment and torsional moments of the crankshaft were determined to be 81. 03 Nm and 71.625 Nm respectively. The diameter of the axle was calculated to be 25 mm. A 4 kW IC engine was used.

3.4 DESIGN OF THE RECIPROCATING MECHANISM

The design of the reciprocating mechanism, involves the determination of the optimum length of crank that will allow for weeding with minimum overlapping of the weeding surface and also the travel speed correlating with reciprocating motion of the cutting blade.

Diameter of the wheel = 40 cm,
Designed speed of travel = 2 m/s,
Let the length of crank be x cm
The distance covered by the wheel at 1 revolution = $\pi \times 40cm = 126cm$.
But engine speed = 3000rpm.
The speed ratio of the reducing gear =15 : 1.
Therefore, the rpm of the crank, which is attached to the shaft from the reducing gear =200rpm.
If the speed of rotation of crank, n_c is 5 times that of the wheel. Hence, when $\pi w = 1 revolution = 126cm$.
$\qquad n_c = 5$ revolution of blades $= 10 strokes$
i. e in 1 revolution of crank $= 2 strokes$ of the blade
Therefore, the wheel covers $= \frac{126cm}{5} = 25.2cm$.

To attain an overlap of 3cm of cut by the blade, the total length travel of the blade should exceed the distance covered by the wheel. i.e. $25.2cm + 3cm = 28.2cm$ (Adesoji, 1990).

Therefore, $x \rightarrow 3 + (2x) = 28.2cm$
x, the lenght of crank $= \frac{25.2cm}{2} = 12.6cm$.

3.5 PRODUCTION COST

The cost of production of the machine was estimated according to Fayose et al (2017). This include the cost of bought-out components, e.g. the 4 kW IC engine, cost of the materials used in the fabricating the various components of the machine, cost of machining and non-machining jobs.

4 PRELIMINARY MACHINE TESTING

The components of the test carried out on the weeder include the width of cut, the overlap of cut and the depth of cut of the weeding machine. Thereafter, the field capacity of weeding, the weeding efficiency, the quality performance efficiency and the operator's drudgery were determined.
The width, overlap and depth of cut were randomly measured by a steel rule. The field capacity, the functional efficiency (E_f), the quality performance efficiency (E_q) were estimated according to Igbeka (2001) as follows in equations 9 and 10.

$$E_f = \frac{\text{Weight of weeds removed on the farm}}{\text{Actual weight of weeds}} \times 100 \qquad (9)$$

$$E_q = \frac{P_o - P_d}{Pm} \times 100\% \qquad (10)$$

where P_o is the total weeds removed, P_d - no of bruised maize stalk, P_m is total no of weeds on the quadrant.

The Field capacity = Area weeded/time taken

The drudgery involved in the use of the equipment by the operator was measured by taking their pulse (heartbeat rate) before and after the weeding operations. A plot 10m × 10m in size planted to maize was used. The weeding was done manually and with use of the machine. After weeding the cut and surviving weeds were collected separately and measured. Time taken to complete each weeding operations was noted. Each experiment was replicated thrice.

5 RESULTS AND DISCUSSION

The engineering drawings of the machine are shown in Figures 2 to 4 while the picture of the machine is shown in Figure 5. The results of the tests carried out showed that the effective cutting width, overlap of cut and depth cut of the machine were 27.50, 3.00 and 2.06 cm respectively while the functional and quality performance efficiencies of the machine were 98.2 % and 82.7 %. The field capacity for the machine was 0.036m²/s while that for manual weeding was 0.01m²/s. These results compare favourably well with result from previous works (Manuwa et al., 2009; Ajewole and Elegbeleye, 2014). Also, the result is preferred to soil degradation caused by wrong use of chemicals in the communities since mechanical weeding keeps the soil surface loose by producing soil mulch which results in better aeration and moisture conservation (Shridhar 2005). A rake could be attached to the back of the blades to pack the weeded materials from the weeded plots to improve the efficiency of the machine. The reason for the above performance could be due to occasionally slips, function of speed, rough and uneven ground terrains.

The level of exertion was 26.33/mm for the machine where as it is 28.3/mm for manual weeding. These exertion levels are quite high both for machine and manual weeding. The following reasons might be responsible for this high exertion level of the machine: The machine is difficult to be turned right or left during operation. This problem can be solved by providing a steering mechanism for the machine. Also, the weight of the machine is high, making it difficult to be pushed manually. To overcome this problem, the mild steel that were used could be replaced with aluminium alloy materials on various identified components of the machine where loads are not concentrated.

Moreover, the use of sensing, control, automation and mechanization technologies have been an important means for increasing agricultural productivity, improving worker health and safety, optimizing resource utilization, and reducing labour requirements (Shamshiri et al 2018). Latest technologies should be explored to reduce high energy requirements of indigenous machines for small scale farming. A unit of the machine costs NGN 175, 000.00. This can be reduced if the machine is produced en masse and preferable to imported machines which may not be easy to repair due to complexity of designs.
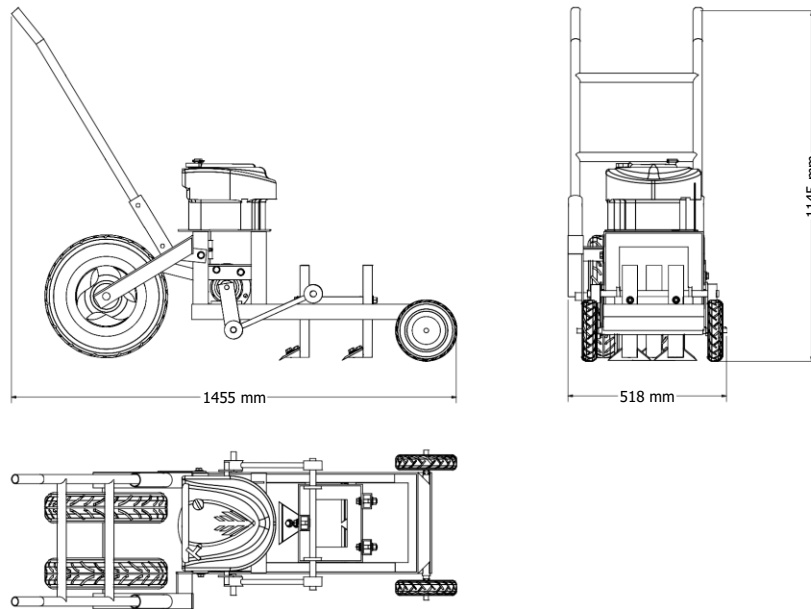
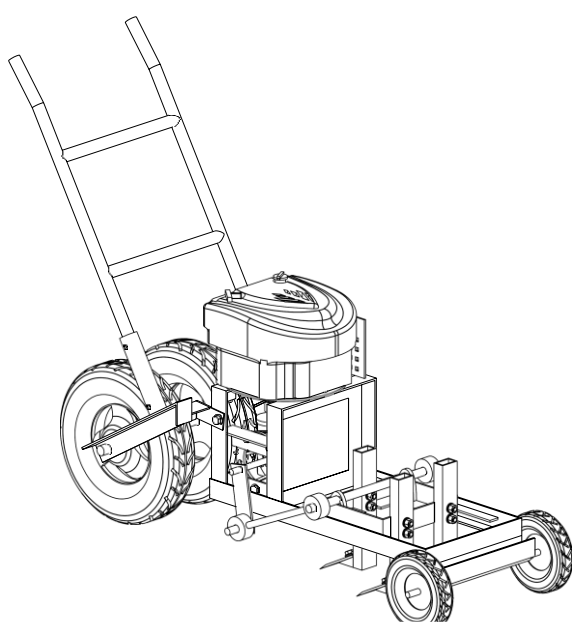Fig. 2: Orthographic drawing of the machine

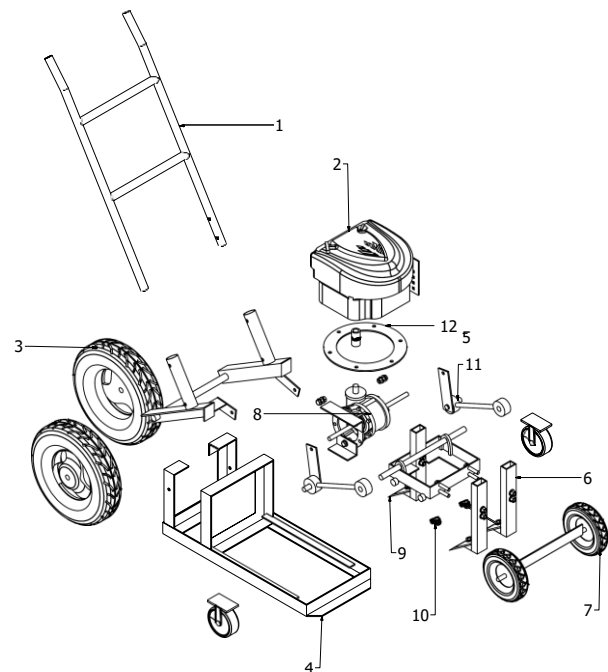Fig. 3: Isometric drawing of the weeding machine

Fig. 4: Detailed/exploded view of the weeding machine (LEGEND: Handle, IC Engine, Back Wheel, Frame, Coupling, Blade Arm, Front Wheel, Gear box, Blade, Bolt and Nut, Crank shaft, Engine Seat

Fig. 5: Preliminary testing of machine

6 CONCLUSION

A reciprocating weeder was designed and fabricated for small scale production of crops. Preliminary test result indicated a functional efficiency of 98.2%, and a quality performance efficiency of 82.7%. A field capacity of 0.036m²/s was attained by the machine as against 0.01m²/s with manual weeding. 4-kW IC engine, the weeding machine has an effective cutting width of 28 cm. The performance of the weeder could be improved by using sensors and automation to control its operation. Other suggestions to improve the performance of the machine are provided in the report.

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