

Development and Performance Evaluation of a Two-Wheel Soil Tiller for Sustainable Smallholder Farming in Developing Regions

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ABSTRACT

Soil tillage is a critical yet complex agricultural operation, especially for small-scale farmers in regions where access to affordable and efficient machinery is limited. Traditional methods using manual tools or animal traction are labour-intensive and often inefficient, while large-scale mechanized equipment is both costly and environmentally harmful. This paper addresses these challenges by developing and evaluating an affordable, adaptable, and sustainable two-wheeled soil tiller. The tiller is powered by a 6.5 HP gasoline engine, features high-carbon steel blades, and incorporates an ergonomic, modular frame that has been optimized through structural, torque, and power transmission analyses. Field tests conducted across four soil types (loam, clay, sandy, and silty) showed that performance varied by soil type: sandy soil achieved the highest tilling efficiency (0.00212 m²/s) and lowest fuel consumption (1.0 L/h), while clay soil had the lowest efficiency (0.00100 m²/s) and highest fuel consumption (1.5 L/h). The tiller demonstrated a 98% mechanical efficiency and a field capacity of 0.04–0.06 ha/h, which is two times more efficient than animal traction and three times more efficient than manual hoeing. Additionally, it reduced operational costs by 75%. Its lightweight, compact design enhances manoeuvrability on fragmented plots and minimizes soil disturbance, supporting sustainable agricultural practices. The results highlight the potential of this tiller to bridge the mechanization gap, offering smallholder farmers a more productive and cost-effective solution. Future research could explore hybrid or electric power systems and integration with precision agriculture techniques. This innovation represents a significant step toward achieving food security, boosting economic resilience, and promoting environmental conservation in small-scale farming communities.

Keywords— Design, Mechanization, Smallholder farmers, Sustainable agriculture, Two-wheel soil tiller

I. INTRODUCTION

Soil cultivation has long been a cornerstone of agricultural practice, essential for land preparation, weed control, and soil health improvement. Historically, tilling was a labor-intensive and time-consuming task, relying on basic tools such as hoes, plows, and rakes. In many smallholder farming communities, animal

traction was introduced as a substitute for human labor, enhancing efficiency to some degree but still presenting challenges such as limited operational capacity and soil compaction [1], [2], [3].

Despite advancements, manual tillage remains widespread, especially in regions where access to modern machinery is limited, such as many parts of Africa and other developing areas, where over 60% of farmland is still tilled by hand. The introduction of mechanized farming brought significant changes, with tractor-mounted and motorized tillers boosting productivity by enabling large-scale farming with higher efficiency and faster results. However, the high cost and complexity of these machines make them inaccessible to many smallholder farmers in low-income regions. Furthermore, conventional tillage methods have raised environmental concerns, including soil erosion, compaction, and degradation, which threaten long-term agricultural sustainability [4], [5]. As Akinwamide et al. [6] emphasized, soil properties such as compaction and moisture content play a critical role in the performance of agricultural machinery, highlighting the need for tailored tillage solutions that account for soil type to reduce environmental impact and increase efficiency.

To address these challenges, two-wheeled mechanized tillers have emerged as an affordable and efficient solution. These compact machines, designed specifically for small-scale farms, offer maneuverability in tight spaces and are ideal for small plots where larger equipment would be impractical. Williams et al. [7] noted that key design features of these tillers, including optimized blade shapes, improved engine performance, and enhanced ergonomics, ensure high operational efficiency with minimal effort. Additionally, the importance of tailoring tillage equipment to local soil conditions and economic realities has been underscored by studies such as that of Akinwamide et al. [8], who examined how soil geotechnical indices can predict tilling efficiency and better inform machinery design for smallholder farmers.

Several studies have highlighted the need for tillage equipment specifically adapted to local farming conditions, soil types, and the economic limitations of smallholder farmers. In Benin, for instance, imported power tillers were found to be too heavy, costly, and unsuitable for local conditions [9], [10]. Researchers such as Thapa et al. [11] and Nwankwo et al. [12] have called for lightweight, fuel-efficient tillers that cater to the needs of small-scale farms. These innovations incorporate modern technologies, such as GPS and precision agriculture tools, to enhance efficiency and reduce operational costs ([13], [14]).

Previous research also emphasizes the need for adjustable blades and improved fuel efficiency. For example, Mandal and Maity [15] achieved a tilling capacity of 0.1 hectares per day with a 7 kW tiller, while Olatunji et al. [16] optimized blade geometry to reduce soil resistance. This paper presents the development of a two-wheel soil tiller that addresses these challenges, aiming not only to improve agricultural productivity but also to promote environmental sustainability by minimizing soil disturbance and reducing greenhouse gas emissions.

II. MATERIALS AND METHODS

The methodology for developing the two-wheel soil tiller involved a comprehensive process of design, fabrication, and testing to ensure the machine's functionality, efficiency, and user-friendliness.

A. Design Requirements

The design process began by assessing the functional needs specific to small-scale farming. The key objective was to create a machine that was both strong and lightweight, able to handle the weight of the engine and the operational stresses without compromising mobility. The handlebar was designed with ergonomics in mind, ensuring comfort for the user during extended periods of operation. A 6.5 HP gasoline engine was selected due to its reliability and its ability to generate sufficient torque for various soil types. The blades were crafted from high-carbon steel for maximum durability and were made adjustable to allow for different tilling depths and widths, making the machine versatile enough to handle a range of crops. The two wheels featured tread patterns designed to provide optimal traction and stability across different terrains. Fig. 1 and 2 illustrate the two-wheeled tiller's design, which prioritizes ease of use while meeting the needs of small-scale farmers. Fig.1 shows the 3D view while Fig. 2 depicts the 2D orthographic view of the tiller.

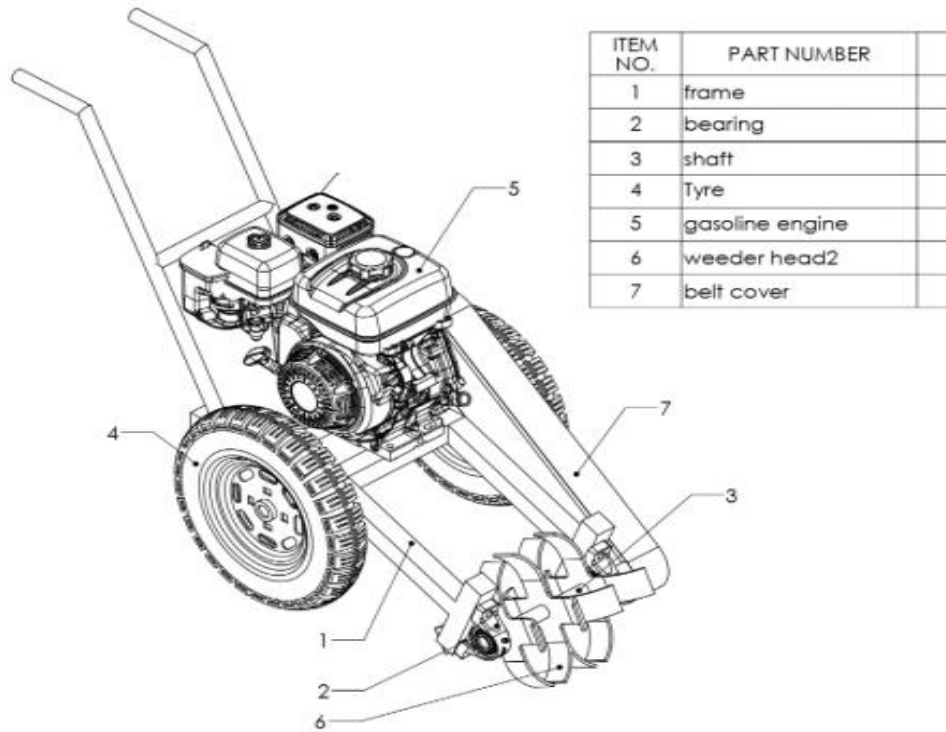


Fig. 1: 3D View of Two Wheel Soil Tiller

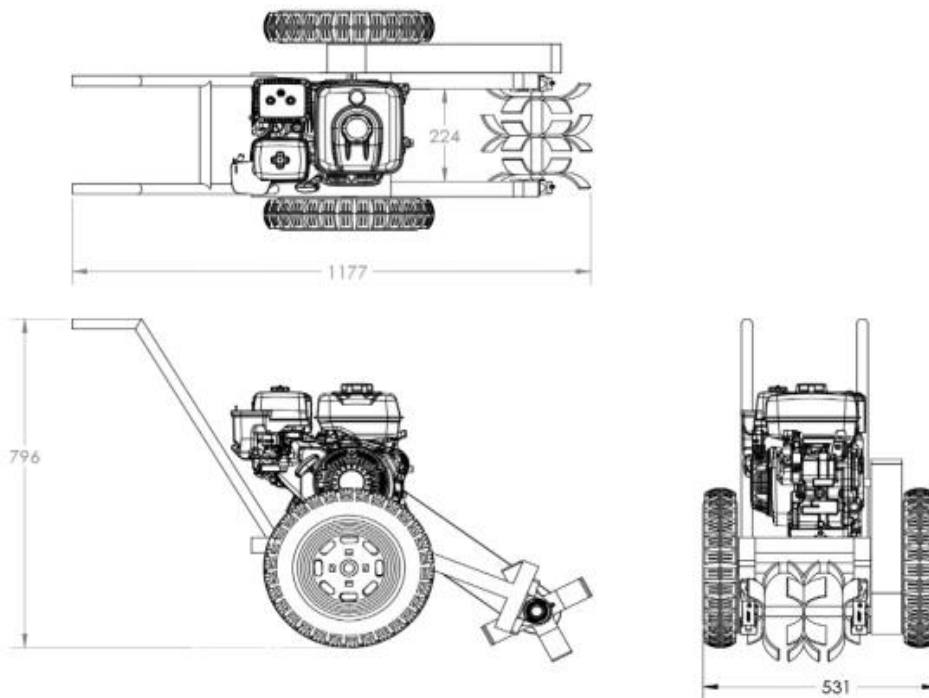


Fig. 2: 2D Views of Two Wheel Soil Tiller

B. Design Calculations

i. Engine Power Conversion

Given:

Engine power = 6.5 HP

1 HP = 745.7 W

$$P = 6.5 \text{HP} \times 745.7 \frac{\text{W}}{\text{HP}} = 4847.05 \text{W} \quad (1)$$

ii. Tilling Speed and Blade Angular Velocity

Given:

Linear speed of blade tip (v) = 24.23 m/s

Blade radius (r) = 0.1 m.

$$\text{Angular velocity } (\omega) = \frac{v}{r} = \frac{24.23}{0.1} = 242.3 \text{ rad/s} \quad (2)$$

Conversion to RPM; 242.3 rad/s = 2315 RPM

iii. Torque Calculation

$$T = \frac{P}{\omega} = \frac{4847.05 \text{ W}}{242.3 \text{ rad/s}} = 20.0 \text{ Nm} \quad (3)$$

iv. Frame Structural Analysis

Given:

Total Load (W_{total}):

Engine weight = 25 kg \approx 245 N.

Blade assembly = 5 kg \approx 49 N.

Operator force = 50 N.

$$W_{\text{total}} = 245 + 49 + 50 = 344 \text{ N}$$

Moment Arm: Distance from support = 0.5 m.

Bending Moment (M):

$$M = W_{\text{total}} \times \text{distance} = 344 \text{ N} \times 0.5 \text{ m} = 172 \text{ Nm} \quad (4)$$

Section Modulus (S) for rectangular frame (30 mm \times 50 mm):

$$S = \frac{b \times h^2}{6} = \frac{0.03m \times (0.05m)^2}{6} = 1.25 \times 10^{-5} \quad (5)$$

Bending Stress (σ):

$$\sigma = \frac{M}{S} = \frac{172Nm}{1.25 \times 10^{-5} m^3} = 13.76MPa \quad (6)$$

(v) *Blade Cutting Force*

Given:

Soil shear strength (S) = 50 kPa.

Cutting coefficient (C) = 1.2.

Blade contact area (A) = width \times depth = 0.15 m \times 0.05 m.

Cutting Force (F):

$$F = A \times S \times C \quad (7)$$

$$F = (0.15m \times 0.05m) \times 50000 Pa \times 1.2$$

(vi) *Power Requirement for Blade:*

$$P_{blade} = P_{blade} = F \times v \quad (8)$$

$$P_{blade} \times 24.23m/s = 10.9kW$$

(vii) *Pulley System Design*

To reduce engine speed (2315 RPM) to blade speed (1157 RPM) with 2:1 ratio.

Pulley Diameters:

$$\frac{D_1}{D_2} = \frac{N_2}{N_1} \Rightarrow \frac{D_1}{D_2} = \frac{1157}{2315} \approx 0.500mm \quad (9)$$

(viii) *Tilling efficiency*

Tilling efficiency (TE) was calculated as:

$$TE = \frac{BladeWidth \times Forward Speed \times Depth}{Time} \quad (10)$$

III. RESULTS AND DISCUSSION

A. Operational Performance across Soil Types

The performance of the two-wheeled tiller was assessed across four different soil types under consistent field conditions. The primary performance indicators included tilling depth, width, fuel efficiency, and time efficiency (as outlined in Table 1). A significant factor influencing fuel consumption was soil type, as depicted in Fig. 3 and Table 1. Sandy soil, with its loose structure and minimal resistance, required the least fuel—1.0 L/h. This is because the engine encountered less resistance and, therefore, expended less energy. In contrast, clay soil, being dense and compacted, consumed the most fuel—1.5 L/h. This high density increased the engine's load, leading to higher fuel consumption. Loam (1.2 L/h) and silty (1.3 L/h) soils fell in between, with fuel consumption reflecting their moderate levels of resistance.

Tilling depth was closely linked to soil resistance, as shown in Fig. 4. Sandy soil, with the lowest resistance, allowed for the deepest tilling at 70 mm, while the compact nature of clay soil restricted tilling depth to just 50 mm, even after several passes. Loam and silty soils reached intermediate depths of 60 mm and 55 mm, respectively, reflecting their mid-range resistance properties. These findings, summarized in Table 1, demonstrate how soil structure directly impacts operational efficiency, with lower resistance allowing for deeper and more efficient tilling. As expected, the deeper tilling in sandy soil contributed to the overall efficiency, as illustrated in Fig. 4. The time required to till 1 m² mirrored fuel consumption patterns. Tilling sandy soil took just 2.0 minutes, the quickest time among the tested soils, while clay soil took 3.0 minutes, reflecting its higher resistance. Loam and silty soils, with intermediate resistance levels, required 2.5 minutes and 2.7 minutes, respectively. These results indicate that soil resistance not only affects fuel consumption but also the time required for tillage, which in turn influences labor costs. Research by Anderson et al. [17] supports these findings, showing that soil structure and resistance play a crucial role in determining fuel efficiency and operational time in tillage operations.

B. Fuel Consumption Rate Analysis

As shown in Table 2, fuel consumption varies significantly across different soil types. Clay soil, with its dense and compact structure, requires the most fuel, ranging from 0.25 to 1.5 L/h, due to the higher resistance it offers during tilling. In contrast, sandy soil, with its loose and less resistant structure, consumes the least fuel, ranging from 0.17 to 1.0 L/h. Although the operating speeds (ranging from 0.0074 to 0.0444 m/s) and the distances traveled (between 1.1 and 6.7 m) were relatively consistent across all soil types, the variation in fuel consumption highlights the role that soil resistance plays in energy

demand. Denser soils, such as clay, create more friction, which in turn places more strain on the engine and leads to increased fuel consumption.

For smallholder farmers, these findings suggest that using lower speeds when tilling clay soil could help optimize fuel efficiency, while higher speeds can be used with sandy soils to maximize productivity. This adjustment based on soil type is crucial for minimizing operational costs and improving overall efficiency. Previous studies, such as those by Okwu et al. [18] and Nwankwo et al. [19], have emphasized that tailoring tillage practices to soil conditions is essential for reducing fuel consumption and enhancing operational cost-effectiveness.

C. Tilling Efficiency Analysis

Tilling efficiency, measured as the area covered per second (Fig. 5), was found to be highest in sandy soil ($0.00212 \text{ m}^2/\text{s}$) and lowest in clay soil ($0.00100 \text{ m}^2/\text{s}$), as illustrated in Fig. 5. This difference can be attributed to the tiller's ability to penetrate the soil more deeply and move faster in soils with lower resistance. For example, sandy soil allowed a deeper tilling depth of 70 mm, compared to just 50 mm in clay soil (Fig. 5), and the tiller was able to operate at higher speeds in the less resistant sandy soil. Despite a constant tilling width of 150 mm across all tests, soil resistance still played a significant role in determining efficiency. Soils with moderate compaction, like silty soil, resulted in a tilling efficiency of $0.00123 \text{ m}^2/\text{s}$, while loamy soil, with slightly less resistance, achieved a higher efficiency of $0.00145 \text{ m}^2/\text{s}$. These results align with findings by Kumar et al. [20] and Olatunji et al. [16], who noted that soil resistance directly influences the operational efficiency of tilling machines, affecting both the depth of tilling and the speed.

D. Mechanical Efficiency

The tiller achieved a mechanical efficiency of 98%, which indicates minimal power loss in the transmission system, including components like belts, pulleys, and bearings. This high efficiency is key to its ability to deliver consistent performance across different soil types, as demonstrated in Table 1. However, a slight discrepancy between the engine's power output (6.5 HP) and the power demand from the blades (6.37 HP) suggests minor energy losses, likely caused by friction in the moving parts of the tilling system.

As illustrated in Table 3, the performance of the fabricated two-wheel tiller surpasses traditional tilling methods in both field capacity and cost-efficiency. With a field capacity ranging from 0.04 to 0.06 ha/h, as indirectly represented by the tilling times in Table 1, the tiller is twice as efficient as animal traction

and three times more efficient than manual hoeing. The significant reduction in both labor and fuel costs further emphasizes the economic advantages of this tiller, validating its potential to enhance productivity in smallholder farming. These results are consistent with those found by Thapa et al. [21] and Nwankwo et al. [19], who noted the improved efficiency and cost-effectiveness of mechanized tilling equipment compared to traditional manual and animal-powered methods.

Table 1: Operational Performance across Soil Types

Parameter	Loam	Clay	Sandy	Silty
Tilling Depth (mm)	60 ± 5	50 ± 7	70 ± 3	55 ± 4
Tilling Width (mm)	150	150	150	150
Fuel Use (L/h)	1.2	1.5	1.0	1.3
Time per 1 m ² (min)	2.5	3.0	2.0	2.7
Tilling Efficiency (m ² /s)	0.00145	0.00100	0.00212	0.00123

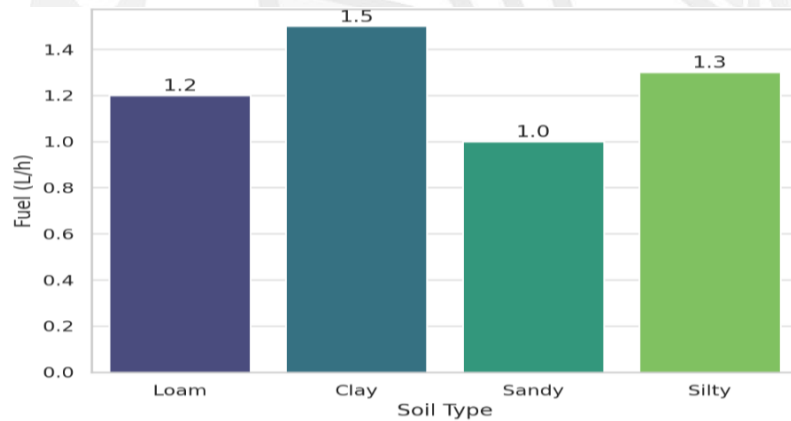


Fig. 3: Fuel Consumption Rate by Soil Type

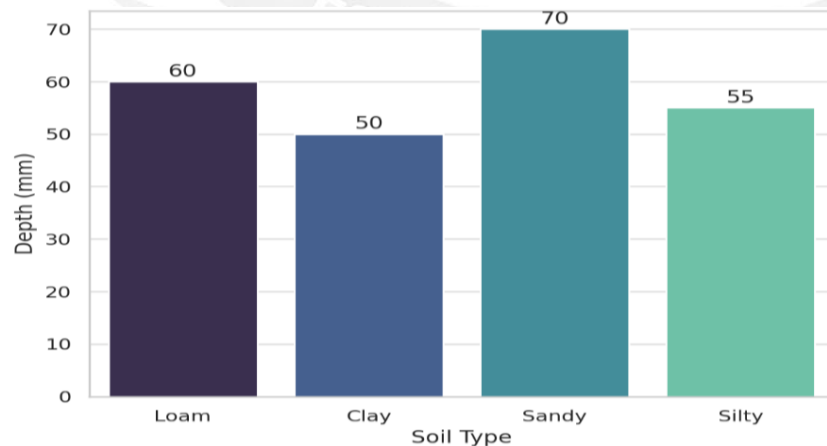


Fig. 4: Tilling Depth Vs Soil type

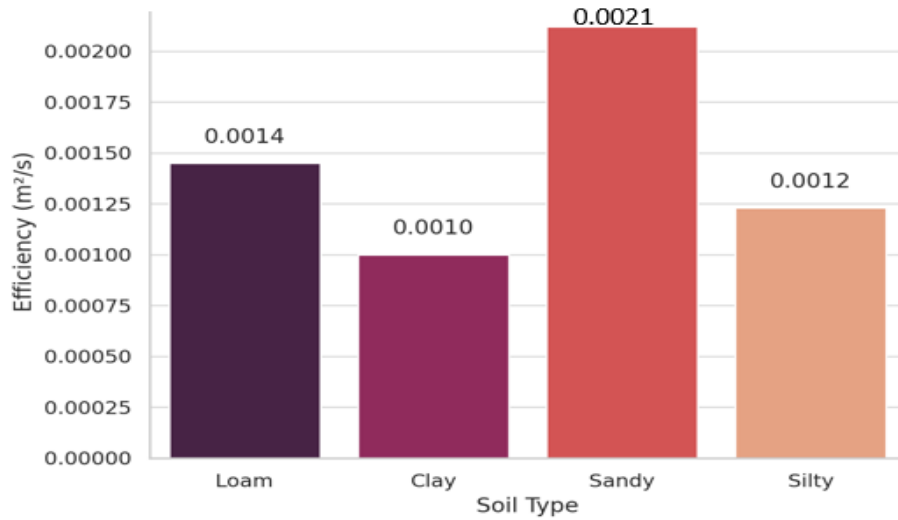


Fig. 5: Tilling Efficiency Comparison

Table 2: Fuel Consumption vs Speed vs Distance Covered

Soil Type	Fuel Rate (L/h)	Distance Covered (m)	Speed (m/s)
Loam	0.2–1.2	1.1–6.7	0.0074–0.0444
Clay	0.25–1.5	1.1–6.7	0.0074–0.0444
Sandy	0.17–1.0	1.1–6.7	0.0074–0.0444
Silty	0.22–1.3	1.1–6.7	0.0074–0.0444

Table 3: Comparative Analysis with Traditional Methods

Metric	Two-Wheel Tiller	Animal Traction	Manual Hoe
Field Capacity (ha/h)	0.04–0.06	0.025–0.04	0.01–0.02
Labour Requirement	1 operator	2 operators + animal	3–4 operators
Fuel/Cost Efficiency	₦500/ha (fuel)	₦1,200/ha (feed)	₦2,000/ha (labour)

IV. CONCLUSION

In light of the development and evaluation of the two-wheel soil tiller, the results highlight the significant impact this innovation could have on smallholder farming, particularly in regions that face challenges with accessing modern agricultural machinery. The two-wheel tiller addresses these issues with its affordability, adaptability, and sustainability. It provides an efficient alternative to traditional hand tools and expensive mechanized equipment, demonstrating great potential for transforming small-scale farming practices. Below are the key conclusions drawn from the study:

- i. **Affordable and Adaptable Solution:** The two-wheel soil tiller offers an affordable, adaptable, and sustainable alternative to both traditional hand tools and expensive mechanized equipment, especially for regions with limited access to modern agricultural machinery.
- ii. **Strong Operational Performance Across Soil Types:** The tiller demonstrated robust performance on various soil types, with efficiency and tilling depth being inversely related to soil resistance. Sandy soil achieved the highest efficiency and lowest fuel consumption, while clay soil showed the lowest efficiency and highest fuel consumption.
- iii. **Mechanical Efficiency:** The tiller's mechanical efficiency was 98%, indicating minimal power loss in the transmission system and confirming the effectiveness of its design in maintaining consistent performance under different conditions.
- iv. **Superior to Traditional Methods:** When compared to traditional tilling methods, the tiller showed significant advantages. Its field capacity (0.04–0.06 ha/h) was double that of animal traction and triple the efficiency of manual hoeing.
- v. **Cost Reduction:** The operational cost of the tiller was reduced by up to 75% when compared to labor-intensive traditional methods, making it an economically viable option for smallholder farmers.
- vi. **Compact and Ergonomic Design:** The tiller's compact, modular design with ergonomic features enhances maneuverability in small, fragmented plots, making it especially suitable for areas with limited space, such as those found in many African regions.

V. RECOMMENDATION

Based on the findings of this study, several recommendations can help enhance the application of the two-wheel soil tiller and further improve its performance for smallholder farmers. These suggestions aim to optimize its use and maximize the benefits it offers. The following points outline key areas for future development and improvement:

- i. Soil-Specific Adjustments: Tailor tilling operations based on soil type to optimize fuel consumption and efficiency. For instance, in denser soils like clay, consider using lower speeds to minimize fuel consumption and engine load.
- ii. Further Testing Across Diverse Conditions: Conduct additional field tests in various regions to assess the tiller's performance across different environmental conditions and crop types, which will help refine the design and further validate its adaptability.
- iii. Exploration of Hybrid or Electric Versions: Investigate the potential for hybrid or electric-powered versions of the tiller to further reduce environmental impact and fuel dependency, aligning with sustainable farming practices.
- iv. Affordability and Accessibility: Continue to focus on keeping the machine affordable for smallholder farmers, particularly in developing regions, by considering subsidies, government support, or community-based distribution systems to enhance accessibility.
- v. Integration with Precision Agriculture: Explore integrating the tiller with precision farming technologies, such as GPS, to enable more efficient and targeted tilling, which can lead to further reductions in fuel use and labor costs.
- vi. Ergonomics and User Training: While the tiller's ergonomic design is a significant advantage, offering training for users, particularly in regions with limited access to modern equipment, will help maximize its potential.

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