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

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Abstract: Soil tillage remains a crucial yet complex agricultural operation, particularly challenging for small-scale farmers lacking access to affordable and efficient machinery. Manual tools and animal traction are labour-intensive, while large-scale mechanized equipment is often unaffordable and environmentally damaging. This study developed and tested an affordable, adaptable, and sustainable two-wheeled soil tiller. The tiller features a 6.5 HP gasoline engine, high-carbon steel blades, and an ergonomic modular frame. Field testing across four soil types revealed soil-dependent performance: sandy soil achieved the highest tilling efficiency (0.00212 m²/s) and lowest fuel consumption (1.0 L/h), while clay soil demanded the most fuel (1.5 L/h). The tiller demonstrated 98% mechanical efficiency, with a field capacity (0.04–0.06 ha/h) doubling animal traction and tripling manual hoeing, while reducing operational costs by 75%. The tiller's lightweight and compact design enhances manoeuvrability and reduces soil disturbance, aligning with sustainable practices. This innovation bridges the mechanization gap, empowering small-scale farmers through improved productivity and cost-effectiveness. Future research directions include hybrid/electric power systems and precision agriculture integration, marking a key milestone toward food security, economic resilience, and environmental conservation in small-scale farming communities.

Keyword: Design, Mechanization, Two-wheel Soil tiller, Smallholder farmers, Sustainable agriculture

1. Introduction

Cultivation of the soil has been one of the most critical aspects of agriculture for centuries. Tillage serves a very important purpose in land and seedbed preparation, weed control, and soil health improvement. Traditional methods of tillage used to be extremely labour and time-consuming because of dependence on hoes, plows, and rakes. In many small-scale farming communities, animal traction became a popular alternative to manual labour, offering improved efficiency but still presenting challenges such as limited field capacity and soil compaction (Dayoua et al., 2021; Hobbs, et al., 2017; Cheong et al., 2013). These innovations notwithstanding, the use of manual tillage equipment remains widespread, particularly in areas that lack access to modern machinery, such many parts of Africa and many other under-developed and developing areas of the world, where more than 60% of cultivated land is tilled using manual tools.

The advent of mechanized agriculture brought significant changes, with tractor-mounted and motorized tillage equipment revolutionizing farming practices. These large machines allow farmers to achieve large-scale efficiency and productivity. However, access to these large machines is restricted by their high cost and complication for many smallholder farmers in developing regions. Lal (2017) highlighted some of the negative impacts that conventional tillage imposes on the environment: soil erosion, compaction, and loss of soil structure are some long-term negative factors affecting the health of the soil and agricultural sustainability.

Mechanized soil tillers emerged as a more practical solution toward these challenges and have been proven to be cost-effective, versatile, and sustainable. Two-wheel soil tillers are compact, light machines designed exclusively for small-scale farming and gardening purposes. They easily manoeuvre through confined spaces and cultivate small plots, making them a good fit for areas where other methods and large equipment are not practical. According to Srivastava et al. (2017), the design of such machines has concentrated on optimizing blade geometry, engine performance, and user ergonomics to ensure maximum efficiency and ease of operation.

Studies have further emphasized the need for locally tailored tillage solutions that consider soil conditions, crop requirements, and economic constraints. For instance, in Benin, imported power tillers have been criticized for being too heavy, expensive, and ill-suited for local farming conditions (Degla et al., 2020; Pradhan et al., 2017). Researchers like Kumar et al. (2021)&Adamu et al., 2014 have advocated for the development of lightweight, fuel-efficient tillers capable of meeting the specific needs of smallholder farmers.

These studies involve the incorporation of new emerging technologies, such as precision agriculture tools, GPS-based systems, and others that promote efficiency in tillage or even reduce input costs (Parhar et al. 2017; Klotoe et al., 2017). Previous studies highlight the needs for lightweight tillers fitted with changeable blades and reduced fuel consumption. Mandal & Maity (2011) obtained 0.1 ha/day capacity with a 7 kW tiller, while Ademiluyi et al. (2007) focused on blade geometry for minimizing soil resistance.

This study reports on the development of a two-wheel soil tiller. This development aims at meeting these challenges through sustainable, cost-effective, and versatile means of soil preparation. This tiller is designed not only to improve agricultural productivity but also to promote environmental conservation by reducing soil disturbance and minimizing greenhouse gas emissions.

2. Methodology

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.

2.1 Design Requirements

The design stage began with an analysis of functional requirements to meet the small-scale farm needs. Among them, the frame was supposed to be robust yet light-weight by receiving the engine and operational loads, the handle bar has to be designed ergonomically for comfort during long-use periods, and the 6.5 HP gasoline engine was chosen by its reliability and the ability to produce torque sufficient for any type of soil. The blades were designed from high-carbon steel for durability, adjustable to till different depths and widths to accommodate various crops. The two wheels were equipped with tread patterns to provide stability and traction in varying terrains. Fig 1 shows the pictorial representation of the design two wheel tiller machine suitable for small scale use with easy user usability features.

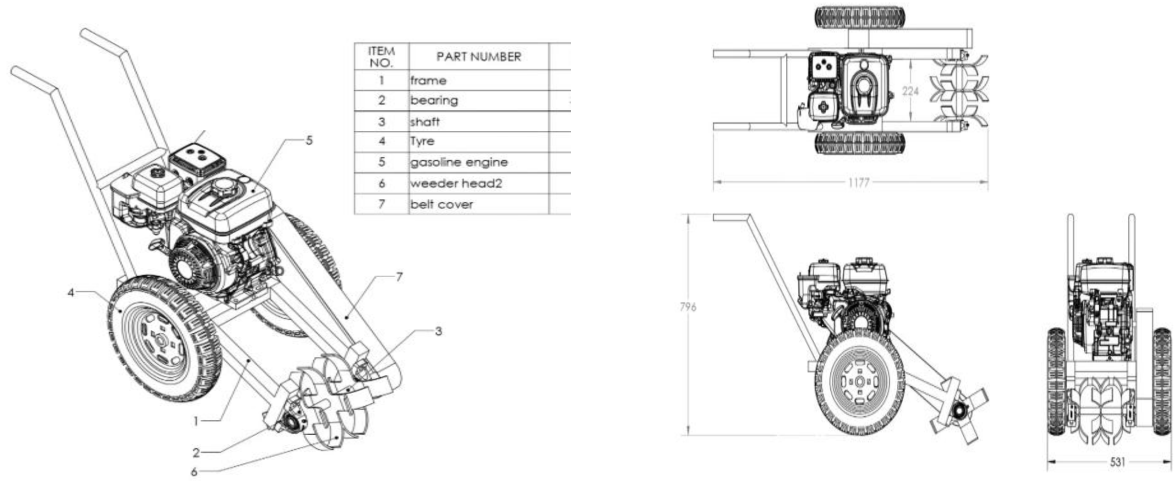

Fig 1: 3D View of Two Wheel Soil Tiller

2.2 Design Calculations

a. Engine Power Conversion

Given:

Engine power = 6.5 HP

1 HP = 745.7 W

$$P = 6.5Hp \times 745.7\frac{W}{HP} = 4847.05W$$

b. Tilling Speed and Blade Angular Velocity

Given:

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

Blade radius (r) = 0.1 m.

Angular velocity (ω): = $\frac{v}{r} = \frac{24.23}{0.1} = 242.3$ rad/s

Conversion to RPM; 242.3 rad/s = 2315 RPM

c. Torque Calculation

$$T = \frac{P}{\omega} = \frac{4847.05W}{242.3rad/s} = 20.0Nm$$

d. Frame Structural Analysis

Given:

Total Load (W_{total}):

Engine weight = 25 kg ≈ 245 N.

Blade assembly = 5 kg ≈ 49 N.

Operator force = 50 N.

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

Moment Arm: Distance from support = 0.5 m.

Bending Moment (*M*):

$M = W_{total} \times distance = 344\ N \times 0.5\ m = 172$ Nm

Section Modulus (*S*) for rectangular frame (30 mm × 50 mm):

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

Bending Stress (σ):

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

e. Blade Cutting Force

Given:

Soil shear strength (*S*) = 50 kPa.

Cutting coefficient (*C*) = 1.2.

Blade contact area (*A*) = width × depth = 0.15 m × 0.05 m.

Cutting Force (*F*):

$$F = A \times S \times C$$

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

f. Power Requirement for Blade:

$$P_{blade} = P_{blade} = F \times v$$

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

g. Pulley System Design

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

Pulley Diameters:

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

h. Tilling efficiency

Tilling efficiency (TE) was calculated as:

$$TE = \frac{BladeWidth \times Forward\,Speed \times Depth}{Time}$$

3. Results and Discussion

3.1 Operational Performance across Soil Types

The tiller's performance was evaluated across four soil types under standardized field conditions. Key metrics included tilling depth, width, fuel efficiency, and time efficiency (Table 1).

The fuel consumption rate was highly dependent on the type of soil as shown in Fig. 2 and Table 1. Sandy soil consumed the lowest amount of fuel, 1.0 L/h, because it had a loose structure and minimum resistance that the engine did not face a lot of load to burn. Clay soil consumed the highest amount of fuel, 1.5 L/h, because it had high density and was highly compacted, hence increased the load on the engine. Loam (1.2 L/h) and silty (1.3 L/h) soils were in between, corresponding to their intermediate resistance levels.

Tillage depth was directly related to the resistance of the soil (Fig. 3). Sandy soil, which had the least resistance, penetrated the deepest (70 mm), whereas compact clay limited the penetration to 50 mm despite multiple passes. Loam and silty soils attained intermediate depths of 60 mm and 55 mm, respectively. These are summarized in Table 1 and indicate a compromise between resistance of the soil and operational efficiency. In sandy soil, the deeper tilling contributed to the efficiency as presented in Fig. 3.

More importantly, the time taken to till 1 m² followed the same pattern as fuel consumption. Sandy soil took only 2.0 minutes, whereas clay took 3.0 minutes (Table 1). This again shows that soil resistance increases the time taken for operations, thereby increasing labour costs. Loam (2.5 minutes) and silty soil (2.7 minutes) were once more in the middle, showing their balanced resistance profiles.

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 m² (min)	2.5	3.0	2.0	2.7
Tilling Efficiency (m²/s)	0.00145	0.00100	0.00212	0.00123

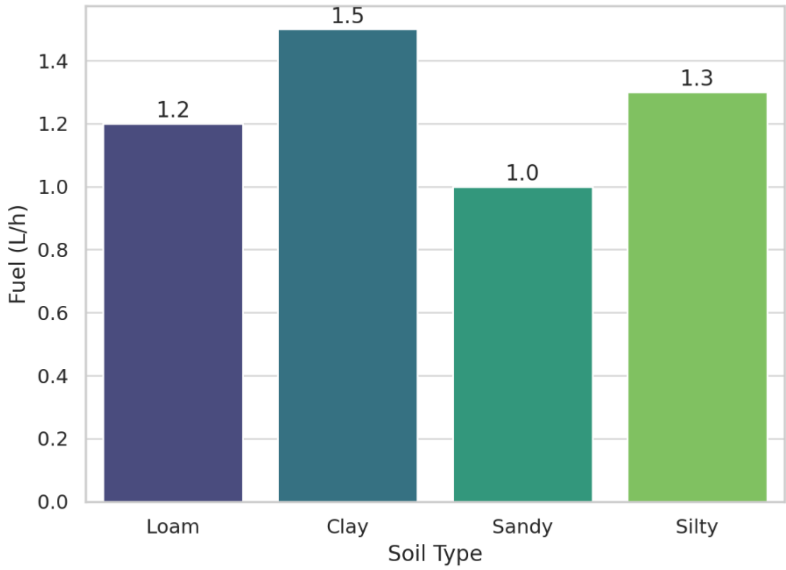

Fig. 2: Fuel Consumption Rate by Soil Type

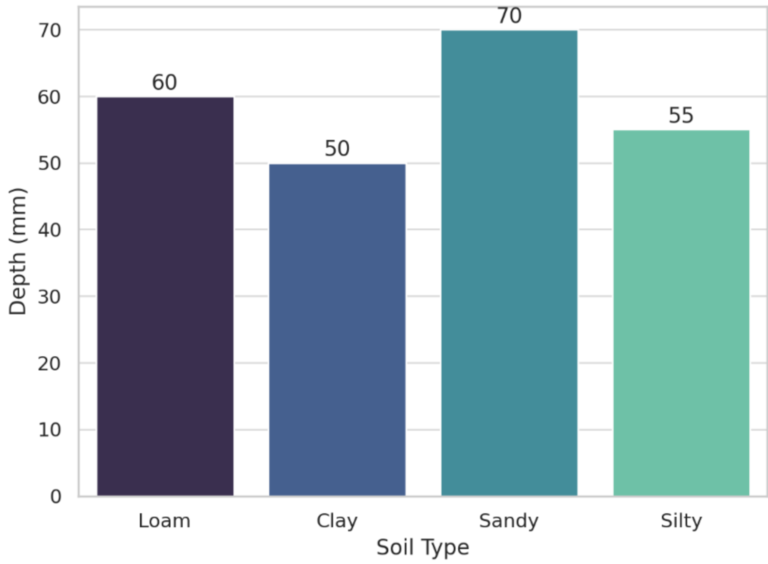

Fig. 3: Tilling Depth vs Soil type

3.2 Fuel Consumption Rate Analysis

Table 2 shows that the fuel consumption varies greatly by soil type, with clay requiring the highest fuel rate at 0.25–1.5 L/h because of its dense and resistant nature, while the sandy soil requires the least at 0.17–1.0 L/h because of minimal resistance. Despite similar operating velocities (0.0074–0.0444 m/s) and lengths traveled (1.1–6.7 m) for all soils, the fuel difference demonstrates how soil friction determines energy utilization: denser soils stress the engine, which translates to increased fuel use. For the farmer, it means using lower speeds with clay to match fuel efficiency, while higher speeds with sandy soils maximize productivity. The data reinforces the need for soil-specific adjustments to optimize fuel use and operational costs.

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

3.3 Tilling Efficiency Analysis

Tilling efficiency (Fig 4), calculated as the area tilled per second, was highest in sandy soil (0.00212 m²/s) and lowest in clay (0.00100 m²/s), as shown in Fig. 4. This disparity stems from the tiller's ability to achieve greater depths (70 mm in sandy soil vs. 50 mm in clay, Fig. 4) and faster forward speeds in low-resistance soils. The constant tilling width of 150 mm ensured uniformity between tests, but the efficiency was still controlled by soil-specific resistance. For instance, moderate compaction in silty soil yielded an efficiency of 0.00123 m²/s, whereas loam showed an efficiency of 0.00145 m²/s.

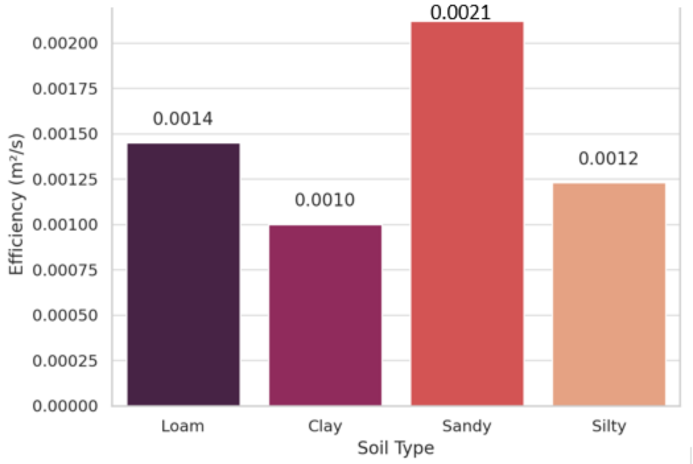

Fig. 4: Tilling Efficiency Comparison

4. Mechanical Efficiency

The tiller demonstrated 98% mechanical efficiency, indicating minimal power loss in the transmission system (belts, pulleys, bearings). This high efficiency explains its ability to maintain consistent performance across soil types, as shown in Table 1. However, the discrepancy between engine power (6.5 HP) and blade power demand (6.37 HP) suggests slight losses, likely due to friction in moving parts.

As shown in Table 3, the fabricated two-wheel tiller outperformed traditional methods in field capacity and cost efficiency. Its 0.04–0.06 ha/h capacity, visualized indirectly through tilling time in Table 1, is double that of animal traction and triple manual hoeing. Reduced labour and fuel costs further validate its economic advantage.

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)

5. Conclusion

The development and assessment of the two-wheel soil tiller presented here are in response to critical challenges in smallholder agriculture, especially for regions that cannot afford modern agricultural machinery. With affordability, adaptability, and sustainability in its integration, this machine has a great chance of being an alternative to traditional hand tools and expensive mechanized tools for large-scale farming. From the design and fabrication stages, and from field testing, major findings have confirmed its potential in changing the scenario of small-scale farming.

The tiller showed strong operational performance on various types of soils, with tilling depth and efficiency inversely related to soil resistance. Sandy soil had the highest efficiency at 0.00212 m^2/s and the lowest fuel consumption at 1.0 L/h, while clay soil consumed the most fuel at 1.5 L/h and had the lowest efficiency at 0.00100 m^2/s. These results indicate the need for soil-specific adjustments to optimize fuel use and productivity. The mechanical efficiency of 98% further validated the tiller's design, with minimal power loss in its transmission system, ensuring consistent performance under varying conditions.

Furthermore, comparative analysis with traditional methods revealed large advantages. The field capacity of the tiller; 0.04 to 0.06 ha/h-doubled that obtained with animal traction and tripled manual hoeing, while the operational cost was reduced by up to 75% compared to labour-intensive practices. Its compact, modular design with ergonomic features ensures good manoeuvrability in confined spaces, making it especially suitable for fragmented plots such as those found in Africa.

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