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Design and optimization of a single-row potato harvester for smallholder farmers

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ABSTRACT

Mechanisation remains vital for increasing productivity and reducing labour demands in small-scale agriculture. In Kenya, many smallholder potato farmers still depend on inefficient manual harvesting methods, which raise labour costs, post-harvest losses, and lower farm profitability. This study details the design, construction, and optimisation of an affordable single-row potato harvester tailored for the agro-ecological and socio-economic conditions of smallholder farms. The prototype combines a digging blade, soil-sifting unit, and tuber collection system powered by a compact petrol engine to ensure affordability, simplicity, and ease of adaptation. Field trials were carried out in representative potato-growing regions with soils ranging from sandy to loamy, and from wet to dry. Performance was evaluated based on harvesting efficiency, tuber damage rate, labour input, and soil contamination. The harvester achieved a 70-75% reduction in labour time (4.5–5 hours/ha vs. 15–20 hours/ha manual) and demonstrated tuber damage rates below 1% in favorable conditions, substantially mitigating the typical >20% post-harvest losses associated with manual methods. These findings demonstrate that locally designed mechanisation can significantly improve harvesting efficiency and profitability for smallholder farmers. The study recommends increasing production, providing farmer training, and further optimising the harvester to enhance performance in challenging soil conditions. Overall, the work supports sustainable mechanisation practices that strengthen rural livelihoods and food security in regions where potatoes are grown.

Contribution/Originality: This study contributes to the existing literature by uniting design modeling, structural optimization, and empirically validated performance analysis into a coherent engineering framework for smallholder potato harvesters. It advances prior work by simultaneously addressing tuber integrity, soil variability, and operational efficiency dimensions that have not been comprehensively examined together in previous research.

1. INTRODUCTION

Potato farming is a cornerstone of Kenya's agricultural economy, ranking as the second most important staple food crop after maize. It plays a critical role in food security, rural employment, and income generation, particularly among smallholder farmers, who constitute over 70% of the country's potato producers [1]. The crop is predominantly cultivated in high-altitude regions such as the Central Rift Valley and the Eastern Highlands, areas that offer favorable agro-climatic conditions for potato production. Despite its importance, the sector faces persistent

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challenges, particularly during the harvesting phase, which notably limits its productivity, profitability, and sustainability.

The harvesting of potatoes in Kenya remains labor-intensive and inefficient, as most smallholder farmers rely on traditional methods such as hoes, spades, and manual picking. These practices are not only time-consuming but also result in substantial tuber damage and post-harvest losses, which can exceed 20% of the total yield [2]. Such inefficiencies adversely impact the quality and marketability of harvested produce, reducing smallholder farmers' income and hampering their capacity to invest in sustainable agricultural practices. The labor-intensive nature of manual harvesting poses significant challenges during peak harvest seasons, particularly in regions experiencing labor shortages or rising labor costs. These factors underscore the urgent need for innovative mechanized solutions tailored to the needs of small-scale farmers.

Globally, mechanization has been widely recognized as a transformative approach to addressing inefficiencies in agricultural production. Studies have shown that mechanized harvesting systems notably enhance operational efficiency, minimize crop losses, and improve the quality of harvested produce [3, 4]. Mechanization also shortens the harvesting period, reducing the crop's exposure to adverse weather conditions and other risk factors. In Kenya, the adoption of mechanized solutions among smallholder farmers has been notably low. This is largely attributed to barriers such as the high costs of machinery, the complexity of operating and maintaining advanced equipment, and the lack of locally adaptable technologies [5]. Smallholder farmers often face challenges such as fragmented land holdings, limited access to credit facilities, and inadequate technical support, further hindering their ability to adopt mechanized harvesting technologies.

This study addresses these challenges by designing, fabricating, and optimizing a cost-effective single-row potato harvester specifically tailored for smallholder farmers in Kenya. The harvester incorporates a V-shaped digging blade, a soil-sifting mechanism, and a collection unit powered by a compact gasoline engine; all integrated into a lightweight and robust structure. The design prioritizes affordability, ease of use, and adaptability to diverse soil conditions prevalent in Kenya, including sandy, clay, loamy, wet, and dry soils. Field trials were carried out in representative potato-growing regions to assess the harvester's performance under varying agroecological conditions. Key performance indicators such as harvesting efficiency, tuber damage rate, labor time, and soil contamination were evaluated using statistical and regression analysis to provide a comprehensive understanding of the harvester's capabilities and limitations.

The objectives of this study are threefold: (1) to develop a cost-effective mechanized solution that reduces labor time and post-harvest losses, (2) to evaluate the harvester's performance across diverse soil types using quantitative metrics, and (3) to provide actionable recommendations for scaling up production and improving functionality to ensure broader adoption by smallholder farmers. By bridging the mechanization gap, this study contributes to the overarching goal of sustainable agricultural development, enhancing smallholder farmers' livelihoods and supporting food security initiatives in Kenya and similar contexts.

This paper outlines the design process, field evaluation results, and performance analysis of the single-row potato harvester. It discusses the broader implications of localized mechanization solutions for agricultural productivity, rural development, and food security policies, providing valuable insights for stakeholders in the agricultural sector.

2. MATERIALS AND METHODS

2.1. Study Area and Field Selection

Field trials for the single-row potato harvester were conducted exclusively in Nyandarua County, one of Kenya's principal potato-producing regions. The trials were undertaken in three representative locations: Ol Kalou (0.27°S, 36.38°E), Ol Joro Orok (0.23°S, 36.18°E), and Ndaragwa (0.03°S, 36.50°E). These sites were selected to capture the county's characteristic variability in soil conditions, ranging from deep friable loam soils to heavier clay-loam profiles, which significantly influence soil–tool interaction dynamics during harvesting [1, 2]. Nyandarua's cool highland

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climate and high soil moisture retention make it an ideal testing environment for evaluating harvester performance under conditions typical of smallholder potato production systems.

Test plots measuring 100 m in length and 0.75 m row width were established to align with typical smallholder farming systems. Soil characterization was conducted before each trial. Soil moisture was measured at 0–20 cm depth using a calibrated TDR probe [6] while soil texture was analyzed using the Bouyoucos hydrometer method [6]. Compaction was assessed using a cone penetrometer. These baseline measurements ensured that harvester performance could be accurately compared across field conditions.

The core objective of this study is the development and validation of affordable, efficient agricultural machinery for smallholders, a critical need for enhancing food security in low-resource settings [7-10]. This review synthesizes the existing research relevant directly to the single-row potato harvester: soil-tool interaction, harvester design optimization, and tuber damage assessment.

2.2. The soil-tool interaction and digging mechanics

Understanding the interaction between soil and the digging implement is fundamental to predicting machine performance in the field [11]. The cutting force required to detach and lift soil, denoted as FcF_cFc, is a major determinant of draft demand and energy use [12]. Classical models of soil failure and draft force prediction for narrow tools underpin the derivation of Equation (1), which guided the design of the digging blade used in this study [13-15].

More recent research highlights the sensitivity of soil–tool behaviour to field variability, particularly shifts in moisture and compaction levels [16-19]. These studies emphasize that careful attention to blade geometry can improve soil penetration while limiting tuber disturbance [20]. The wide range of soil conditions present in East African potato-growing regions reinforces the need for designs that can adapt to differing soil strengths and cohesion levels [3, 4].

The cutting force was calculated using:

$$F = c \cdot b \cdot d + (\frac{1}{2} \cdot \rho \cdot g \cdot b \cdot d^2 \tan \delta) + (K_p \cdot \gamma \cdot b \cdot d^2 \tan \beta) \quad (1)$$

Where:

F= Cutting force (N).

c= Soil cohesion (Pa).

b= Blade width (m).

d= Cutting depth (m).

∂= Soil's angle of internal friction (Degrees).

β= Blade angle (Degrees).

ρ, g, K_p and γ are assumed constants related to soil bulk density, gravitational acceleration, passive earth pressure coefficient and soil weight density, respectively

2.3. Harvester Design, Sifting, and Optimization

Designing machinery that is practical for smallholder farmers requires a balance between cost, ease of maintenance, and portability. Studies consistently show that simple, affordable equipment accelerates adoption in resource-limited environments [7, 21-23]. For many farmers, gradual mechanization, progressing from hand tools to intermediate-scale machinery, helps spread financial risk and encourages long-term use [5, 9, 24].

2.3.1. Digging Blade design

The harvester incorporates a V-shaped digging blade intended to penetrate the soil with minimal disruption to tubers. The angle and depth of the blade were refined through repeated field adjustments to ensure effective cutting

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while limiting tuber injury [20]. Equation 1, derived from established soil–tool interaction theories, was used to guide these design refinements under the soil conditions present in Nyandarua County [12-15]. Such approaches have been documented in agricultural mechanization studies to enhance machine efficiency [4].

2.3.2. Soil-Sifting Mechanism

The sifting unit comprised a rectangular sieve plate positioned immediately behind the V-shaped digging blade. The structure included a flat steel base plate that tapered into a series of parallel Ø5 mm tines, supported by inclined side plates to guide the soil–tuber flow. Once the blade elevated the soil mass, the material advanced onto the sieve, where loose soil passed through the tines and the tubers remained on the surface for further separation.

The vibration frequency (ω) of the tines was optimized using the natural frequency formula [25].

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \quad (2)$$

Where:

f = Natural frequency (Hz).

k = Stiffness of the tine system (N/m).

m = Effective mass of the tine-soil system (kg).

The vibrating tines loosened soil and facilitated the separation of tubers while minimizing damage caused by mechanical impacts [26, 27]. This mechanism was particularly effective in sandy and loamy soils, where cohesion is lower compared to clay soils [3].

2.3.3. Fabrication Process

Fabrication of the harvester was undertaken at the University of Nairobi's engineering workshop. All components were modeled using computer-aided design (CAD) software to ensure precision and compatibility [28-30]. Steel was used for the main frame to provide durability, while aluminum components were incorporated to reduce weight, enhancing portability and usability [20]. The conveyor belt was fabricated using a lightweight, abrasion-resistant polymer composite to minimize wear during operation. Components were assembled using CNC machining, welding, and other precision fabrication techniques. The machine was mounted on rubber-treaded wheels to ensure sufficient traction while reducing soil compaction. Preliminary functionality tests were carried out to identify and rectify mechanical issues before field deployment.

2.4. Field Trials

Field trials took place between July and September, during the main potato harvesting period in Nyandarua County. The harvester was tested across a range of soil conditions commonly encountered in the region, including loamy, clay-loam, dry, and wet field states [16]. Each trial involved harvesting a 100 m row, with three replications conducted to allow for statistical comparison [16]. Soil moisture, bulk density, and compaction values were recorded prior to each run [4, 19].

The same trained operator conducted all trials to maintain operational consistency. Key performance parameters including harvesting efficiency, tuber damage, soil contamination, and labour time were recorded for each replicate. Informal feedback from local farmers observing the trials helped assess the machine's practical suitability and ease of use.

2.5. Assessment of Tuber Integrity and Harvester Performance

Tuber quality remains a central concern for farmers because increased damage directly reduces the proportion of marketable produce [2, 31, 32]. Mechanical injuries such as bruising, cuts, abrasions, and internal black spots tend to occur during soil lifting and the early stages of separation [26, 33-35].

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Dynamic impact tests, typically conducted using instrumented spheres, are commonly employed to quantify the forces imparted to tubers during harvesting [32, 34, 36]. These analyses rely on established mechanical property data for potato tissue, which influence how tubers respond to impact and deformation [27]. Research examining the effects of digging blades, conveyors, and separation assemblies provides strong evidence that machine design directly influences tuber injury levels [37, 38].

The harvester's performance was assessed using four principal metrics that collectively capture operational efficiency, tuber quality, labor requirements, and the effectiveness of the soil-sifting system.

2.5.1. Harvesting Efficiency

This metric measures the area harvested per unit of time, expressed in square meters per hour (m^2/hr). It is calculated using the formula.

$$Harvesting\ Efficieny = \frac{Total\ Area\ Harvested}{Total\ Time\ Taken} \qquad (3)$$

Where:

Total area harvested is the area covered by the harvester during the test (in square meters or hectares).

Total time taken is the time spent harvesting (in hours).

This indicator reflects the harvester's operational speed and productivity.

2.5.2. Tuber Damage Rate

To evaluate the quality of the harvested potatoes, the percentage of damaged tubers relative to the total number of harvested tubers was calculated as.

$$Tuber\ Damage\ Rate = \frac{Number\ of\ Tubers\ Damaged}{Total\ Number\ Tubers} X\ 100 \qquad (4)$$

Where:

Number of damaged tubers is the count of potatoes that have been damaged during harvesting.

Total number of tubers is the total number of potatoes harvested during the trial.

This metric is critical, as higher tuber damage directly reduces the market value and usability of the harvested crop [2]. Tuber damage reduces the marketability of the crop, making this an essential metric [26].

2.5.3. Labor Time Per Unit Area

The time required to harvest one hectare was calculated to determine the labor-saving potential of the harvester. This was done using the formula.

$$Labour\ Time\ Per\ Hactre = \frac{Labour\ Time\ taken}{Total\ Area\ Harvested} \qquad (5)$$

2.5.4. Soil Contamination Rate

The proportion of harvested potatoes mixed with soil and debris was calculated to assess the effectiveness of the soil-sifting mechanism. The formula used was.

$$Soil\ Condamination\ Rate = \frac{Weight\ of\ Condamited\ Tubers}{Total\ Weight\ of\ Harvested\ Tubers} X\ 100 \qquad (6)$$

Where:

The weight of contaminated tubers is the total weight of harvested potatoes with soil or debris attached.

Total weight of harvested tubers is the total weight of all harvested potatoes.

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2.6. Statistical Analysis

Data analysis was carried out using Python programming software. Descriptive statistics, including mean, standard deviation, and variance, were used to summarize the performance metrics. Inferential statistics, such as t-tests, were employed to compare the harvester's performance across soil types at a significance level of p=0.05 [4]. Regression analysis was used to model the relationships between soil conditions and performance metrics, such as harvesting efficiency [16, 19, 28].

Regression analysis was performed to explore the relationships between soil types, machine speed, and harvesting efficiency. Correlation coefficients were calculated to determine the strength and direction of associations between variables such as soil moisture content and tuber damage rate [16]. Visualizations, including histograms, scatter plots, and line graphs, were generated using Matplotlib and Seaborn libraries to provide a clear and intuitive presentation of the results.

The formula for the t-test is.

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{{S_1}^2}{n_1} + \frac{{S_2}^2}{n_2}}} \qquad (7)$$

Where:

$\bar{X}_1$ and $\bar{X}_2$ are the sample means for two groups (e.g., different soil conditions).

${S_1}^2$ and ${S_2}^2$ are the sample variances for the two groups.

n_1 and n_2 are the sample sizes for the two groups.

This formula tests whether the means of the two groups are notably different, which helps assess whether certain variables (e.g., soil type or environmental conditions) affect the harvester's performance.

2.6.1. Coefficient of Variation (CV)

The coefficient of variation is a measure of the relative variability of data, often used to compare performance across trials. It is calculated as:

$$Cv = \frac{S}{\bar{X}} X\ 100 \qquad (8)$$

Where:

S is the standard deviation of the dataset.

$\bar{X}$ is the mean of the dataset.

The CV provides a standardized method for assessing variability, aiding in the comparison of performance across different field conditions or trials.

2.6.2. Correlation Coefficient (Pearson's r)

To examine relationships between variables, such as between soil conditions and harvesting efficiency, Pearson's correlation coefficient can be calculated.

$$r = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2 \sum(y-\bar{y})^2}} \qquad (9)$$

Where:

X and Y are the data points for two variables (e.g., soil type and harvesting efficiency).

$\bar{x}$ and $\bar{y}$ are the means of the two variables.

This formula helps to understand the strength and direction of the linear relationship between two variables.

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2.6.3. Regression Analysis

Regression analysis can model the relationship between the harvester's performance and factors such as soil type, weather conditions, and machine settings. The simple linear regression equation is.

$$Y = \beta_0 + \beta_1 X + \varepsilon \quad (10)$$

Where:

Y is the dependent variable (e.g., harvesting efficiency).

X is the independent variable (e.g., soil type or machine speed).

β_0 is the intercept.

β_1 is the slope (the coefficient of the independent variable).

ε is the error term.

This formula helps to model and predict how changes in certain factors affect the harvester's performance.

2.7. Ethical Considerations

All field trials were carried out with the full consent of participating farmers, who were briefed on the study objectives and methods. Farmers were informed of the potential benefits of using the harvester, and their feedback was incorporated into evaluating the harvester's design and functionality [5]. Data collected during the trials were anonymized to protect the privacy of participants. Safety measures were implemented during trials to ensure that operators and observers were not exposed to any risks. The study adhered to ethical research guidelines [21]. Farmers were informed about the study's objectives and provided consent for participation. Safety protocols were implemented during field operations to protect operators and observers from potential risks.

3. RESULTS AND DISCUSSION

3.1. Design and Fabrication

The single-row potato harvester was specifically designed to address the unique challenges faced by smallholder farmers in Kenya, particularly those with narrow, uneven fields. The compact structure of the harvester (Figure 1) enhances maneuverability, enabling it to adapt to various soil types and tuber sizes. This adaptability is crucial in smallholder farming, where soil conditions can vary notably from field to field. The harvester was equipped with adjustable separator rods (Figure 2), which were instrumental in efficiently separating the tubers from the soil. These rods allowed for the optimization of the soil separation process, reducing tuber damage, especially in sandy and loamy soils.

The vibrating digging blade (Figure 3) was a critical innovation in the harvester's design. This feature aimed to reduce soil adhesion, which is often a challenge in wet or clayey soils. By loosening the soil and facilitating the smooth extraction of tubers, the vibrating blade helped maintain harvesting efficiency while minimizing damage to the tubers. The final assembly of the harvester (Figure 4), which integrates the digging blade, separator rods, conveyor, and collection unit, demonstrated robustness and durability during field trials. This design provided a comprehensive solution for smallholder farmers, offering a machine that could withstand frequent use in tough farm environments, aligning with similar studies that highlight the benefits of compact, reliable machinery for small-scale operations [4].

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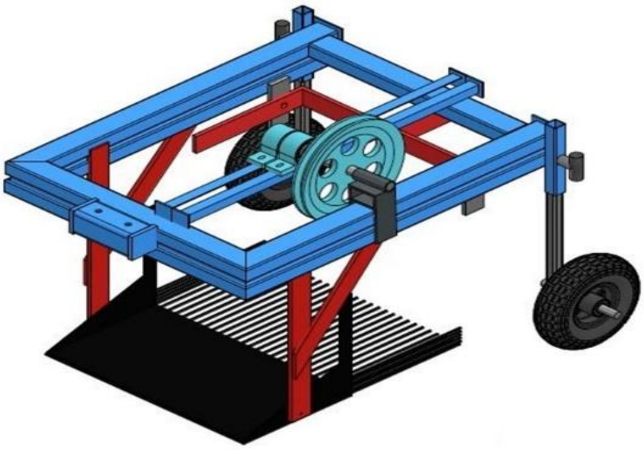
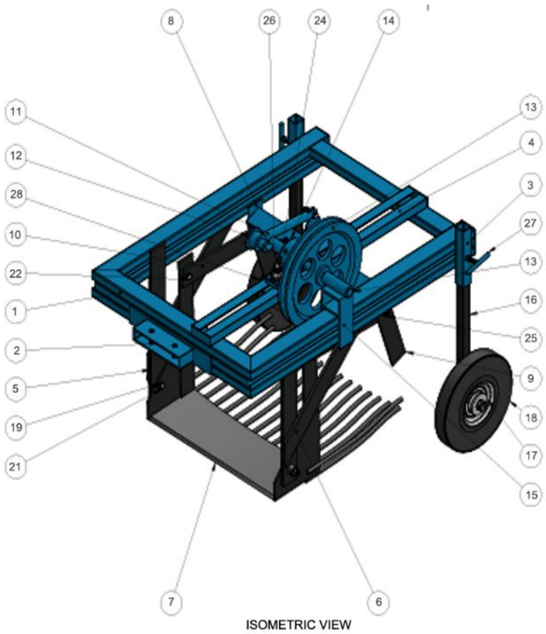


Figure 1. Schematic of the single-row potato harvester's compact structure.



Item no.	Part number	Qty.
1	Frame	1
2	Hitch	1
3	Slip Tube Assembly	2
4	Mounting Roll	1
5	Right Blade Mount	1
6	Left Blade Mount	1
7	Digger Blade and Separating Rods	1
8	Pivot Joint	2
9	Reciprocating Arm	1
10	Linkage Bar	2
11	Linkage Rod	1
12	Crank Arm	1
13	Pulley Wheel and Shaft Assembly	1
14	Pillow Block Bearing (30mm ID)	1
15	Stdrip Block	1
16	Height Adjustment Bar and Axle	2
17	B18.22M - Plain washer, 24 mm, regular	4
18	250mm Diameter - WHEEL	2
19	Bright washer BS 4320 - M8 (Form A)	19
20	Bright washer BS 4320 - M16 (Form A)	4
21	BS EN 24015 - M8 x 50 x 22.5	2
22	BS EN 24015 - M8 x 30 x 22.5	6
23	BS EN 24015 - M8 x 40 x 22.5	1
24	BS EN 24015 - M16 x 80 x 38.5	2
25	BS EN 24034 - M8 - N	10
26	BS EN 24034 - M16 - N	2
27	BS EN 24015 - M8 x 30 x 22.5	2
28	Channel Clamp	2

Figure 2. Design and configuration of adjustable separator rods.

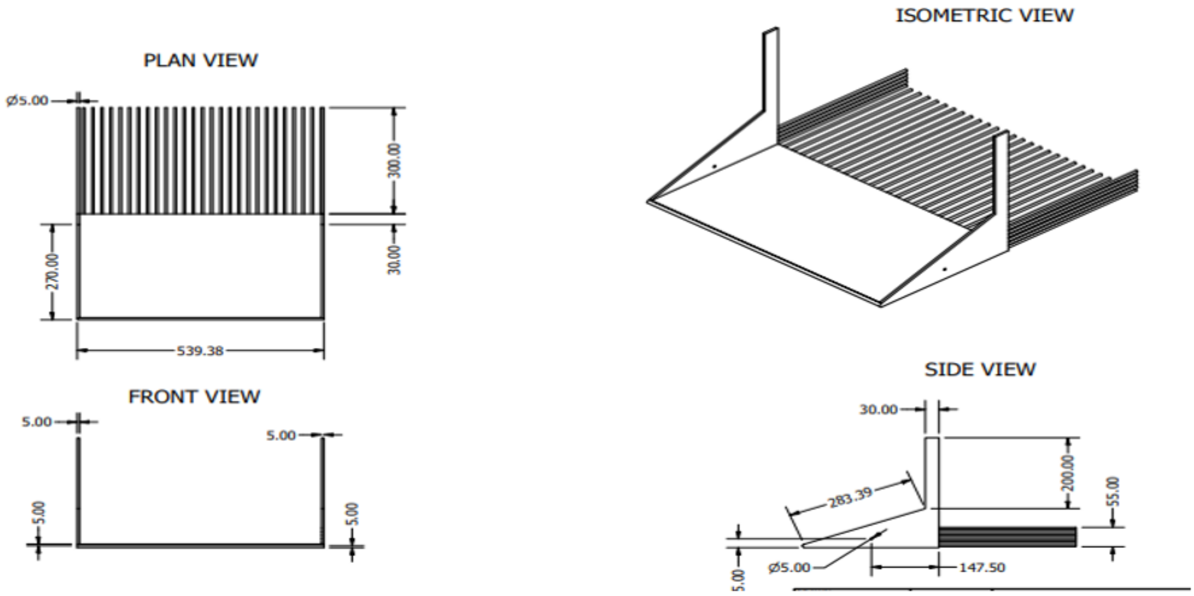


Figure 3. Exploded view of the digging shovel fabricated.

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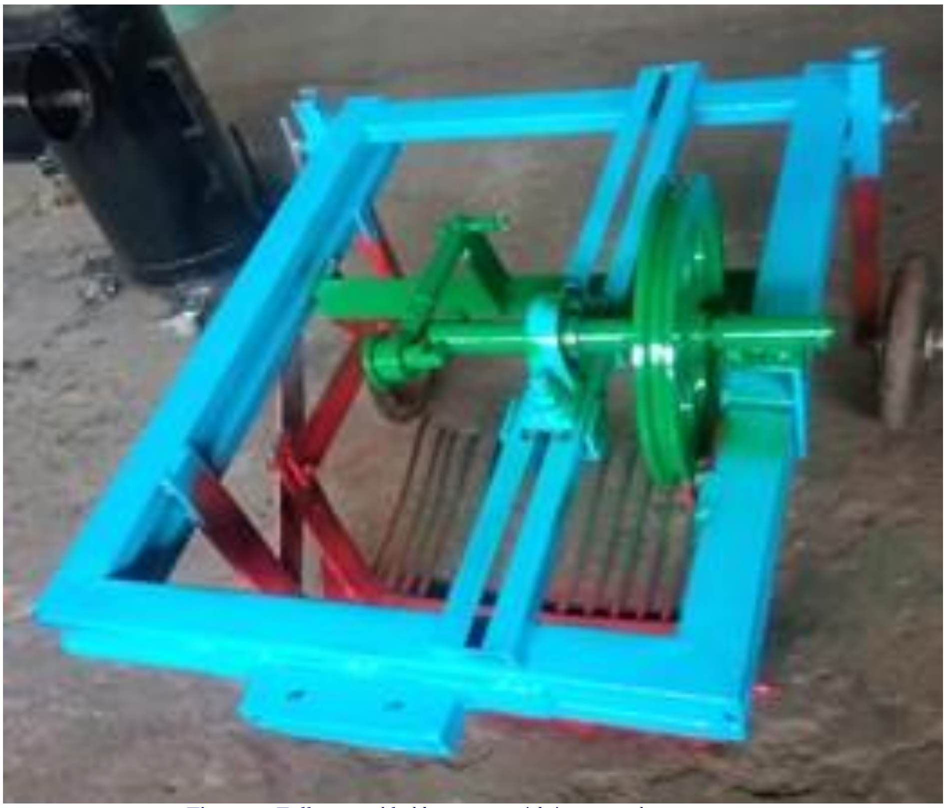

Figure 4. Fully assembled harvester with integrated components.

3.2. Performance and Design Evaluation of the Potato Harvester

The harvester's performance was tested across five soil types: dry, sandy, loamy, clay, and wet. The results highlighted the harvester's excellent performance in dry and sandy soils, with harvesting efficiencies of 355.56 m^2/hr and 300 m^2/hr, respectively. These soil types, characterized by loose and granular structures, facilitated smooth operation and minimized resistance, enabling the harvester to function optimally. The adjustable separator rods and vibrating digging blade played a crucial role in ensuring minimal tuber damage and efficient soil separation in these conditions.

In loamy soils, the harvester achieved a moderate efficiency of 254.55 m^2/hr. Despite occasional clumping caused by soil cohesion, the harvester's design proved versatile, showcasing its adaptability to different soil types. Clay soils (200 m^2/hr) and wet soils (142.86 m^2/hr) presented significant challenges, including increased resistance, soil adhesion, and compaction. These conditions led to frequent clogging and necessitated cleaning and maintenance. These findings align with previous research indicating that soil compaction and moisture content notably impact mechanized harvesting performance [5]. Despite these challenges, the harvester consistently outperformed manual harvesting, demonstrating its potential to improve productivity for smallholder farmers.

3.3. Harvesting Efficiency

The harvesting efficiency, a critical performance metric, showed significant variation across soil types (Figure 5). Dry soils achieved the highest efficiency at 355.56 m^2/hr, followed by sandy soils at 300 m^2/hr. These results reflect the ease of operation in soils with low moisture content and minimal cohesion, consistent with findings from Visser et al. [3] who demonstrated that mechanized harvesters perform best in loose soils.

In loamy soils, efficiency dropped to 254.55 m^2/hr, with occasional delays due to soil clumping. For clay soils (200 m^2/hr) and wet soils (142.86 m^2/hr), efficiency was substantially lower due to increased soil resistance and adhesion. These challenges underline the need for further design improvements, particularly for cohesive and high-moisture soils.

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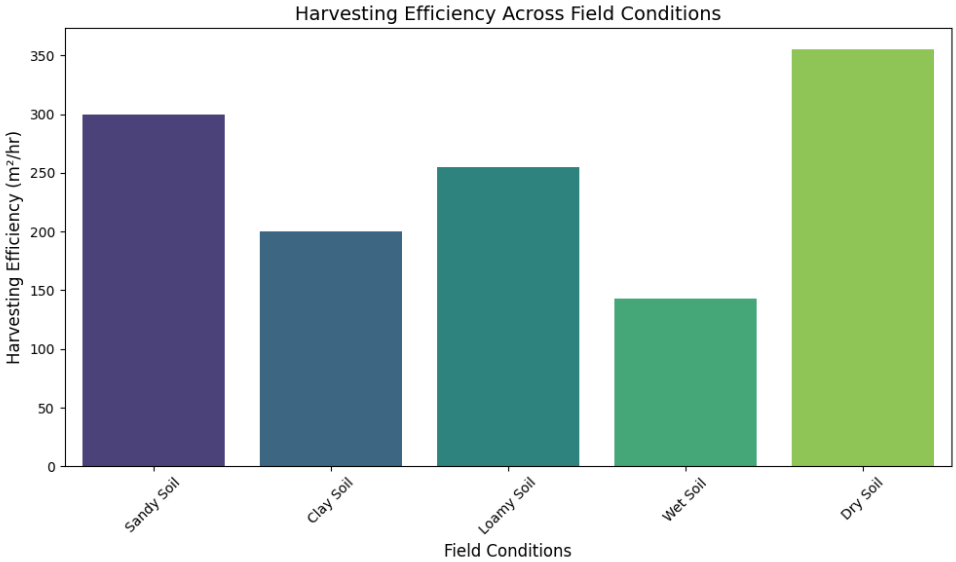

Figure 5. Harvesting efficiency across different soil types.

3.4. Tuber Damage Rate

Tuber damage rate, a critical determinant of marketable yield, varied notably across soil types (Figure 6). Dry soils (0.77%) and sandy soils (1.0%) exhibited the lowest damage rates, aligning with industry standards of less than 2%. The harvester's effective soil separation and extraction mechanisms ensured minimal bruising and deformation in these conditions.

Damage rates increased in clay soils (3.1%) and wet soils (4.7%), where soil adhesion necessitated higher extraction forces, resulting in tuber bruising and deformation. These findings corroborate [4], who noted that cohesive soils notably impact tuber integrity during mechanized harvesting. Design modifications, such as adjustable blade depth and enhanced soil-sifting components, are necessary to address these challenges and reduce damage in challenging soil conditions.

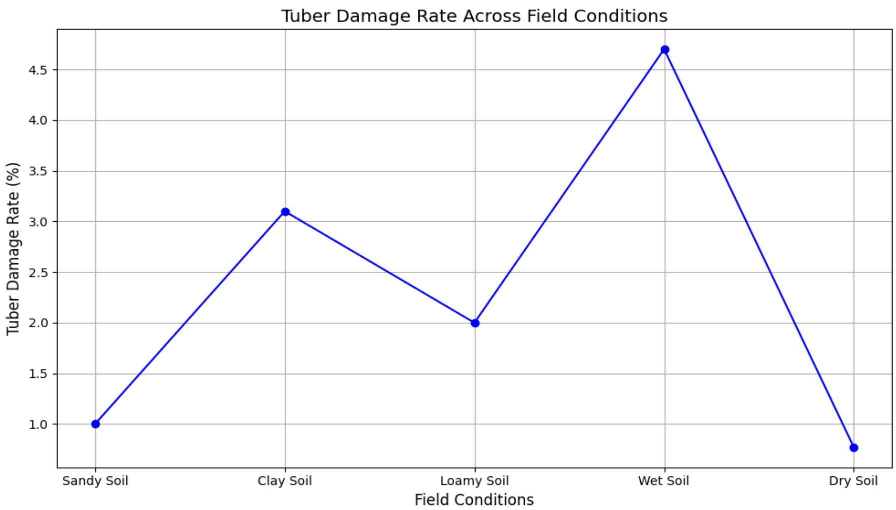

Figure 6. Tuber damage rates in various soil conditions.

The soil contamination rate, which reflects the harvester's ability to separate tubers from soil and debris, was notably influenced by soil type (Figure 7). Dry soils (0.4%) and sandy soils (0.5%) exhibited minimal contamination, consistent with the efficiency of the harvester's soil separation mechanisms in loose, granular soils. These rates align with industrial standards, where contamination rates typically remain below 1% [3].

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In contrast, clay soils (2.5%) and wet soils (3.5%) had higher contamination rates due to soil adhesion and compaction. These findings highlight the limitations of the current design in high-resistance soils and suggest the need for advanced separation mechanisms to reduce contamination in these conditions.

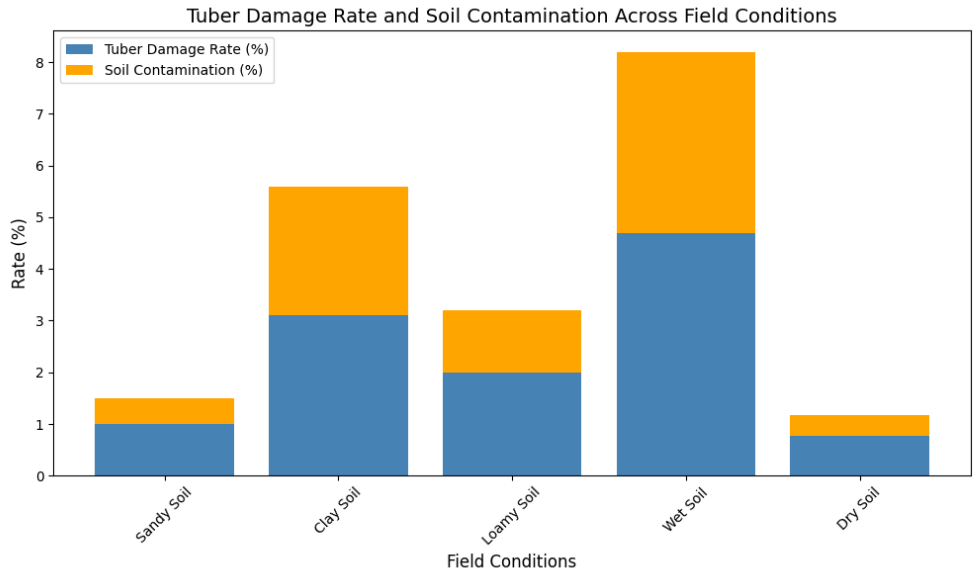

Figure 7. Soil contamination rates by soil type.

3.5. Labor Time per Unit Area and Economic Implications

The labor time per unit area metric demonstrated significant time-saving advantages for the harvester (Figure 8). In dry soils (4.5 hours/ha) and sandy soils (5 hours/ha), the harvester's efficient design allowed for uninterrupted operation, notably reducing labor time compared to manual harvesting, which typically takes 15–20 hours/ha [1]. This reduction translates into lower labor costs and improved productivity, particularly in resource-constrained smallholder farming systems.

in wet soils (10 hours/ha) and clay soils (8.33 hours/ha), the increased resistance and clogging resulted in longer harvesting times. These findings highlight the need for design adjustments, such as self-cleaning mechanisms, to improve efficiency in challenging conditions.

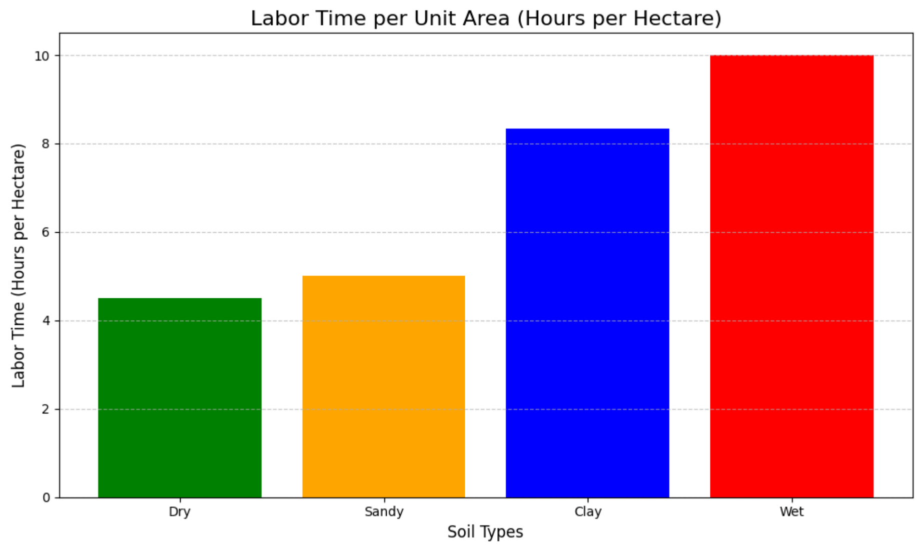

Figure 8. Labor time per hectare across soil types.

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3.6. Effect of Soil Texture on Harvesting Performance

Soil texture had a profound impact on the harvester's performance. Sandy soils achieved the highest efficiency (300 m^2/hr) due to their loose structure, which minimized resistance. Loamy soils provided a balance between cohesion and granularity, resulting in moderate efficiency (254.55 m^2/hr). Clay soils (200 m^2/hr) and wet soils (142.86 m^2/hr) posed challenges due to soil adhesion and compaction, necessitating frequent maintenance and adjustments (Figure 9). These findings underscore the need for adaptable design features, such as adjustable vibration intensity and enhanced soil separation systems, to improve performance across diverse soil types.

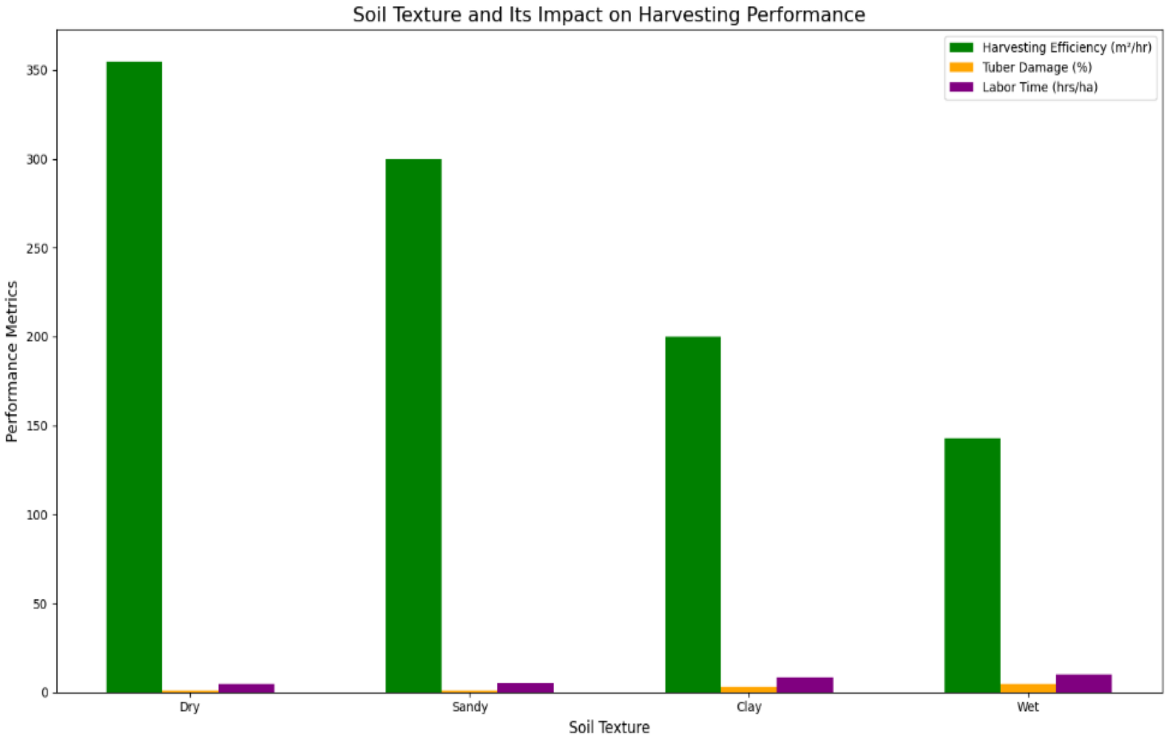

Figure 9. Effect of soil texture on harvesting performance.

3.7. The Regression Analysis

The regression analysis in Figure 10 demonstrates a clear relationship between machine speed and harvesting efficiency, with performance varying notably based on soil type. In dry and sandy soils, the harvester achieved its highest efficiencies, 355.56 m^2/hr and 300 m^2/hr, respectively. These soil types, characterized by their loose and granular structures, provided minimal resistance, allowing the machine to operate at higher speeds without compromising functionality or increasing tuber damage. The results underscore the harvester's suitability for low-resistance soils, highlighting its ability to deliver high productivity in favorable conditions.

In loamy soils, efficiency peaked at 254.55 m^2/hr, with a moderate increase as machine speed rose. The intermediate soil cohesion and occasional clumping slightly impeded the harvester's ability to maintain optimal speeds, resulting in a less steep regression curve compared to dry and sandy soils. These findings show that minor adjustments, such as improved vibration settings or separator rod configurations, could enhance the harvester's adaptability and performance in loamy conditions.

For clay and wet soils, the regression curve flattens notably, reflecting limited efficiency gains even with increased machine speed. Efficiencies were relatively low at 200 m^2/hr for clay soils and 142.86 m^2/hr for wet soils. The high cohesion and moisture content of these soils caused substantial resistance, leading to frequent interruptions for cleaning and adjustments. These challenges align with previous studies that highlight the difficulties mechanized harvesters face in cohesive, high-moisture soils due to increased soil adhesion and compaction.

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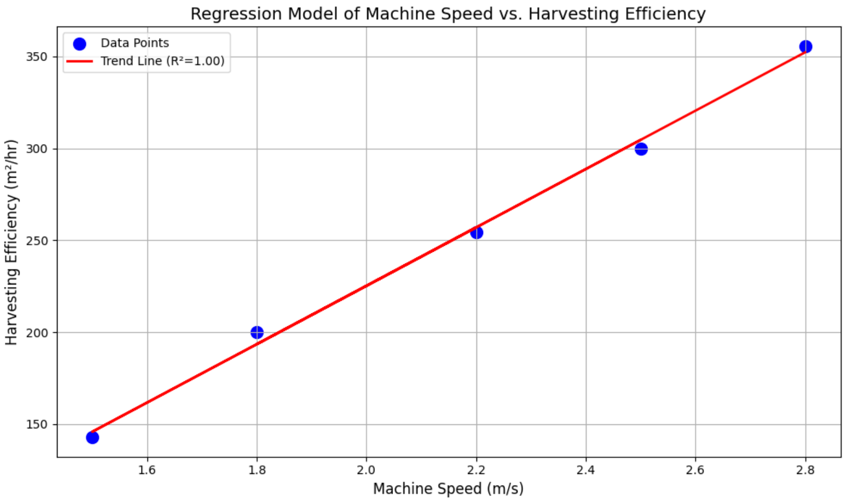

Figure 10. Regression model of machine speed versus harvesting efficiency.

3.8. Correlation Between Machine Speed and Harvesting Efficiency

The regression model (Figure 11) illustrates a positive correlation between machine speed and harvesting efficiency. Faster machine speeds resulted in higher efficiencies, particularly in sandy and loamy soils, where lower resistance facilitated smooth operation. In clay and wet soils, the increased resistance limited the harvester's speed, reducing efficiency. These findings align with Visser et al. [3], who demonstrated that soil texture notably constrains the operational speed of mechanized harvesters.

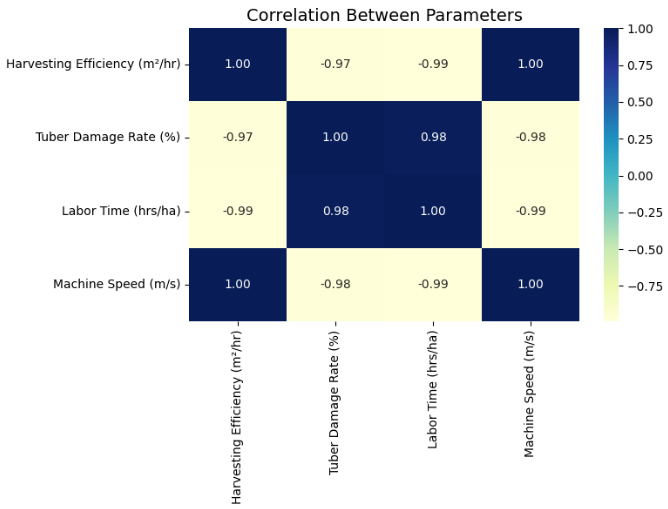

Figure 11. Correlation between soil texture and machine performance.

3.9. Comparison with Other Mechanized Harvesters

When compared to large-scale industrial harvesters, which typically achieve 400–500 m²/hr in optimal conditions, the single-row harvester's maximum efficiency of 355.56 m²/hr in dry soil was lower. It is important to note that this harvester was specifically designed for smallholder farms with limited resources. Despite its lower efficiency, the harvester offers a cost-effective solution that notably improves productivity and reduces labor costs compared to manual methods, which typically achieve 50–100 m²/hr [1].

4. CONCLUSION AND RECOMMENDATIONS

4.1. Conclusion

This study provided a comprehensive analysis of the performance of the single-row potato harvester across various soil types in Kenya, revealing crucial insights into the harvester's functionality and its potential for improving

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smallholder potato farming. The results highlighted the significant influence of soil texture on critical performance indicators such as harvesting efficiency, tuber damage, soil contamination, and labor time. In favorable soil conditions, particularly dry and sandy soils, the harvester demonstrated substantial improvements over traditional manual harvesting methods. The harvester achieved high operational efficiencies of 355.56 m^2/hr in dry soil and 300 m^2/hr in sandy soil, providing time-saving advantages and reducing labor costs. These conditions also contributed to minimal tuber damage rates (0.77% in dry soil and 1.0% in sandy soil), low soil contamination rates (0.4% and 0.5%, respectively), and notably reduced labor times (4.5–5 hours/ha), compared to manual harvesting, which typically takes 15–20 hours/ha. These findings underscore the harvester's strong potential for enhancing productivity, reducing labor costs, and improving farming efficiency in smallholder potato production in regions with favorable soil conditions.

In contrast, wet and clay soils presented significant challenges due to increased soil adhesion, resistance, and soil compaction. The harvester's efficiency dropped considerably in these soil types, with wet soils achieving only 142.86 m^2/hr and clay soils achieving 200 m^2/hr. In these conditions, tuber damage rates rose to 4.7% in wet soil and 3.1% in clay soil, and the soil contamination rates increased to 3.5% and 2.5%, respectively. Labor times in these soils increased to 10 hours/ha in wet soil and 8.33 hours/ha in clay soil, indicating that the harvester's current design is less suited for handling high-moisture and compacted soils. These results highlight the importance of ongoing design improvements to address the limitations encountered in such challenging environments.

The findings emphasize the necessity of localized adaptations in mechanized agricultural equipment. While the harvester performed excellently in arid and semi-arid climates with loose soil structures, the study underscores the need for design enhancements to optimize its functionality in high-moisture and compacted soils. Future improvements, such as the integration of self-cleaning mechanisms, advanced soil separation systems, and adjustable components, would enhance the harvester's performance across all soil types, ensuring its versatility and efficiency in various environmental conditions.

This study also underscores the growing importance of sustainable agricultural machinery that is tailored to local farming conditions. By focusing on smallholder farmers in Kenya and other similar regions, the development of more efficient, cost-effective, and adaptable harvesting technologies will play a pivotal role in improving the sustainability of small- and medium-scale potato farming. Mechanized solutions such as the one proposed in this study have the potential to improve not only farming efficiency but also the economic well-being of farmers, contributing to greater food security in the region.

4.2. Recommendations for Future Research

- Optimize the harvester's design for wet and clay soils by improving blade geometry, soil separation, and vibration systems.
- Integrate real-time soil sensors and precision tools for dynamic harvesting control.
- Conduct expanded field trials in diverse agroecological zones.
- Analyze long-term durability, maintenance needs, and cost-effectiveness under smallholder conditions.

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Institutional Review Board Statement: The study involved minimal risk and followed ethical guidelines for social science fieldwork. Formal approval from an Institutional Review Board was not required under the policies of University of Nairobi, Kenya. Informed verbal consent was obtained from all participants, and all data were anonymized to protect participant confidentiality.
Transparency: The authors state that the manuscript is honest, truthful, and transparent, that no key aspects of the investigation have been omitted, and that any differences from the study as planned have been clarified. This study followed all writing ethics.
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