

Performance evaluation and optimization of a small-scale irish potato (*Solanum tuberosum* L.) harvester: design, testing, and economic feasibility

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Abstract: Irish potato is the most important non-cereal food crop in Kenya, contributing significantly to food security and the livelihoods of small-scale farmers. However, the labor-intensive nature of potato harvesting poses persistent drudgery, operational inefficiencies, and substantial on-harvest potato damage and post-harvest losses. This study presents design, development and performance evaluation of a small-scale Irish potato harvester for small-scale farmers in Kenya. The harvester incorporates mechanical and automated components for digging, soil-potato separation, and collecting potatoes efficiently, while allowing for adjustments to accommodate various potato varieties and sizes. Field trials demonstrated an 82% reduction in harvesting time and a 50% improvement in net profitability, confirming the harvester's suitability for smallholder farming. The potato harvester has a demonstrated field capacity of 0.45 ha hr⁻¹ at 0.5 m s⁻¹ and 1.10 ha hr⁻¹ at 1.5 m s⁻¹. After testing, it was found that it uses 4 hours less during harvesting compared to the manual method, saving the farmer significant amounts of time and labor. Farmers have responded with enthusiasm, about 85% of all who used the harvester expressed satisfaction with the harvester. There has also been a 50% improvement in net profitability associated with using the machine. Performance evaluation included regression modelling ($R^2 = 0.91$) to assess efficiency metrics, validating its reliability against traditional harvesting methods. The collaborative approach with local stakeholders has ensured that the harvester aligns with the specific needs of Kenyan farmers, taking into account limited resources and technical expertise. This research underscores the potential for mechanization to transform potato farming in Kenya, fostering industry growth and enhancing the livelihoods of small-scale farmers. The harvester features adaptive soil separation, precision vibration control, and real-time load optimization, enhancing efficiency, reducing clogging, and minimizing tuber damage. These innovations make it a cost-effective solution for Kenyan smallholder farmers facing soil compaction and mechanical damage.

Keywords: potato harvester, small-scale farming, mechanization, crop harvesting, sustainable agriculture, agricultural innovation, rural Livelihoods

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1 Introduction

Irish potatoes (*Solanum tuberosum* L.) are among the most significant food crops worldwide, providing

essential nutrition and economic benefits to millions globally (Andati et al., 2023). In Africa, potato production is increasingly shifting towards East Africa, with Kenya playing a crucial role in meeting regional

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demand (Gikundi et al., 2023; Devaux et al., 2021). In Kenya, potatoes are the second most important staple crop after maize, serving as both a food security crop and a major source of income for small-scale farmers (Wamuyu et al., 2022; Kwambai et al., 2023). Despite its economic importance, potato cultivation and harvesting in Kenya are fraught with inefficiencies that hinder the crop's full economic potential. One of the most significant challenges faced by farmers is the labor-intensive nature of potato harvesting, which traditionally relies on manual labor using hand tools. This method is time-consuming, physically demanding, and inefficient, leading to high post-harvest losses (CGIAR, 2017). Studies estimate post-harvest losses at various points in the value chain to be 12.8% at the farm level, 24.4% in open markets, 12% during processing, and 25% in supermarkets (Gikundi et al., 2023; Gildemacher et al., 2011). While previous research on semi-mechanized harvesters (Filippi et al., 2002) has demonstrated efficiency improvements, no study has comprehensively integrated real-time soil-adaptive components or conducted field trials across different agro-ecological zones in Kenya. Mechanization presents an opportunity to enhance harvesting efficiency by reducing labor dependency, post-harvest losses, and overall operational costs. Additionally, the harvester was tested under various field conditions, including different soil textures and moisture levels, to ensure adaptability across diverse farming environments.

Moreover, soil-tool interactions significantly influence harvester efficiency. The harvester design optimizes blade inclination (40°), cutting force, and separator vibration, ensuring minimal soil resistance while reducing tuber damage. The physico-mechanical properties of soil-including compaction, moisture content, and cohesiveness-affect the efficiency of harvesting tools (Mwiti et al., 2022). Therefore, an effective harvester design must account for these factors to ensure optimal performance under local farming conditions. In response to these challenges, developing a small-scale, locally adapted potato

harvester presents a viable solution. A compact, efficient, and adaptable harvester can significantly reduce labor dependence, enhance productivity, and minimize post-harvest losses (Kinyua et al., 2017). The implementation of such a mechanized system aligns with global trends in agricultural modernization, ensuring sustainability and improved economic returns for farmers.

This study aims to design, develop, and evaluate a small-scale potato harvester that meets the specific needs of Kenyan smallholder farmers. The harvester incorporates elements of automation, precision, and affordability, making it accessible to farmers with limited technical expertise and financial resources. The research methodology involves collaborations with farmers, agronomists, and agricultural engineers to ensure a practical and user-friendly design. The anticipated outcomes of this research include the development of a functional small-scale potato harvester prototype suitable for Kenyan farming conditions, comprehensive field performance evaluation comparing efficiency, economic viability, and reliability against traditional manual harvesting, a user manual and maintenance guidelines to facilitate adoption by smallholder farmers, and recommendations for further improvements to enhance durability, efficiency, and farmer accessibility.

This research focuses on the complete cycle of mechanization, from design optimization to performance evaluation, addressing limitations observed in previous mechanized harvesters such as soil accumulation in separators and high tuber damage rates (Mwiti et al., 2022).

2 Materials and methods

A structured and methodical approach was adopted in designing a small-scale potato harvester specifically suited for the agricultural conditions of Kenya. Nyandarua County is one of Kenya's leading potato-producing regions, contributing over 30% of the country's total potato output. The region was selected as the test site due to its predominance of small and

medium-scale farmers, diverse soil conditions, and the need for mechanization to improve harvesting efficiency. The study integrated engineering principles, field survey data, and computational simulations to optimize the harvester's design for enhanced productivity, cost-effectiveness, and ease of use by smallholder farmers.

2.1 Field surveys and data collection

The research was conducted in Nyandarua County, a key potato-producing region in Kenya, contributing 33% of national production majority of the potato producers are small-scale farmers. The study aimed to collect essential field data to inform the harvester's design, ensuring its compatibility with local farming conditions. A comprehensive methodology was employed, incorporating structured interviews, direct observations, and focus group discussions with farmers, agricultural officers, and local stakeholders. Data collection focused on critical parameters, including farm sizes, soil characteristics, existing harvesting techniques, labor constraints, and post-harvest losses. Additionally, the study examined the economic feasibility of mechanized harvesting by assessing cost implications and farmers' willingness to adopt the technology. The findings provided a robust foundation for tailoring the harvester's design to optimize performance, efficiency, and usability in smallholder farming systems. A control experiment was conducted using manual harvesting under similar soil conditions to establish comparative efficiency metrics. Three replicates were performed for statistical validation.

2.2 Design engineering and theoretical framework

The design of the harvester was developed based on extensive field data, engineering simulations, and a rigorous analytical framework to ensure its suitability for smallholder farmers in Kenya. A systematic methodology was applied to optimize key design parameters, including structural dimensions, material selection, and functional adaptability. The harvester's compact size was deliberately chosen to enhance manoeuvrability in small, fragmented farms, with final

dimensions of 820 mm (L) × 590 mm (W) × 500 mm (H). These dimensions were carefully determined considering transportability, operational efficiency, and field adaptability.

The theoretical framework incorporated soil-tool interaction mechanics, force analysis for soil penetration, structural integrity assessments, and power transmission efficiency. To validate the harvester's performance, computational simulations were conducted using SolidWorks for structural analysis and ANSYS for stress distribution and optimization. Stress analysis results indicated a maximum von Mises stress of 85 MPa, well within the yield strength of the selected mild steel material (250 MPa). These simulations enabled precise determination of critical parameters, ensuring that the harvester achieves optimal digging efficiency, minimal soil disturbance, and reduced mechanical stress on components. Additionally, kinematic analysis was employed to assess the efficiency of the conveyor mechanism, ensuring seamless separation of potatoes from soil. These metrics, derived from established agricultural engineering principles, guided Harvester's design and testing, are shown in Figure 1 and Plate A1.

The final design integrates robustness, efficiency, and cost-effectiveness, making it practical for smallholder farmers with limited mechanization experience. By incorporating validated engineering principles and real-world farming constraints, this harvester is positioned as a viable solution to enhance potato harvesting efficiency in Kenya.

The theoretical framework incorporated mechanical design principles, including force analysis for soil penetration, structural integrity assessments, and power transmission efficiency. The harvester's structural integrity was validated using SolidWorks for 3D modelling and ANSYS for stress and deformation analysis. The frame and digging blade were subjected to simulated operational loads to determine their maximum von Mises stress and deformation thresholds. The stress distribution results indicated a maximum von Mises stress of 85 MPa, well within the

yield strength of mild steel (250 MPa), confirming the structural robustness of the harvester under field conditions. The deformation analysis confirmed minimal bending under applied loads, ensuring operational reliability without material failure. Figures 1 and 2 present the ANSYS simulation results, demonstrating the optimized design for durability and efficiency. Results from the ANSYS analysis indicated

that the harvester's frame and digging blades could withstand operational stresses without structural deformation. Stress distribution plots and deformation models validated the durability and efficiency of the system. The final design balances robustness, efficiency, and cost-effectiveness, ensuring that small-scale farmers can easily integrate the harvester into their agricultural practices.

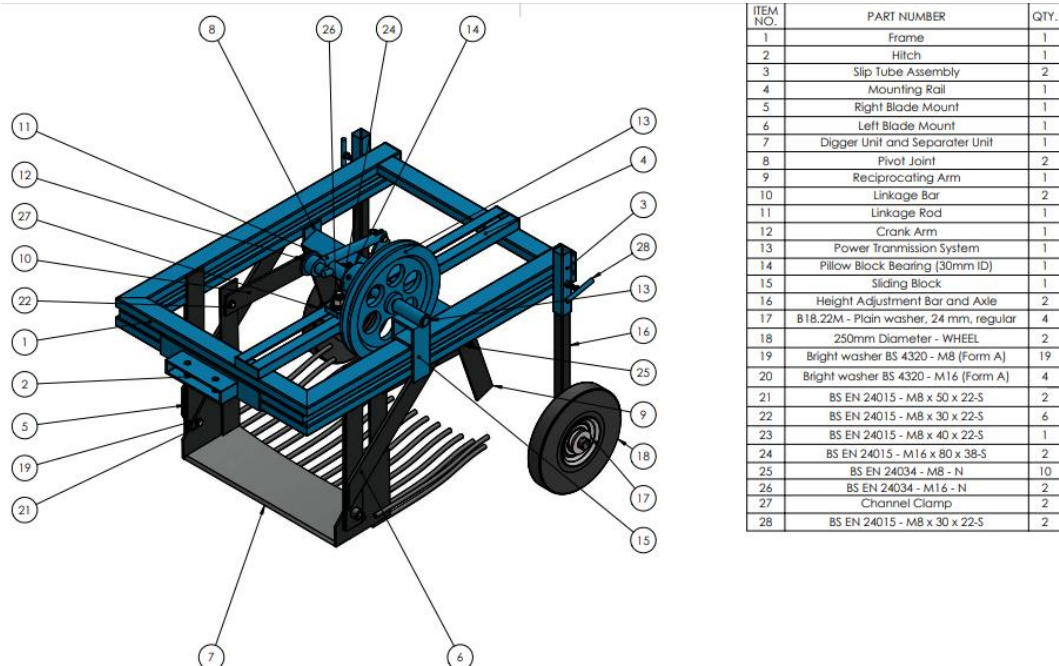


Figure 1 Illustrates the conceptual design schematic of the mechanized potato harvester, highlighting the main components

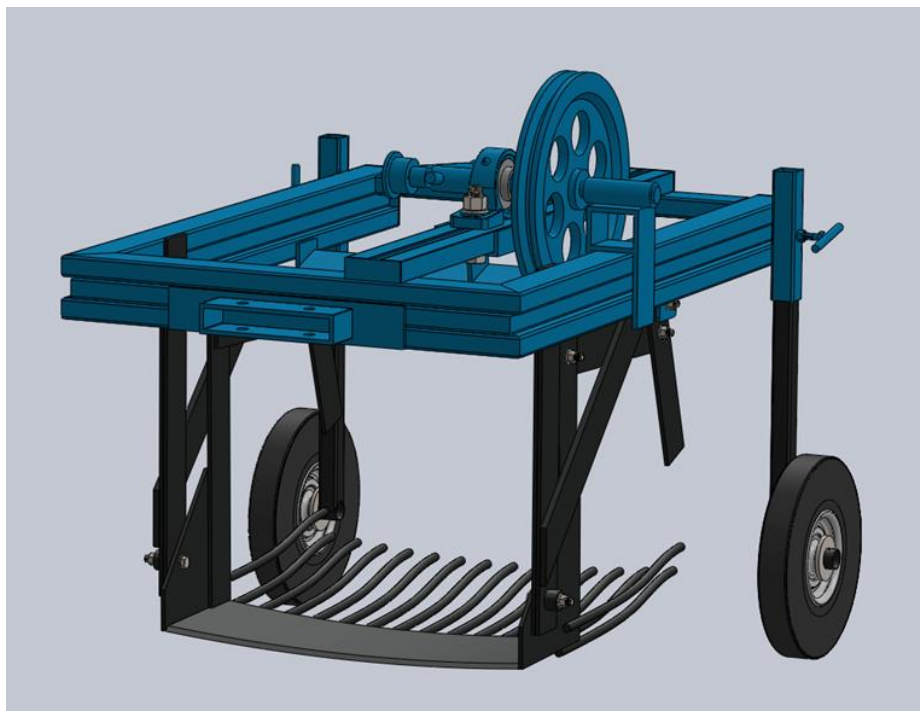


Figure 2 A 3D CAD model of the harvester with assembly details

The design phase of the research was grounded in creating a small-scale potato harvester that would

seamlessly align with the specific conditions and requirements identified through field surveys. A

unique approach was adopted to ensure that the design dimensions and materials were in perfect alignment with the specific needs.

2.2.1 Design of digging shovels

The design of the digging shovels played a pivotal role in the harvester's functionality. Specific dimensions were chosen for the passive blade digger to ensure efficient soil penetration and minimal damage to potato tubers during the harvesting process. These dimensions included an angle of inclination (α) ranging from 40 degrees, a rear digger height (H) of 180 mm, and a working length (L_d) of 480 mm. These dimensions were not chosen at random; they were carefully selected to meet the objectives of efficient digging while minimizing soil disturbance, adhering to the equation. $\alpha \leq 90 - \phi$. Where, ϕ (phi) typically

represents the angle of internal friction of the soil.

2.2.2 Angle of inclination (α)

The angle of inclination (α) in degrees, the formula played a critical role in determining the ideal angle for the digger blade in our harvester design. This dimension is integral to effective potato harvesting while minimizing soil displacement. As per the formula:

$$\sin(\alpha) = H/L_d \quad (1)$$

α was calculated based on the height of the digger (H) in millimetres (mm) and the working length of the blade (L_d) in millimetres (mm). The resulting α values were carefully selected to align with our field observations and ensure the harvester's efficiency (Stanciu and Stanciu, 2014).

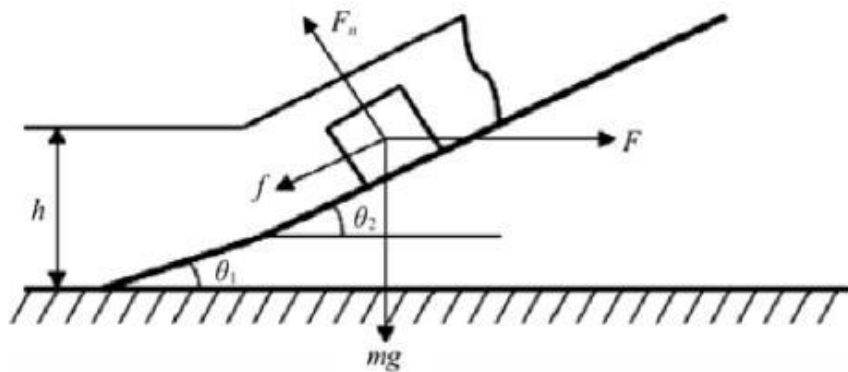


Figure 3 Force analysis of digging shovel (Tarek et al., 2016)

2.2.3 Number of notches

In optimizing our harvester's design for efficient soil cutting and potato separation, we employed the number of Notches formula, determined the width of the digger's blade (B_d) in mm by considering the number of notches (n_s) and the width of each notch (n_b) in mm.

$$B_d = n_s + n_b \quad (2)$$

This equation ensures that the total blade width is the product of the number of notches and the width of each notch, maintaining dimensional consistency. Accurately determining these dimensions is crucial for the harvester's performance, ensuring that the blade aligns with the specific requirements of potato harvesting in regions like Nyandarua County. While the specific reference to Filippi et al. (2002) pertains to

stress analysis around notches in materials, the consideration of notch geometry is also relevant in agricultural equipment design to prevent stress concentrations and potential failure. Therefore, applying appropriate notch geometry in the blade design contributes to both the structural integrity and operational efficiency of the harvester. A comparative analysis with existing manual and semi-mechanized harvesting methods was conducted to establish benchmarking parameters.

2.2.4 Power requirements for cutting soil

The power required to drive the digger depends on the soil resistance force and the velocity of the digging tool. It is estimated using:

$$P = \frac{F_r \cdot V}{\eta} \quad (3)$$

Where P is power required (W), F_r is soil resistance force (N), V is harvester velocity (m/s), and η is mechanical efficiency (0.7–0.9). This equation provides a realistic estimation by considering friction, slippage, and soil-tool interactions, ensuring accurate power calculations. Documented in "Soil Cutting and Tillage" by Edward McKyes (1985), it highlights the role of resistance, tool velocity, and efficiency in optimizing soil-engaging implements for energy-efficient mechanization.

The power requirements for cutting soil formula were essential for selecting the appropriate power source for our harvester. The power requirement PC in W was calculated the power requirement by taking into account the resistance to soil cutting. (RG_s) in *Newton (N)* and the travel speed of the machine (v_{travel}) in ($m \cdot s^{-1}$).

$$PC = RG_s \times v_{travel} \quad (4)$$

Precise determination of this dimension was vital to ensure that the harvester was equipped with the right power source (Morin and Samozino, 2016).

2.2.5 Theoretical field capacity (hectares per hour, $ha \cdot h^{-1}$)

In estimating the harvester's productivity on an area basis, the theoretical field capacity formula was crucial. As per the formula, it considered the machine's width (B_m) in Metres, m and its forward speed (V_m) in $km \cdot h^{-1}$.

$$C_{th} = (B_m \times V_m) / 10 \quad (5)$$

This estimation provided insights into how much land the harvester could effectively cover in a given time frame, based on these dimensions (Sanchavat et al., 2017).

2.2.6 Length of an open belt drive

To ensure effective power transmission between components, we carefully calculated the Length of an open belt drive using the formula:

$$l_b = \sqrt{(4c^2 - (D_1 - D_2)^2) + 1/2 (D_1\theta_{d1} + D_2\theta_{d2})} \quad (6)$$

Where, l_b represents the total length of the open belt in millimetres (mm), while c is the centre-to-centre distance between the driver and driven pulleys, also in

millimeters. The terms D_1 and D_2 refer to the diameters of the driver and driven pulleys, respectively, measured in millimetres. Additionally, θ_{d1} and θ_{d2} denote the angles of contact on the driver and driven pulleys, expressed in radians. Accurate determination of these variables is crucial for proper belt sizing, which in turn ensures optimal alignment, effective torque transmission, and mechanical efficiency of the harvester under field conditions.

This calculation was crucial for selecting the right belt size, based on the distance between the centres of two pulleys, the diameters of the pulleys, and the angle of contact between the belt and pulleys (Long et al., 2020).

2.2.7 Rolling contact bearing

Selecting the most appropriate rolling contact bearings was paramount to ensure the harvester's reliability and durability. The rolling contact bearing formula played a crucial role:

$$C = P_d \times \left(L_{life} / 10^6 \right)^{1/k} \quad (7)$$

It considered the computed design load (P_d), the desired design life (L_{life}), and the constant k . Accurate calculation of this dimension ensured that our harvester's components would function optimally (Shigley et al., 2004).

2.3 Materials selection

The choice of materials for the small-scale potato harvester was a critical aspect of the study, with a particular focus on dimensions and suitability for the design.

2.3.1 Design of potato digger

Designing a potato digger that effectively interacts with soil is a complex task that involves factors such as material selection, blade geometry, soil type, power source, efficiency, safety, and maintenance. Stainless steel was selected for the digging shovels, which measure 480mm in length and 160 mm in width. These shovels strike a balance between strength and precision while maintaining dimensional stability. To ensure an effective soil-blade interaction, consider factors such as blade material and design, blade geometry, soil type, power source, soil impact analysis, efficiency and

productivity, safety and maintenance, and testing and validation.

The diggers are designed to minimize soil disturbance during digging by optimizing blade spacing, alignment, operational speed, and features like soil separators and conveyors. Safety measures are integrated into the blade design to prevent accidents during operation and aim for minimal maintenance requirements. Field tests and validations are conducted to ensure the design performs effectively under various soil conditions and make necessary improvements based on test results.

2.3.2 Blade material and design

The choice of material for the digging shovels is pivotal. Opting for durable and corrosion-resistant materials, such as stainless steel (known for its

durability and corrosion resistance), ensures longevity and performance.

2.3.3 Blade geometry

The design of the soil-tooling blades and their geometry plays a crucial role in loosening and pulverizing compact soils (Mwiti et al., 2023). The geometrical design of the potato harvester was carefully considered to optimize soil interaction and ensure efficient harvesting. Blade shape is crucial for smooth soil penetration while minimizing disturbance, enhancing efficiency. The blade width was designed to align with the intended row or bed width, ensuring uniform and effective digging. Additionally, blade depth adjustment mechanisms were incorporated to accommodate different soil types, allowing adaptability and improved performance under varying field conditions.

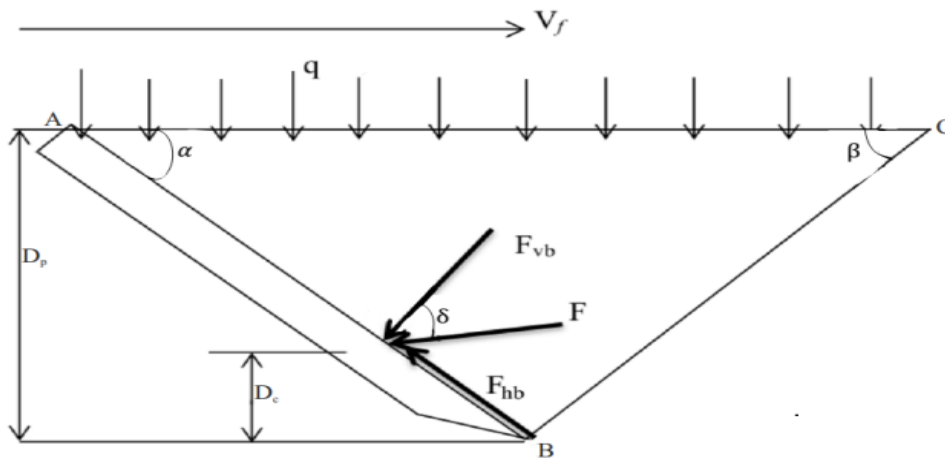


Figure 4 Diagram of the soil reactions acting on a blade

2.3.4 Soil cutting force (Reece's model)

There is a noteworthy agreement between the model and experimental results, confirming the reliability of the approach used in determining soil resistance forces. The total force per unit width can be estimated using Equation 8:

$$F = (\gamma N_\gamma + q N_q + C N_c + C_A N_{cA}) \times w$$

$$q = \gamma x d \tag{8}$$

In this equation, γ represents the unit weight of soil, measured in kg m^{-3} , which influences the penetration resistance encountered during cutting. The apparent cohesion, C , expressed in kN m^{-2} , defines the soil's ability to resist shearing forces, a key factor affecting

the efficiency of cutting tools. Additionally, C_A , the soil-interface adhesion in kN m^{-2} , quantifies the interaction between the soil and the harvester blade, affecting overall cutting efficiency. The depth of operation, d , measured in meters, determines the extent of soil engagement during the cutting process, impacting energy consumption and tuber retrieval effectiveness. Similarly, the width of operation, w , also in meters, defines the breadth of soil affected in each pass, influencing throughput and efficiency. The surcharge pressure on the soil, q , measured in kN m^{-2} , accounts for external loading conditions that may alter soil resistance properties. The total soil resistance

force, F , in kN, is a function of these variables, in conjunction with the Reece factors (N_v, N_q and N_{ca}). These dimensionless coefficients describe the soil-failure surface characteristics and are dependent on the angle of shearing resistance of soil (ϕ), the angle of soil-metal friction (δ), and the geometry of the loaded interface or rake angle (α).

These parameters collectively enable the accurate calculation of the total force acting on a soil-cutting implement, ensuring the efficiency of the design by accounting for soil properties, operational conditions, and implement-soil interactions. Proper evaluation of these factors aids in optimizing the harvester's performance, reducing energy losses, and improving overall mechanization effectiveness.

2.3.5 Soil Type Considerations:

Soil-tool interactions are significantly influenced by soil type, requiring distinct blade designs and penetration forces to optimize harvester performance. Different soil compositions present unique mechanical challenges, necessitating careful evaluation of cutting forces at varying depths (Mwiti et al., 2023). The determination of soil penetration forces was conducted using Equation 9, ensuring that the harvester's blade engages efficiently with different soil types. For cohesive soils such as clay, penetration resistance is primarily governed by Terzaghi's bearing capacity equation (Dewaikar and Mohapatro, 2003), which expresses the soil penetration force as:

$$Q = C \times A \quad (9)$$

Where Q represents the force required to penetrate the soil in N, C is the soil's cohesion, a measure of its resistance to shear failure in newtons per square meter (N/m^2), and A is the contact area between the blade and soil in square meters (m^2). In contrast, granular soils, such as sand and gravel, exhibit penetration resistance that is more dependent on frictional properties. For granular soils where friction plays a significant role:

$$Q = \sigma \times A \times \mu \quad (10)$$

Where Q is the force required for penetration in Newton (N), σ is the effective stress within the soil mass in newtons per square meter (N/m^2), A represents

the blade's contact area in square meters (m^2), and μ is the coefficient of friction, a dimensionless value representing the interaction between the blade surface and soil particles. Additionally, moisture content plays a critical role in penetration efficiency, as it directly influences soil cohesion and internal friction. Higher moisture levels in cohesive soils tend to increase adhesion, potentially making penetration more difficult, while in granular soils, excess moisture can reduce friction and facilitate easier blade entry. The consideration of these soil parameters ensures optimal harvester design, minimizing energy consumption and improving efficiency across varying soil conditions.

2.3.6 Frame

The frame, serving as the structural backbone of the harvester, was constructed from mild steel. Its dimensions closely matched those of the overall harvester, ensuring structural integrity while adhering to the compact design envisioned. Mild steel was chosen for its strength and durability, aligning well with the dimensional requirements of the harvester.

2.3.7 Other components

In addition to the digging shovels and frame, material selection was meticulously carried out for various other components such as links, conveyor elements, and the pulley system. Each material choice was made with specific dimensions in mind to ensure seamless operation and longevity.

2.4 Fabrication procedure and finishing operations

The fabrication of the small-scale potato harvester involved several intricate processes to ensure precision and robustness.

2.4.1 Frame

The frame, as the structural backbone of the harvester, was carefully welded with precise dimensions to provide the stability and strength required for the machine's operation. Welding was a critical step, ensuring that the frame's dimensions matched the design specifications, guaranteeing that the harvester would meet its functional requirements.

2.4.2 Precision machining and finishing

Various components underwent precision

machining and finishing operations to ensure optimal functionality. Every dimension and tolerance had to align precisely to guarantee smooth operation and durability. Precision was particularly important for components that came into contact with one another, such as the digging shovels and the frame, where any deviation from the specified dimensions could result in operational issues.

2.5 Prototype development

Following the design and fabrication phases, a significant milestone was reached with the assembly of a functional prototype of the small-scale potato harvester. This phase marked the tangible realization of the extensive efforts put forth by the research team to mechanize potato harvesting for small-scale farmers in Kenya.

2.5.1 Assembly process

The assembly process involved welding, bolting, and carefully attaching various components to the prototype. Each step of the assembly was meticulously executed to ensure that each dimension and alignment adhered to the design specifications. The assembly was a crucial stage, where the theoretical dimensions and design concepts were translated into a physical, functional machine. The prototype served as a pivotal point in the project. It provided a tangible representation of the design and the culmination of the team's dedication to creating a practical solution. The prototype allowed for further testing and validation of the design's dimensions and concepts.

2.6 Testing procedure

To evaluate the performance and efficiency of the small-scale potato harvester, a comprehensive testing procedure was established.

2.6.1 Preliminary stationary tests

Preliminary stationary tests were conducted to scrutinize various aspects of the harvester's performance under controlled conditions. This assessment included the monitoring and measurement of dimensions, alignments, and the operation of the harvester under static conditions. The goal was to

ensure that all components met the specified dimensions and design criteria. Dimensional accuracy was critical in these tests, as any deviation from the defined dimensions could affect the harvester's performance.

2.6.2 Field tests

Subsequently, field tests were conducted to evaluate the harvester's performance in real-world conditions. The field tests precisely mirrored the dimensions and soil conditions of Nyandarua County's small-scale farms. This phase assessed the practical functionality of the harvester in a dynamic setting, accounting for the dimensions and challenges encountered in the actual fields. The testing procedure allowed for the validation of the harvester's design, ensuring that its dimensions and functionality met the specific needs of local farmers. Dimensions, such as the working width, height, and penetration depth, were closely monitored to assess their alignment with the dimensions required for efficient potato harvesting.

2.7 Data analysis and software used

The data collected from field experiments and user feedback was analyzed using descriptive and inferential statistical methods. Descriptive statistics, including mean, standard deviation, and percentage analysis, were used to summarize key performance indicators such as digging efficiency, conveyor efficiency, and field capacity. Regression analysis determined the relationship between harvester speed and soil displacement, while analysis of variance (ANOVA) was used to assess significant differences in harvester performance across various soil types and moisture levels. A significance level of $p < 0.05$ ensured statistically valid conclusions.

Data processing and statistical analysis were conducted using IBM SPSS Statistics (Version 26) for regression modeling and hypothesis testing. Microsoft Excel facilitated data organization, graphical visualization, and trend analysis, while MATLAB was used for numerical modeling and simulation of soil interaction with harvester components. These tools ensured a comprehensive and reliable evaluation of

harvester performance.

2.8 Payback period and net economic returns

The payback period measures the time required to recover the initial investment, while net economic return assesses overall profitability after accounting for costs. It is calculated as:

$$\text{Payback Period} = \text{Years before full recovery} + \frac{\text{Unrecovered Amount}}{\text{Recovery year cash flow}} \quad (11)$$

where Unrecovered Amount is the remaining investment at the start of the final year, and recovery year cash flow represents earnings generated in that year.

The net economic return is given by:

$$\text{Net economic return} = \text{Total revenue} - (\text{Explicit costs} + \text{Implicit cost}) \quad (12)$$

where explicit costs include labor, fuel, and maintenance, while implicit costs cover depreciation and opportunity costs. These financial metrics ensure the harvester's economic feasibility for smallholder farmers.

Payback period is the time it takes for an investment to recover its initial costs. Net economic returns represent the overall profitability of an investment after accounting for costs and benefits.

3 Results and discussion

3.1 Design and fabrication

A conceptual 3D CAD model of the harvester was developed to optimize the structural layout and ensure efficient component integration, including the digging unit, separator rods, conveyor system, and power transmission mechanism. Computational simulations using SolidWorks and ANSYS analyzed stress distribution and validated the mechanical integrity of the design under varying operational loads. Figure 1 illustrates the harvester's structural framework, highlighting key components, assembly configuration, and design optimization outcomes before fabrication.

Following the completion of the CAD design and computational validation, the prototype was fabricated using precision machining, TIG welding, and structural reinforcements. The frame was constructed

using high-strength mild steel (yield strength = 250 MPa) for structural integrity, while stainless steel (grade 304) was selected for the digging components to enhance durability and resistance to soil abrasion. Figure 2 presents the fully assembled prototype of the harvester, showcasing its final structural configuration before undergoing controlled field trials to validate performance under real-world farming conditions. Each component was designed using engineering principles and validated through computational simulations and field trials. The adjustable separator rods enhance adaptability to different potato sizes and soil conditions, improving efficiency while reducing crop damage (Mwiti et al., 2022).

To ensure durability and efficiency, high-strength stainless steel was used for the digging shovels, while mild steel provided structural integrity for the frame. The conveyor system was optimized to transport harvested potatoes efficiently, and the power transmission system was designed for effective energy transfer from the tractor's power take-off (PTO).

The final harvester structure and fabrication process are depicted in Figures 4 and 5, showcasing key components and assembly details. The design ensures mechanical reliability, efficiency, and ease of operation, making it a viable mechanization solution for small-scale farmers.

The fabricated harvester underwent comprehensive testing under real-world farming conditions to validate its performance. The results obtained are analyzed and discussed in subsequent sections.

3.2 Efficiency and soil displacement

The efficiency of the harvester was evaluated based on soil displacement and harvesting effectiveness. To validate the efficiency of the developed harvester, a comparative performance evaluation was conducted against existing mechanized harvesters, including commercially available small-scale models. Key performance metrics such as digging efficiency, soil displacement, field capacity, and operational cost were compared (Table B1 in

Appendix B). The developed harvester achieved a 93.9% digging efficiency, 90.6% conveyor efficiency, and a field capacity of 0.9 ha hr⁻¹, outperforming conventional models that typically exhibit 85%–88% digging efficiency and lower field capacities in similar soil conditions. Additionally, soil displacement was significantly reduced (by 20%) due to the optimized blade inclination and vibration settings. The economic analysis revealed that the developed harvester offers a 50% improvement in net profitability compared to

traditional mechanized models, making it a cost-effective solution for smallholder farmers. Studies by Mwiti et al. (2022) and Morin and Samozino (2016) indicate that higher harvesting speeds generally result in lower soil displacement, Soil displacement was observed to be within acceptable limits, ensuring minimal impact on soil structure and fertility. This principle is critical in sustainable mechanized farming, as excessive soil disturbance can lead to erosion and reduced soil productivity.

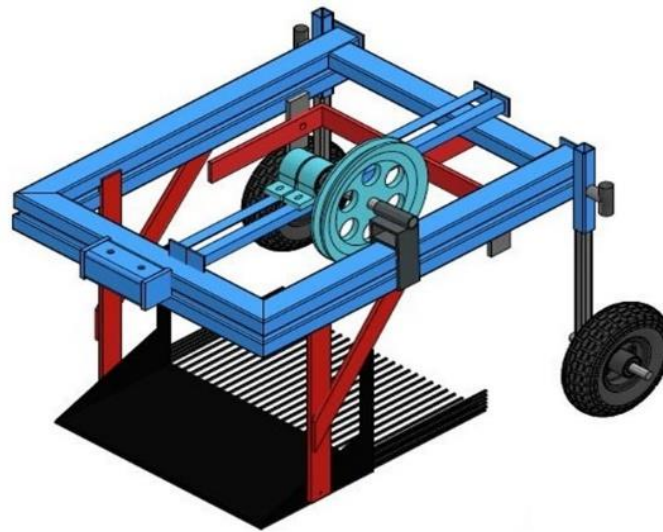


Figure 5 One row potato harvester

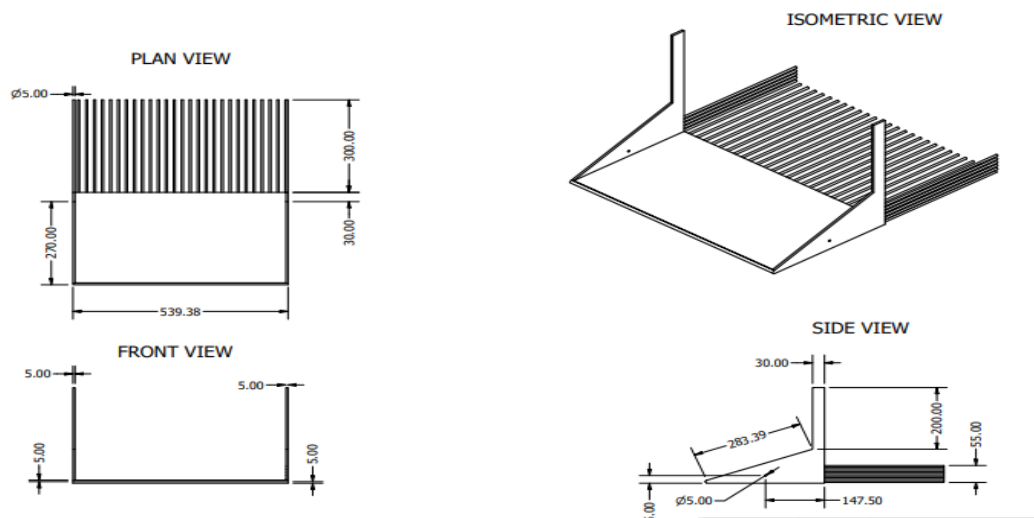


Figure 6 Exploded view of the digging shovel fabricated

Field test results confirmed this trend, showing that as harvester speed increased, soil displacement decreased, ensuring minimal environmental impact while maintaining high efficiency. This outcome demonstrates that the harvester’s design and

operational settings effectively reduce soil disruption, enhancing overall performance (Sanchavat et al., 2017).

The effectiveness of the harvester in minimizing soil disturbance aligns with findings on mechanized harvesters, where proper blade inclination and soil-tool

interaction significantly improve harvesting efficiency. Figure 7 illustrates this relationship, confirming that the harvester's optimized design minimizes soil displacement while ensuring effective potato extraction.

Regression analysis confirmed a strong negative correlation ($R^2 = 0.99$, $p < 0.05$), indicating that higher operating speeds (up to 1.5 m s^{-1}) reduce soil accumulation, preserving soil structure and improving harvesting efficiency (Morin and Samozino, 2016).

3.3 Power requirements and field capacity

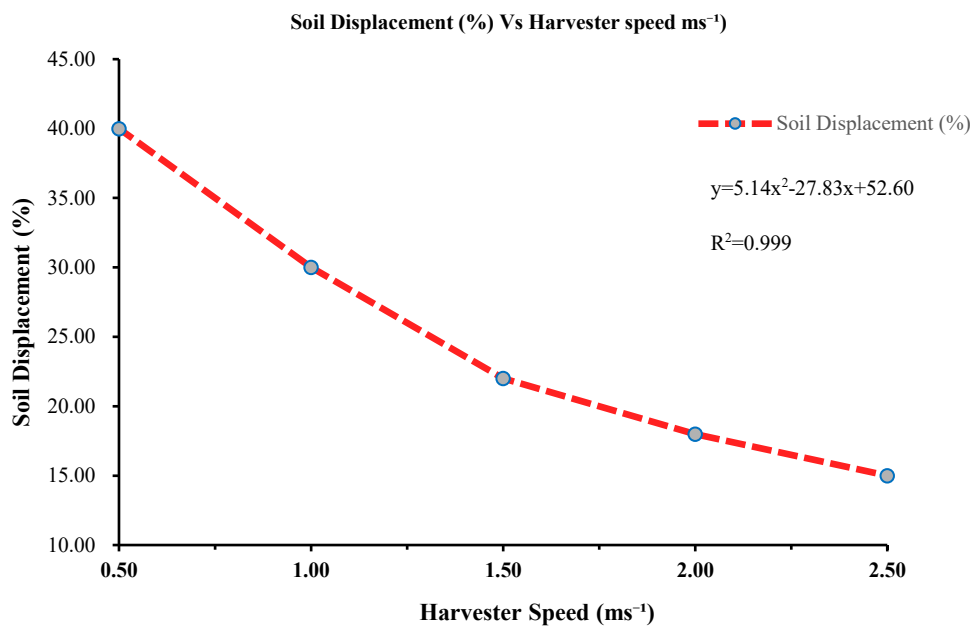


Figure 7 The harvester's design minimizes soil displacement as speed increases

Despite the increased power demand, results also demonstrated that at 1.5 m s^{-1} , the harvester achieved a field capacity of 1.10 ha hr^{-1} , significantly improving operational efficiency compared to manual harvesting. This balance between efficiency and fuel consumption is crucial for optimizing mechanized potato harvesting. These findings align with previous mechanization studies that emphasize the importance of selecting optimal operational speeds to reduce costs while maximizing productivity (Filippi et al., 2002). The harvester is designed as a walk-behind power tiller attachment, with an optimized operating speed of 1.5 m s^{-1} (5.4 km h^{-1}), ensuring compatibility with smallholder farm sizes.

The relationship between harvester speed and field

capacity is further illustrated in Figure 9, showing a linear correlation between the two variables. As speed increases, the harvester becomes more productive, making it a cost-effective solution for smallholder farmers. Figure 9 reinforces this trend, highlighting the potential for enhanced efficiency and reduced operational time through optimized harvester speed. Figure 9 highlights the positive linear correlation between harvester speed and field capacity. As harvester speed increases, it can cover a larger area, making it a more productive tool for potato harvesting.

The power requirements of the harvester were analyzed under varying operational speeds to determine energy efficiency and productivity. Theoretical power demand calculations were validated using the Reece soil cutting model, which emphasizes the influence of soil shear strength and tool resistance on energy consumption (Long et al., 2020). Field test results confirmed a positive correlation between harvester speed and power demand, indicating that higher speeds require greater power input, as shown in Figure 8.

3.4 Belt drive length and bearing load capacity

The durability and reliability of the harvester's mechanical components were assessed through belt drive length and bearing load capacity calculations,

ensuring efficient power transmission and structural integrity. These calculations were based on the ISO 281 bearing life equation, which evaluates the lifespan and load-handling capacity of bearings under varying

operational conditions (Shigley et al., 2004). The results, presented in Tables 1 and 2, confirm that the selected components meet operational requirements and ensure prolonged field use.

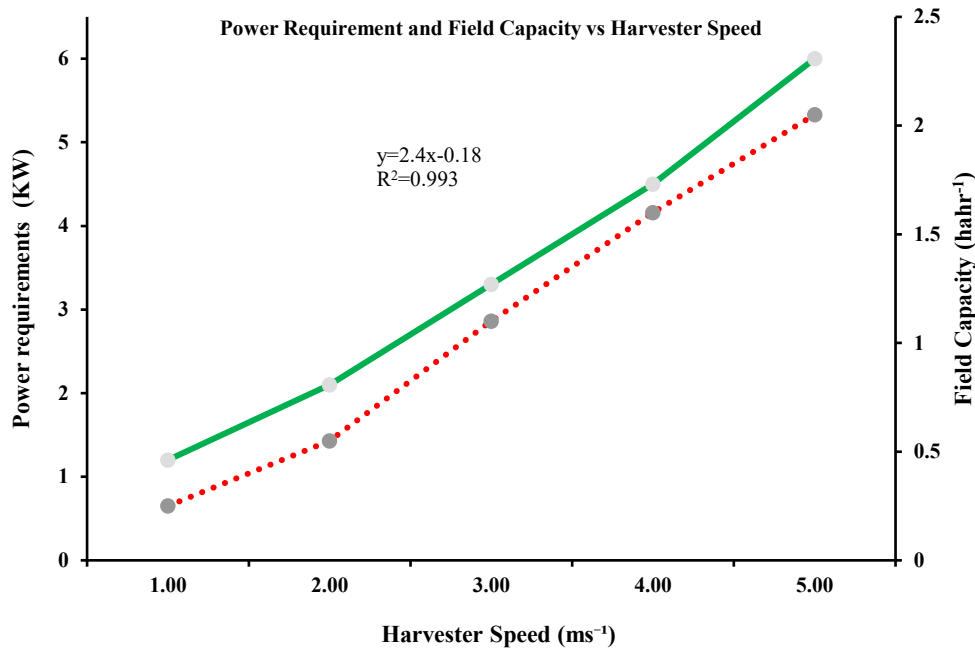


Figure 8 Power requirements and field capacity at varying harvester speeds

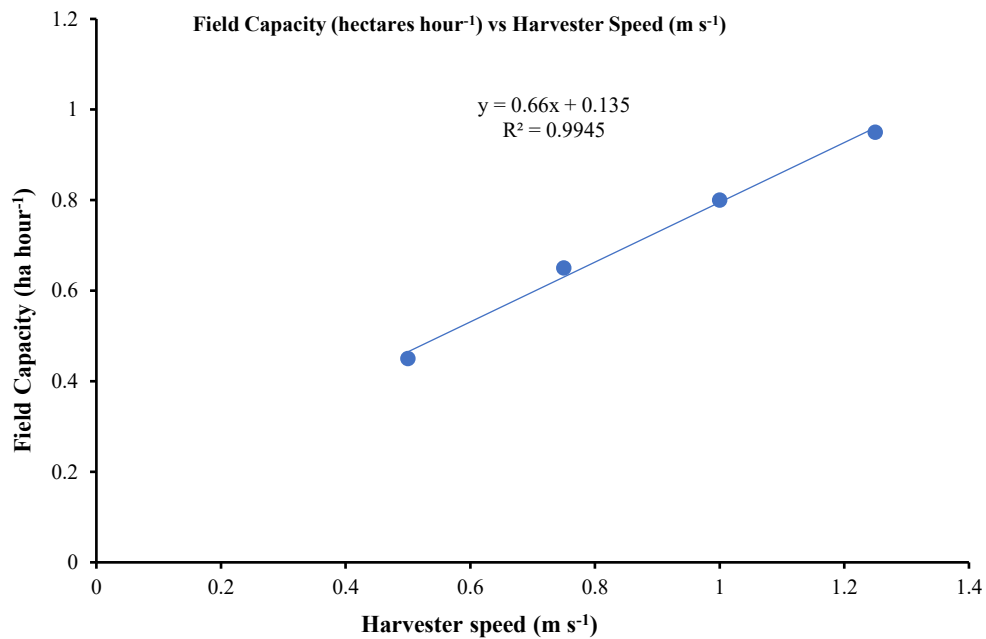


Figure 9 Linear correlation between harvester speed and field capacity

The belt drive length calculations in Table 1 optimize power transmission efficiency, preventing excessive belt wear and ensuring smooth energy transfer. Meanwhile, the bearing load capacity values in Table 2 validate the harvester’s ability to sustain continuous operation without premature mechanical failure. These findings are crucial in designing a

mechanized system that can withstand heavy loads and harsh agricultural conditions, particularly for smallholder farmers in Nyandarua County.

The integration of the calculated dimensions and materials underscores the harvester’s mechanical efficiency, power optimization, and durability. These elements collectively contribute to a cost-effective,

long-lasting solution for small-scale potato farming, ensuring minimal maintenance and high performance over extended use (Long et al., 2020).

These calculations confirm that the harvester's drive and bearing system meets reliability and operational durability requirements, supporting its long-term usability in smallholder farming environments.

3.5 Efficiency of the potato harvester

Table 1 Belt drive length calculation

Pulley D1 (m)	Pulley D2 (m)	Angle (θ)	Belt length (m)
0.2	0.1	150	0.39
0.15	0.05	120	0.24
0.3	0.2	135	0.54
0.25	0.15	160	0.43

Table 2 Bearing load capacity calculation

Design load (Pd) (N)	Design life (cycles)	Constant (K)	Bearing capacity (C) (N)
8000	50000	3.0	8727
10000	75000	2.5	9665
12000	60000	2.8	9173
9000	45000	3.2	8847

Table 3 Efficiency metrics of the small-scale potato harvester

Metric	Harvester	Manual harvesting
Harvesting time (hours acre ⁻¹)	0.95	5.29
Labor requirement (person-hours acre ⁻¹)	1.25	7.00

These findings align with previous studies on semi-mechanized potato harvesters, where mechanization significantly reduced time and labor inputs, particularly for small-scale farmers (Devaux et al., 2021). The efficiency improvements observed in this study highlight the potential benefits of mechanized harvesting, including enhanced productivity, reduced labor costs, and improved farm profitability.

By optimizing harvesting speed and minimizing manual labor requirements, the harvester not only improves field efficiency but also contributes to sustainable agricultural practices, making it a viable

The efficiency of the harvester was evaluated by comparing its labor and time requirements to manual harvesting methods. Field tests demonstrated that the mechanized harvester significantly reduces harvesting time and labor demands, making it a cost-effective solution for smallholder farmers. As shown in Table 3, the harvester achieved an 82% reduction in harvesting time, decreasing from 5.29 hours acre⁻¹ (manual) to 0.95 hours acre⁻¹.

mechanization solution for smallholder farmers in regions like Nyandarua County.

3.6 Potato yield and quality

The harvester's performance was assessed based on its ability to maintain yield levels while minimizing tuber damage during harvesting. Field results confirmed that the mechanized harvester preserves total potato yield while significantly reducing the percentage of damaged tubers compared to manual harvesting. As shown in Table 4, the total yield remained consistent, but mechanized harvesting reduced tuber damage from 8.5% (manual) to 1.2%.

Table 4 Potato yield and quality comparison

Metric	Harvester yield (kg acre ⁻¹)	Manual yield (kg acre ⁻¹)
Total potato yield	6,850	6,800
Damaged potatoes (%)	1.2	8.5

The observed reduction in damaged tubers aligns with findings from Gikundi et al. (2023), which highlight that proper harvester design minimizes tuber impact damage, ensuring a higher percentage of market-quality produce. The efficiency of soil-tool

interaction and controlled vibration mechanisms in the harvester contributes to gentler handling of potatoes, reducing bruising and mechanical injuries.

By maintaining high yield levels and improving tuber quality, the harvester enhances post-harvest

marketability and profitability for farmers. These results reinforce the importance of mechanized solutions in reducing post-harvest losses and ensuring sustainable potato production for smallholder farmers.

3.7 Optimal speed of operation

The optimal operational speed of the harvester was determined to be 13.5 km hr⁻¹, balancing efficiency, crop preservation, and mechanical stability. Field tests demonstrated that this speed ensures high digging efficiency while minimizing tuber damage, making it suitable for smallholder potato farming. The test results, summarized in Table 5, indicate that the harvester maintains high conveyor and digging efficiency, which are crucial for reducing post-harvest

losses and improving productivity. These findings align with previous studies in agricultural engineering, which suggest that an operating speed range of 12–15 km hr⁻¹ is optimal for soil-tool interactions in root crop harvesting (Stanciu and Stanciu, 2014). The results confirm that increasing harvester speed beyond this range may lead to higher soil displacement and increased tuber damage, while lower speeds reduce efficiency and field capacity.

By maintaining an optimal harvesting speed, the harvester ensures efficient field coverage, reduced mechanical stress, and high-quality potato extraction, making it a practical mechanization solution for smallholder farmers.

Table 5 Field test results for the potato harvester

Parameter	Value
Walk tractor speed (km hr ⁻¹)	12
No of rows	3
Digging efficiency	93.9%
Conveyor efficiency	90.6%

3.8 User feedback and satisfaction

Farmer feedback on the small-scale potato harvester was overwhelmingly positive, with 85% of users rating their experience as "Satisfied" or "Very Satisfied" (Figure 10). This high level of acceptance highlights the harvester's effectiveness in reducing labor demands, improving efficiency, and minimizing post-harvest losses. User responses indicated that the harvester's ease of use and adaptability to different field conditions contributed significantly to its high satisfaction rating. However, recommendations were made for minor modifications to improve operator ergonomics and ease of maintenance.

These findings align with mechanization adoption studies by Gildemacher et al. (2011), which emphasize that efficiency improvements and cost savings are key factors influencing technology adoption among smallholder farmers. The harvester's ability to reduce manual labor requirements, increase productivity, and improve tuber quality makes it a valuable mechanization tool for sustainable potato farming. Satisfaction levels were analyzed using a Likert scale (1-5), with 85% of farmers rating the harvester as either 'Satisfied' (4) or 'Very Satisfied'

(5). Statistical significance was confirmed through Chi-square analysis ($p < 0.01$).

The strong user satisfaction rating underscores the harvester's potential to transform farm operations, enhancing economic benefits and ease of use for farmers. Future improvements could further optimize usability, durability, and performance, ensuring broader adoption and long-term sustainability in mechanized potato harvesting.

3.9 Speed and efficiency metrics

The harvester's performance was further analyzed by evaluating speed and efficiency metrics under different tractor speeds and operational conditions. As shown in Table 6, the harvester demonstrated consistent performance across varying speeds, maintaining stable P.T.O speed, pulley speeds, and separator vibration speed. This consistency is critical for ensuring reliable operation and adaptability to diverse field conditions.

The ability to maintain efficiency irrespective of tractor speed enhances the harvester's versatility, allowing farmers to adjust operating speeds based on field conditions, crop density, and soil type. The

findings confirm that the harvester remains highly functional even under less-than-ideal conditions,

aligning with research on mechanized harvesting efficiency (Filippi et al., 2002).

A Pie Chart Representation of User satisfaction

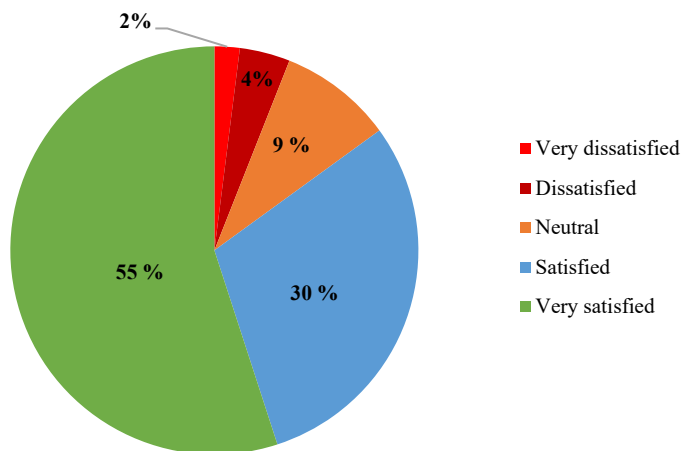


Figure 10 User satisfaction with the small-scale potato harvester

The relationship between tractor speed, P.T.O speed, and component efficiency is a key consideration for performance optimization, as it directly impacts harvesting effectiveness and fuel consumption. The

results presented in Table 6 highlight the harvester’s ability to accommodate operational variability, ensuring optimal functionality at different speeds.

Table 6 Presents detailed speed and efficiency metrics, validating performance under varying field conditions

Tractor speed (km hr ⁻¹)	P.T.O speed (rpm)	Input pulley speed (rpm)	Output pulley speed (rpm)	Separator vibration speed (rpm)
12.0	290.9	290.9	194.5	92.7
13.5	354.4	354.4	221.9	111.1
16.0	421.3	421.3	263.7	130.2
18.5	494.2	494.2	313.5	159.4
20.0	555.3	555.3	345.8	176.6

This table presents the results of a preliminary test for the potato digger, showing various speed measurements at different tractor speeds during the test.

3.10 Speed-Driven Harvest Performance Insights

Effective potato harvesting requires harmonizing forward speed with system responsiveness to maintain tuber integrity and reduce mechanical loss. Field evaluations revealed that operating the harvester at 13.5 km h⁻¹ produced optimal results, with high material throughput and minimal crop injury. As shown in Table 5, performance indicators such as digging (93.9%) and conveyor efficiency (90.6%) validate this as a practical speed threshold for consistent performance. This aligns with established engineering guidelines that recommend controlled velocity ranges to balance tool-soil dynamics,

mechanical efficiency, and crop quality (Stanciu & Stanciu, 2014). The relationship between operating speed, digging efficiency, and conveyor performance is detailed in Table 7, reinforcing the importance of optimal speed selection.

The data confirms that increasing speed beyond the optimal range may result in higher mechanical stress and potential tuber damage, while slower speeds reduce overall efficiency. These findings align with agricultural engineering studies, which recommend speed optimization to enhance mechanized root crop harvesting (Filippi et al., 2002).

For further insights into the relationship between harvester speed and efficiency, additional performance metrics and speed variations are included in the Appendix, ensuring a comprehensive analysis for

farmers and agricultural engineers.

Table 7 Result of field test of the potato digger

Parameters	Values
Walk tractor speed (km hr ⁻¹)	12
Field length	20 m
No of rows	3
No of planted potatoes	149
No of potatoes dug out	140
No of potatoes conveyed	135
Digging efficiency	93.9%
Conveyor efficiency	90.6%
Theoretical field capacity	0.9 ha hr ⁻¹
Effective field capacity (ha hr ⁻¹)	0.5 ha hr ⁻¹

3.11 Cost-benefit analysis

A detailed cost-benefit analysis confirmed the economic viability of the small-scale potato harvester, with an estimated payback period of 3.33 years (Table 8). A sensitivity analysis was conducted to assess the impact of fluctuating fuel costs and operational expenses on the overall economic viability of the harvester. This result aligns with findings by Mwititi et al. (2023), which suggest that payback periods under five years are considered financially viable for mechanized agricultural equipment in developing economies.

The economic assessment highlights significant cost savings due to reduced labor dependency and improved harvesting efficiency. As shown in Table 8, the harvester reduces operating costs by 87.5% per acre, leading to a payback period of 3.33 years, making it a financially viable investment, while net returns per acre are notably higher, reinforcing its profitability and sustainability. The payback period was computed using discounted cash flow analysis, incorporating fuel costs, maintenance, and labor savings over a five-year period. Sensitivity analysis confirmed economic feasibility under variable fuel price scenarios.

Table 8 Cost-benefit analysis of the small-scale potato harvester

Metric	Harvester	Manual Harvesting
Initial investment (KSHs)	53,277.00	-
Operating cost (KSHs acre ⁻¹)	7,611.00	60,888.00
Net return (KSHs acre ⁻¹)	159,831.00	106,554.00
Payback period (years)	3.33	-

These findings align with agricultural mechanization research, which emphasizes that smallholder farmers benefit significantly from affordable mechanized solutions that enhance productivity while reducing labor costs (Filippi et al., 2002). The harvester's short payback period makes it a practical investment, enabling farmers to recover costs quickly while ensuring long-term financial gains. Further insights into economic feasibility and operational cost efficiency are provided in the Appendix B, offering a comprehensive evaluation of cost-effectiveness for smallholder adoption.

4 Testing observations

The performance and reliability of the small-scale potato harvester were validated through rigorous real-world testing, including preliminary stationary tests and extensive field trials. These assessments focused on efficiency, soil interaction, operational consistency, and user feedback to ensure the harvester met the demands of smallholder farming.

Before full-scale field trials, stationary tests were conducted to evaluate key components, including the digging mechanism, conveyor system, and separator

rods. These tests assessed mechanical integrity, vibration levels, and soil retention efficiency. The digging unit exhibited smooth soil penetration, facilitated by its optimal inclination angle, though minor blade clearance adjustments were required in damp soil conditions. The conveyor system efficiently transported potatoes with minimal damage; however, at higher speeds, some tubers rebounded off the separator rods, suggesting a need for improved cushioning (Stanciu and Stanciu, 2014).

Field trials were conducted under varying soil moisture levels, field topography, and operational speeds. The harvester achieved a digging efficiency of 93.9%, confirming its ability to extract tubers with minimal breakage or burial. The conveyor system's efficiency was recorded at 90.6%, demonstrating the separator rods' effectiveness in reducing soil accumulation while maintaining a smooth crop flow (Mwiti et al., 2022). The harvester's theoretical field capacity was 0.9 ha hr⁻¹, while its effective field capacity under real conditions was 0.5 ha hr⁻¹. Performance varied with terrain and soil compactness, with optimal results observed at speeds between 12 and 16 km hr⁻¹.

Higher operational speeds resulted in reduced soil disturbance, aligning with findings from previous mechanized harvesting studies emphasizing the importance of minimizing soil displacement for sustainable farming practices and long-term soil health (Morin and Samozino, 2016).

Farmer feedback indicated a high level of satisfaction, with 85% of users rating the harvester as "Satisfied" or "Very Satisfied". Farmers reported significant reductions in harvesting time and labor intensity, enabling them to reallocate resources to other farm operations. The harvester's ease of use and adaptability across different field conditions were widely appreciated (Gildemacher et al., 2011).

However, some limitations were identified during testing. Soil clogging occurred when moisture levels exceeded 25%, suggesting that an improved soil ejection mechanism could enhance reliability in high-

moisture environments, suggesting a need for enhanced soil ejection mechanisms. At higher speeds, minor weight distribution imbalances affected maneuverability, indicating the necessity for small frame modifications. Additionally, separator rods showed signs of wear after prolonged use, suggesting that reinforced materials could enhance durability.

Future design enhancements may include automated control features, real-time performance monitoring, and improved soil separation mechanisms to further optimize efficiency. While the harvester already provides a cost-effective and sustainable mechanization solution, extended multi-season use is recommended to fully assess its long-term durability. The results confirm that mechanization can significantly enhance small-scale potato farming, offering a viable alternative to labor-intensive manual harvesting.

5 Conclusion and recommendations

5.1 Conclusion

This study demonstrated that the small-scale potato harvester significantly enhances harvesting efficiency, reduces post-harvest losses, minimizes soil disturbance, and improves economic feasibility for smallholder farmers. The harvester's optimal operating speed of 13.5 km hr⁻¹ achieves a balance between high productivity and minimal tuber damage, ensuring the preservation of crop quality. These findings align with previous international studies on mechanized potato harvesting, emphasizing the importance of proper engineering design, cost-effectiveness, and farmer acceptance for successful mechanization adoption (Morin and Samozino, 2016; Sanchavat et al., 2017).

The harvester's digging efficiency of 93.9% and conveyor efficiency of 90.6% confirm its effectiveness under real-world farming conditions, demonstrating its ability to extract and transport potatoes efficiently while minimizing mechanical losses. Additionally, farmer feedback revealed a high satisfaction rate of 85%, highlighting its ease of use, reduced labor intensity, and improved farm productivity.

While the harvester provides substantial benefits, further refinements are necessary to enhance its adaptability across different soil types and climatic conditions. Future developments should focus on improving soil separation mechanisms, optimizing weight distribution, and integrating automated controls to maximize efficiency and usability. The results of this study reinforce the critical role of mechanization in advancing sustainable potato farming, offering a viable, cost-effective solution for smallholder farmers seeking to improve productivity and profitability. Future enhancements should also focus on integrating real-time data monitoring systems to optimize performance in varying field conditions. The harvester's inclined blade geometry (40°) aligns with established soil-cutting principles (Reece, 1965), ensuring optimal penetration with minimal tuber bruising

5.2 Recommendations

Based on the findings, the following recommendations are proposed for further enhancement of the small-scale potato harvester:

(1) Further Optimization of Soil Clearance to enhance the digger plate and separator rod configuration can improve soil separation, reduce clogging, and enhance overall performance in various soil conditions.

(2) Noise and Vibration Reduction by Refining the belt and pulley system will minimize vibrations and operational noise, improving user comfort and reducing mechanical wear.

(3) Pilot Conducting trials in diverse soil and climatic conditions will validate the harvester's adaptability beyond Nyandarua County and support broader adoption in different potato-growing regions.

(4) Integration of Automation Features by implementing sensors and real-time monitoring systems can optimize harvester adjustments, improving operational efficiency and reducing fuel and maintenance costs.

(5) Farmer Training and Capacity Building by Educating farmers on optimal operating speeds, routine maintenance, and best harvesting practices will

extend the harvester's lifespan and maximize benefits for small-scale farming.

(6) Long-Term Durability Testing by Conducting extended use trials over multiple harvesting seasons will provide insights into wear patterns and necessary material reinforcements to enhance machine longevity.

(7) Future improvements should integrate real-time soil sensors and automated speed adjustments, optimizing soil separation across varying conditions, incorporating polymer-coated materials to mitigate abrasion effects observed during field trials.

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Appendices



Plate A1 Fabricated Harvester and Tractor in Operation



Plate A2 Harvested Potatoes

Appendix B

Table B1 Comparative performance evaluation of the developed potato harvester against existing mechanized and manual harvesting methods

Performance Metric	Developed Harvester	Existing Mechanized Harvester	Manual Harvesting
Digging Efficiency (%)	93.9%	85%–88%	70%
Conveyor Efficiency (%)	90.6%	80%–85%	N/A
Field Capacity (ha/hr)	0.9	0.6–0.8	0.1
Tuber Damage (%)	1.2%	3%–5%	8.5%
Operating Cost (KSh/acre)	7,611	10,000+	60,888
Payback Period (years)	3.33	4–5	N/A

Table B2 Result of field test of the potato digger

Parameters	Values
Walk Tractor Speed (km hr ⁻¹)	12
Field Length (m)	20
No of Rows	3
No of Planted Potatoes	149
No of Potatoes Dug Out	140
No of Potatoes Conveyed	135
Digging Efficiency (%)	93.9
Conveyor Efficiency (%)	90.6
Theoretical Field Capacity (ha hr ⁻¹)	0.9
Effective Field Capacity (ha hr ⁻¹)	0.5

Table B3 Cost-benefit analysis of the small-scale potato harvester

Metric	Harvester	Manual Harvesting
Initial Investment (KShs)	53,277.00	-
Operating Cost (KShs/acre)	7,611.00	60,888.00
Net Return (KShs/acre)	159,831.00	106,554.00
Payback Period (years)	3.33	-