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DESIGN AND FINITE ELEMENT ANALYSIS OF AN INTEGRATED POTATO DIGGER FOR SUSTAINABLE MECHANIZATION

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Abstract

Advancement in agricultural mechanization is a need of the time for applying new methods of farming for maximum crop production. Structural design of potato harvester is necessary to enhance harvesting performance, minimize the damage of tubers, and minimize the labor and energy use. This paper demonstrates a system-level optimization of integrated potato digger system, which integrates the structural FEA, modal and field validation. In contrast to the past studies that have enumerated the individual components, this paper assesses blade, frame, and pulley systems as a unit to enhance harvesting efficiency and mechanical reliability. The ANSYS Workbench was used to run Finite Element Analysis (FEA) to assess the stress distribution, deformation and structural integrity of important parts under operative loading conditions. The geometries of the blades (16, 18, 22, and 24 degrees) were tested to find the best design. The findings showed that the 24-degree blade angle gave the least stress (2.4482 MPa) and less deformation (0.00138 mm) which is structurally safe and efficient at penetrating the soil. Frame modal analysis showed that the vibration was stable in the range of acceptable frequencies (3.34 23.70 Hz), which implies that the operation is reliable. The optimized design had been made, and preliminary field test was conducted. The combined system proved to separate the soil and potatoes well using a three-step conveyor, brush rollers and slip rollers and also the direct loading into a trolley. There were, however, limitations, through the passage of hard clods and loss of small-sized tubers (<35 mm). Overall, the system that has been developed offers a cost-effective and energy-efficient method of mechanized harvesting of potatoes.

INTRODUCTION

Potato (Solanum tuberosum) is among the most significant food crops in the world, and it appears fourth after wheat, rice, and maize, and contributes a great part in the provision of food security and earning of rural population. The demand for potatoes is also increasing, which is coupled by the lack of labor and the escalation of the cost of production which have led to the urge to use efficient mechanized systems for harvesting. Nevertheless, potato harvesting is still a complicated task because of the difficulties with high levels of tuber damage, ineffective soil-potato separation, and variations in soil conditions [1][2].

A digging mechanism is an important part of potato harvesters, which directly affects draft forces, soil disturbance, and crop damage. The inappropriately designed digging blades might lead to unwarranted use of energy and structural collapses. It was established in the past that interaction between soil and tools is a major factor affecting the performance of the digging parts and structural optimization is necessary to enhance the efficiency and longevity of the parts [3]. Moreover, harvesting of potatoes entails intricate relations among soil, machine parts and crop substances, which need sophisticated design strategies.

Potato harvesting in the local farming community is usually done with tractor-pulled diggers with tubers of the crop being picked out of the field by hand as shown in Figure 1. Potatoes are collected, sorted and packed by laborers and this adds time, labor and post-harvest losses. This semi-mechanism method brings out the issue of integrated harvesting systems to enhance efficiency and decrease labor dependence.

Potato digging with conventional potato digger

Potato collection at field

Potato collection and bag filling

Potato loading

Figure 1. Currently adopted harvesting mechanism in Pakistan

Effective soil-potato separation is one of the greatest problems in potato harvesting machinery. The failure of the separation mechanisms increases the rates of damage and lowers the efficiency of harvesting. Recent research has been done on vibration assisted separation systems and conveyor mechanisms optimization to improve performance. An example here is vibration-based separation systems that have been shown to have efficiencies of more than 95 percent with lower damage rates [2]. On the same note, roller-based and chain-type separation systems have also been designed to enhance performance when operating in different field conditions [4].

Numerical simulation methods, including Finite Element Method (FEM) and Discrete Element Method (DEM), have become effective in the design of agricultural machinery with the development of computational tools. FEM can be applied extensively to study stress distribution, deformation, and structural integrity of components and DEM can be applied to study soil, crop interactions and flow behavior of materials [1]. The approaches minimize the use of expensive field tests and facilitate effective optimization at the design stage.

Recent studies have proven that FEM is effective in optimization of agricultural machinery components. Digging blades inspired by biomimetic resulted in a major decrease in draft force and a decrease in energy consumption analyzed with FEM [3]. On the same note, the design of potato planting and harvesting machines using finite elements has enhanced stability of the structure and their functionality [5]. Although this has been improved, individual components are the subject of most research as opposed to optimization at the system level.

Thus, there is necessity of thorough examination of various important elements in a single framework. The paper will fill this gap by conducting a finite element model and simulation of integrated potato digger parts, which include the blade, frame, and the pulley system. The core objective is to design and develop structures in the most efficient way, reduce the concentration of stress, and enhance mechanical efficiency to achieve sustainable and energy-efficient agricultural mechanization.

Materials and Methods

3D Design of Integrated Potato Digger

Figure 2 shows the three-dimensional (3D) and exploded view of the developed integrated potato digger. The machine was modeled as a one-pass system which included digging, soil separation and material handling systems. The digging blade, elevator/soil separation unit, pulleys and a structural frame are the main elements. The CAD tools were used to create the geometry of every component and then enter the simulation environment to evaluate the structure.

Figure 2. 3D design and explode view of integrated potato digger

Finite Element Analysis (FEA)

The analysis of the structural integrity and mechanical functioning of the primary components, such as the digging blade, the main frame, and the pulley system, was conducted with the help of Finite Element Analysis (FEA) in ANSYS Workbench. FEA has found extensive application in the design of agricultural machinery to estimate the stress distribution, deformation and failure behavior under operating loading conditions, which lowers the experimental trial costs, which are expensive [6][7].

The analysis was taken at the condition of the structure when in the statical position bearing in mind the dominant loads that occur when undertaking the digging work. Several blade geometries (four cutting angles) were considered to reach the best configuration to reduce stress concentration and deformation and retain their operational efficiency.

Material Properties

Mechanical properties of structural steel were attributed to all significant parts as it is commonly used in agricultural machinery as it is very strong, can be welded and is resistant to wear and corrosion. Table 1 shows the material parameters that were used in the simulation.

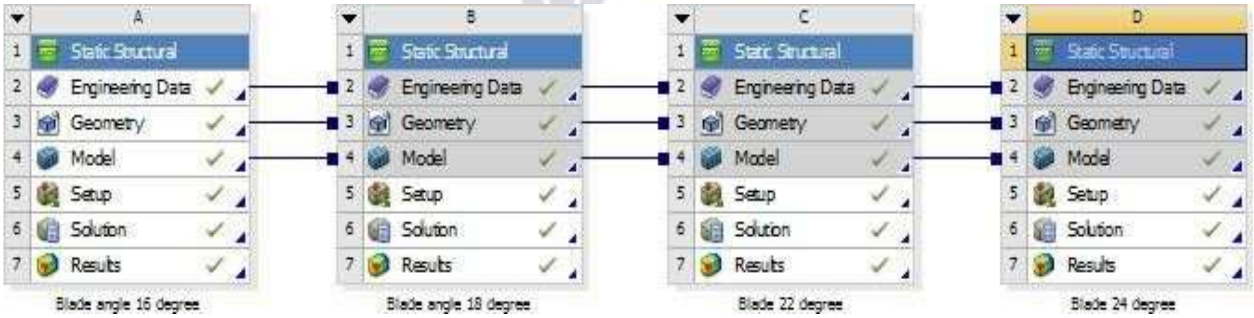
Table 1. Material Properties

Sr. No.	Property	Value	Unit
1	Density	7850	kg/m^3
2	Young’s Modulus	2.0×10^{11}	Pa
3	Poisson’s Ratio	0.30	–
4	Bulk Modulus	1.67×10^{11}	Pa
5	Shear Modulus	7.69×10^{10}	Pa
6	Tensile Yield Strength	2.50×10^{8}	Pa
7	Compressive Yield Strength	2.50×10^{8}	Pa
8	Ultimate Tensile Strength	4.60×10^{8}	Pa

The stiffness of the material is determined by the modulus of Young and the behavior of the deformation of the material when it is loaded in the lateral direction is defined by Poisson ratio. The proper simulation of the soil-tool interaction forces and structural response is impossible without the accurate representation of those parameters [8].

Static Structural Analysis

In ANSYS Workbench, stress distribution and deformation at various blade angles were analyzed using the static structural analysis (Figure 3 & 4). The purpose of the analysis was to determine the most suitable blade design that would be structurally safe and still be effective in penetrating the soil. Material yielding was also evaluated using the equivalent (von Mises) stress criterion because it is common to ductile materials, including structural steel. Complete deformation was also tested to make sure the deflections are not too high during operation [9].



Blade angle 16 degree Blade angle 18 degree Blade 22 degree Blade 24 degree

Figure 3. Static Structural different blade angles in ANSYS Workbench

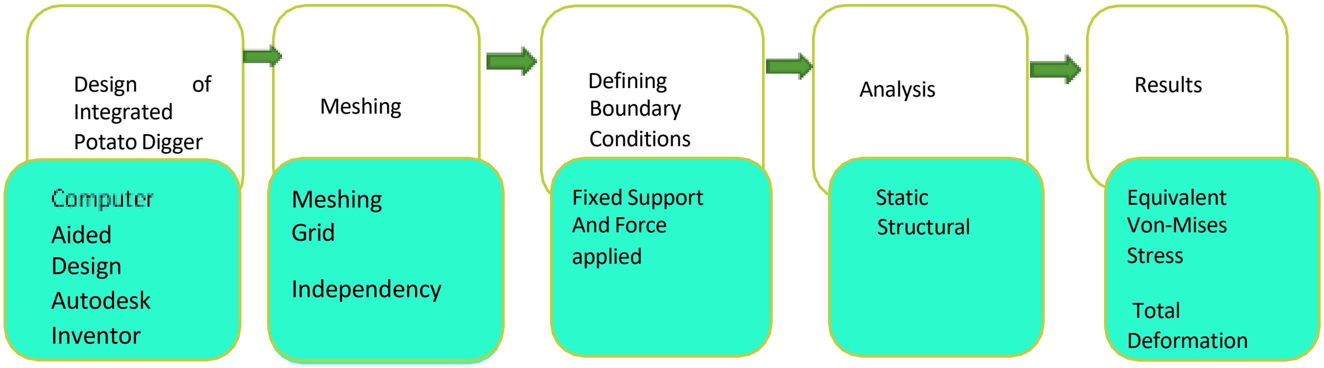


Figure 4. Flowchart of the FEA methodology

Meshing Strategy

The ANSYS meshing module was used to subdivide the CAD geometry into finite elements. The quality of the mesh is important in determining the quality and convergence of the FEA results. The mesh independence study was done by gradually refining the mesh until a small variation in the results was found in the stress. The coarse and fine meshing strategies were also implemented on critical areas like the digging blade where the high stress gradients are likely to be observed. Nearer to contact zones and sharp edges a finer mesh was considered whereas a relatively coarser mesh was taken in the low stress areas to maximize computational efficiency. This method guarantees accuracy and cost of computation [10].

Boundary Conditions

To have realistic simulation of field conditions, definition of boundary and loading conditions must be accurate. The following are the assumed in this study:

- A fixed support was given to the main frame or one end of the component and all degrees of translational and rotation were limited.
- Soil resistance forces in the form of external loads were exerted on the cutting edge of a digging blade.
- Other forces and moments were also taken to mimic the operational environment like traction and vibration.

The loads applied were founded on the common soil-tool interactions loads which were experienced during the potato harvesting activities as reported in earlier studies. A fixed support boundary condition was applied to constrain the displacement of selected regions of the model, ensuring stability during simulation. This condition assumes zero displacement and rotation, effectively representing the attachment of the component to the tractor or machine frame. The use of fixed support simplifies the analysis while providing a realistic approximation of field conditions where certain parts of the machinery remain rigid during operation.

Results and Discussion

Static Analysis was performed on ANSYS software for the analysis of the potato digger's blade different cutting angles, main frame and pulleys of different designs.

Front blade of potato digger

The digging blade is one of the important components of potato digger that is subjected to different forces and loading conditions. The efficiency of the potato harvesting process is greatly influenced by the blade's performance and durability. Finite Element Analysis (FEA) performed four different digging blade angles 16°, 18°, 22° and 24° as one side of the digging blade is fixed and the force applied on the other side.

The best optimized results Equivalent (von-Mises) stress and total deformation of the digging blade achieved on angle 24° as shown in Figure 5. According to the FEA results, the cutting edges and attachments have the highest concentrations of stress. These areas of the digging blades are critical due to direct contact with the soil and the transfer of loads from the blade to the digger frame. The Equivalent (von-Mises) Stress distribution of these different digging blade angles shows that the stress levels are within the limit and the blade can bear the imposed pressure without yielding. Strain distribution significant distribution at the cutting edges with the highest strain (deformation) observed when the blades penetrate the soil. The FEA results may help identify areas with high-stress and deformation are likely to initiate.

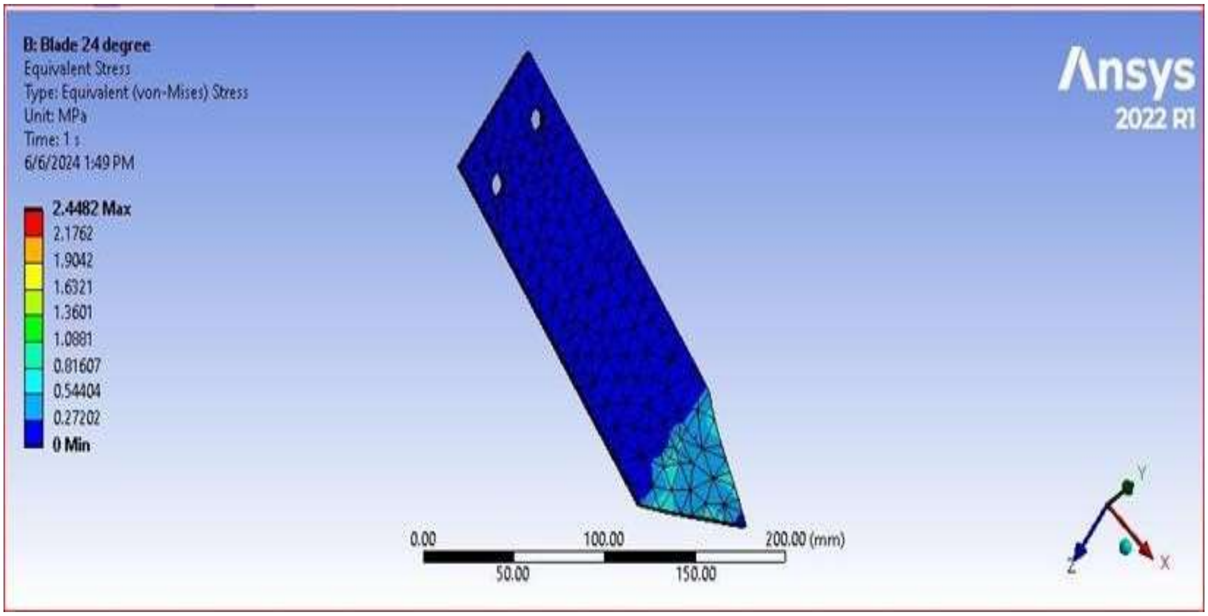


Figure 5. Blade Equivalent (Von-Mises) Stress angle 24 degree

Main Frame

One important part of an integrated potato digger is its frame, which is made to bear weights and other stresses while the potato is being dug up. Peak stress concentrations are found at the joints where the frame joins the digging components and the load bearing portions according to the FEA results. Figure 6 shows the total deformation of the digger's Frame. Peak deformation found in the joints where the frame joins the digging components and the load bearing portions according to the FEA results.

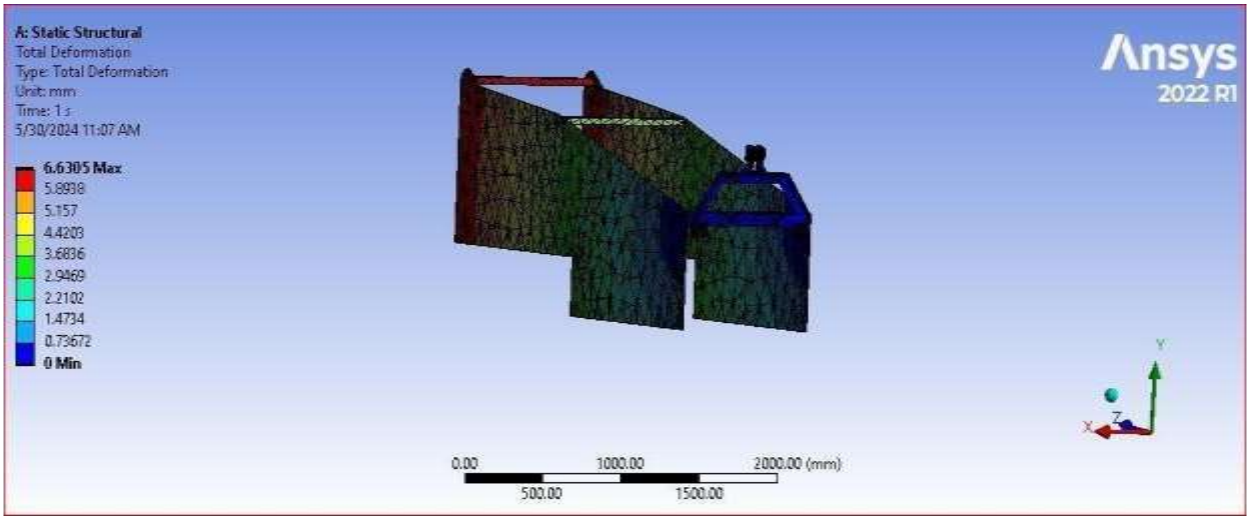
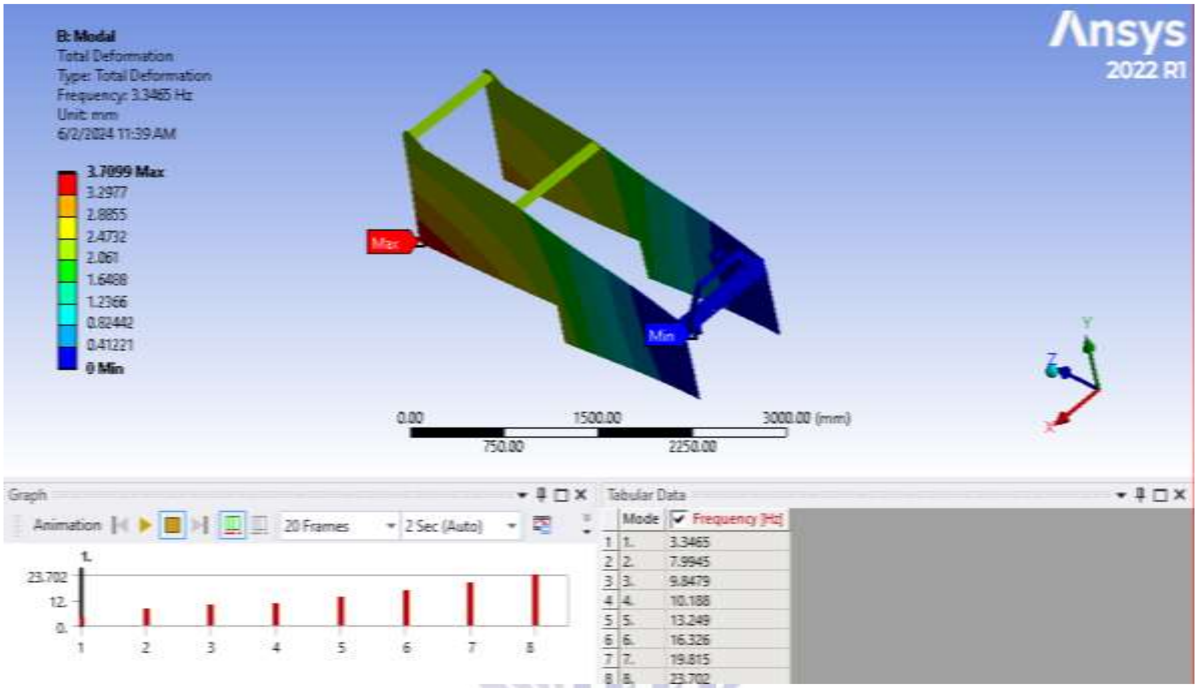


Figure 6. Digger's Frame Total Deformation

Figure 7 shows the Frame Total Deformation is 3.7099 mm at Frequency 3.3465 and mode shape 1. The modes levels to be 8 modes and Frequency values shown in the Figure 8. The maximum Frequency is 23.702 Hz at mode 8. It was observed that minimum value of Frequency at mode 1 which is 3.3465 Hz and minimum deformation as shown in simulation. The efficiency of the digging process is greatly influenced by the vibration of the frame. The quality of the harvested potato and the operating stability of the machine impacted by vibration. With amplitude fluctuation based on operating speed and ground conditions, the major vibration frequencies were found to be between 0.8981 hertz to 20 hertz which is in the acceptable limit [11].



B: Modal
Total Deformation
Type: Total Deformation
Frequency: 3.3465 Hz
Unit: mm
6/2/2024 11:39 AM

	Mode	☑ Frequency [Hz]
1	1.	3.3465
2	2.	7.9945
3	3.	9.8479
4	4.	10.188
5	5.	13.249
6	6.	16.326
7	7.	19.815
8	8.	23.702

Figure 7. Frame Modal Vibration Analysis at mode 1

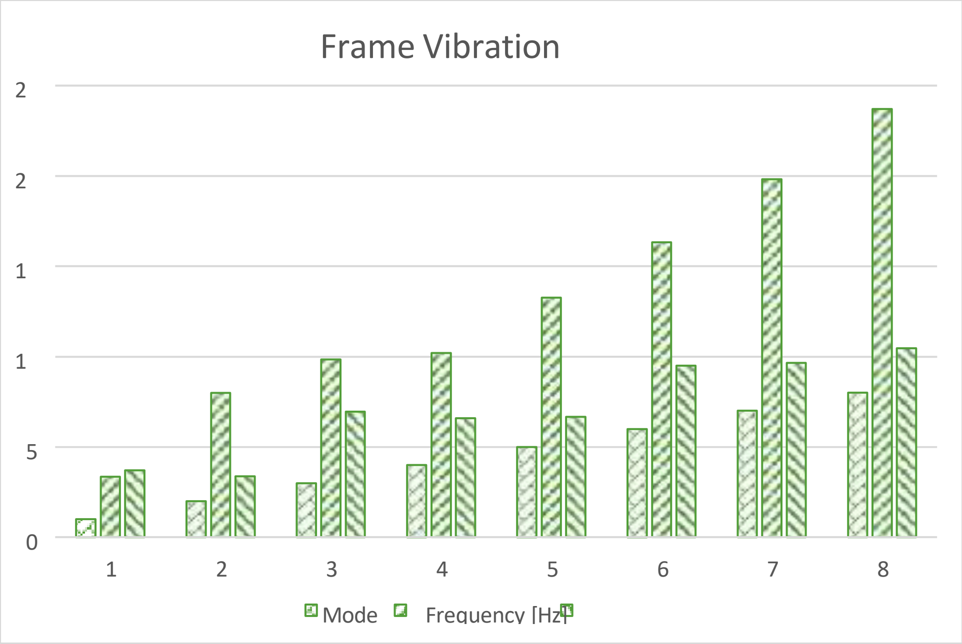


Figure 8. Graphical representation of Frame VA

Table 2 has provided a systematic design of analyzing mechanical behavior of various parts according to high stress areas, stress distribution, and strain features. It also points to very important areas where stress can be found concentration, and this is important in determining the points of failure that may happen. The stress and strain distribution allows a complete insight into the load transfer behavior and deformation behavior under working conditions.

Table 2. Mechanical behavior of various parts as per FEA

Components	High-Stress Areas	Stress Distribution	Strain Distribution	Material Performance
Digging Blade	Blade edges, attachment points	High at edges and attachment points	Significant at blade edges	Requires high-strength steel or reinforcement
Frame	Joints, connections to the tractor	Concentrated around joints	Moderate overall, high at joints	Requires fatigue-resistant materials
Pulley	Sharp edges and corner, Contact surface with belt	High stress at the contact surface between the belt and pulley	High Strain at the entry and exit of the belt due to the tension and friction forces	High strength requires and durability, Wear resistance
Conveyor System	Interaction points with soil and potatoes	Uniform but high at interaction points	Moderate, higher at wear points	Needs abrasion-resistant materials

Component specifications are optimized in terms of structural integrity and balanced load distribution. The high stress areas have been successfully reduced or relocated to lower stress areas, and this minimizes the chances of untimely failure. The distributions of stress and strain show smoother behavior in case of operational loading conditions, which proves that the optimization of geometry and the choice of material are used to improve the performance. Table 3 presents the overall specifications.

Table 3. Specifications of optimized integrated potato digger

Overall Dimensions:	Length	4800mm ± 50mm
	Width	1800mm ± 50mm
	Working Width	1400mm ± 50mm
	Height	1800mm ± 50mm
General:	Tractor Compatibility	Greater than or equal to 60 HP
	Number of Rows	2 rows at a time
	Field Capacity	Greater than or equal to 1 acre
Technical specifications:	Conveyor System	Three-stage conveyor
	Conveyors	Flatbed conveyors Spring carbon steel rods riveted with rubber sheet

	Main Frame	Heavy-duty MS frame
	Cutting Disc	Dual sided cutting disc (8mm) with adjustable depth control
	Cutting Blades	Leaf spring blades with MS Sheet at center bolted with MS square box welded with main frame
	Cleaning System	Brushes infused on a roller while sieving to clean excessive dirt from potatoes
	Loading Conveyor System	Two-step conveyor: First for further sieving and second for lifting the items towards the trolley
	Gear Box	02 Nos. gear boxes connected with MS Shaft with appropriate MS Sheet mountings
	Belt Covers	18-gauge MS Sheet
	Bearings	European Standard or equivalent
	Wheel	Two wheels, one on each side 6.00-16R inflated tires

The design of the optimized potato digger was manufactured successfully, and initial field testing was done as shown in Figure 9 and Figure 10. The machine incorporates a ridger compaction drum that will adequately cut compacted soil ridges into smaller clods and enable better separation of soil and tubers. A three-step belt conveyors system with bar spacing of about 35 mm allows partial cleaning and sideway transfer of potatoes and the presence of two brush rollers and three more slip rollers allows surface cleaning by scraping off the soil and debris. The last elevator system is effective in lifting and transferring the washed potatoes to a trolley so that the material manipulation is smooth. Nevertheless, some deficiencies were noticed in the process: even when the system operates hard and indestructible clods can still go through with the potatoes, as well as smaller tubers (smaller than 35 mm) can fall through the conveyor holes. These results indicate the aspects of future development to achieve a higher level of separation.

Main Frame

Slip roolers

	
Edge cutter disc	Conveyer drive pulleys
	
Slip rollers drive mechanism	Bar Conveyer belts
	
Ridge compaction Drums	Brush roolers

Field Testing of Intigrated Potato Digger Model

Figure 9. Integrated potato digger components machining processes, assembly and field testing

Figure 10. Integrated Potato Digger Working Model

Conclusion

This paper outlined the design, finite element analysis and field analysis of an integrated potato digger that would enhance the harvesting process and lessen labor reliance. The obtained FEA outcomes have validated the fact that structural optimization has a great impact on the performance and durability of major components, in particular, the digging blade and frame. Among the considered designs, the 24-degree blade angle showed the best performance with the least stress concentration and deformation, and this will be safe in operation under the field conditions.

The frame analysis revealed that the concentrations of stress are mostly in the areas of joints which is why reinforcement is very important in the areas that are critical. The modal analysis showed that the vibration frequencies of the structure are not out of any reasonable operating range, which means that the machine is stable enough and that the possible damage is minimal.

The developed prototype was able to combine the process of digging, separation of soil, cleaning and elevate of potatoes to trolly into a one-pass process. Ridger compaction drums, multi-stage conveyors, and roller-based cleaning mechanisms were added which made a big difference in the separation of the soil and tuber cleanliness. The design was tested in the field, which proved the practical feasibility of the design, and its applicability to local farming conditions.

Some limitations were, however, noted such as failure to fully separate hard soil clods and loss of small-sized tubers by conveyor gaps. These problems suggest that the separation and cleaning units should be optimized further, in terms of adaptive conveyor spacing and optimal moisture level harvesting to avoid clods.

The proposed integrated potato digger is a promising option for the sustainable and energy-efficient mechanization of agriculture. Future research in this area should aim at the analysis of soil-crop interaction based on DEM, separation mechanism optimization, and validation of the system on a large scale to increase the system's performance and commercial feasibility.

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