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Development and Performance Evaluation of a Tractor-Drawn Lemongrass Harvesting Machine

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ABSTRACT

The rising production of lemongrass has highlighted the need for mechanisation, especially for harvesting operations. Nonetheless, the most common method of harvesting lemongrass remains manual, which is time-consuming and labour-intensive, resulting in increasing costs. The goal of the study was to design and conduct a structural strength analysis of a lemongrass harvesting machine, followed by fabrication, and to evaluate its field performance. Field performance evaluations were conducted at different operational factors, namely forward speed and digger blade entry angle, to provide a comprehensive understanding of the machine's harvesting efficiency, crop damage, field capacity, and limitations. The results indicated increased stress levels with higher entry angles, although they remained below the material's yield strength. The stress, strain, deformation, and factors of safety of the harvester's different parts comply with resistance requirements. Entry angle analysis revealed that a 15º angle combined with a forward speed of 2 km/h provided maximised cutting efficiency while minimising resistance, resulting in optimal performance. However, higher entry angles presented challenges, leading to decreased efficiency and reduced effective field capacity. The harvested yield remains consistently high, ranging from 80% to nearly 90%. The damage percentage was very low, indicating minimal injury during harvesting. The blade of the harvester can penetrate up to the minimum and maximum cutting depths

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required for harvesting lemongrass, but field efficiency is 45% and needs further improvement. The benefit-cost ratio (BCR), payback period, and break-even point of the harvester are 1.20, 1.25 years, and 150 hours annually, respectively. Economic analysis indicates the harvester is viable for small- to medium-scale farmers.

Keywords: Design analysis, field capacity, financial analysis, and lemongrass harvester

INTRODUCTION

Lemongrass is a perennial grass belonging to the *Poaceae* family, cultivated mainly for its aromatic leaves and stalks utilised as a flavouring agent (Gaba et al., 2020). It is a multifunctional plant recognised for its aromatic characteristics and other health advantages. Recent research has emphasised its pharmacological potential, especially in anti-obesity, antidiabetic, and antibacterial effects (Rahhal et al., 2024). Lemongrass demonstrates anti-obesity properties because of its abundant polyphenols, essential oils, and dietary fibre (Brimson et al., 2021). Mechanisms involve the inhibition of digestive enzymes, appetite reduction, and modification of lipid metabolism. The essential oil especially enhances energy expenditure and reduces adipogenesis (Naz et al., 2024; Wisdawati & Razak, 2024). Research involving animal studies indicates significant reductions in fasting blood glucose levels and enhanced glucose tolerance. Limited human trials confirm these findings, indicating that lemongrass may be advantageous in diabetic control (Naz et al., 2024).

Lemongrass extracts showed significant antibacterial properties against pathogens such as Staphylococcus aureus and Candida albicans. The antioxidant properties are remarkable, with ethanol extracts demonstrating considerable effectiveness in neutralising free radicals (Balakrishnan et al., 2014). Furthermore, lemongrass is valued for its sweet citrus flavour, rendering it a favoured component in many culinary uses. The distinctive aroma, mostly attributed to citral, increases the flavour of meals, especially in Asian cuisines. Lemongrass is extensively utilized in soups, curries, and marinades, providing a unique citrus flavor (Khasanah et al., 2024; Prince et al., 2018). Notably, its application as an organic oil product is increasing in popularity due to its medicinal uses for treating different diseases. In Malaysia, lemongrass is utilised as a natural mosquito repellent and is incorporated into the manufacture of perfumes and soaps (Ahmad et al., 2025; Kamaruddin et al., 2022). The global lemongrass oil market is projected to expand from USD 41.98 million to USD 81.43 million by 2028 (Singh, 2000).

In Malaysia, local farmers continue to employ manual harvesting techniques for lemongrass rather than utilising machinery. Consequently, local lemongrass productivity fails to meet demand due to the inefficient harvesting methods employed by local farmers. Manually harvesting lemongrass poses many challenges that may affect efficiency and output. These challenges arise from an intersection of labour-intensive methods, insufficient

technical understanding among manufacturers, and ergonomic considerations that may pose health risks to workers (Kacaribu & Safarudin, 2022). Manual harvesting raises hazards of musculoskeletal disorders resulting from repetitive movements and improper postures. The absence of ergonomic measures in manual harvesting procedures intensifies these health hazards, especially in underdeveloped regions (Jain et al., 2018).

Several researchers designed harvesting machines for root and tuber crops, focusing on crop-specific design concerns and mechanisation levels. Gaadhe et al. (2023) developed a tractor-mounted harvester for carrot harvesting, with an adjusted digging depth of up to 35 cm and refined conveying belt characteristics, resulting in effective lifting with minimal crop damage. In a similar study, Shirwal et al. (2015) assessed a tractor-mounted carrot harvester including a V-shaped digging blade and soil separator, achieving harvesting efficiency of 97.8% with approximately 4.6% damage. Parab et al. (2019) introduced a manually controlled onion harvester utilising a five-bar connection mechanism, indicating possibilities for future automation. Khura et al. (2011) enhanced onion harvesting efficiency by creating a tractor-drawn method designed for specific soil and crop features. The mechanisation of potato harvesting is attracting much focus. Bangar et al. (2016) found essential design parameters, including blade geometry, operational velocity, and soil conditions, that affect tuber damage. Issa et al. (2020) developed and assessed a tractor-mounted potato digger, highlighting the impact of vibration frequency on lifting efficiency and tuber quality. Blok et al. (2025) recently presented a harvester-mounted system using a 3D form completion network, facilitating real-time potato yield calculation via RGB-D photography, thereby merging AI with harvesting. Nagendra et al. (2018) designed a tractor-drawn harvester for ginger that optimised elevator angle and speed ratios to enhance crop recovery, whereas Sanjay et al. (2015) engineered an engine-powered ginger harvester that emphasised blade design and chain drive parameters, thereby reducing labour intensity and minimising crop loss.

In contrast to root and tuber crops like carrots, onions, potatoes, and ginger, which are collected by removing singular underground storage organs, lemongrass develops in dense fibrous clusters with a broad root network and several closely arranged tillers. Effective harvesting of lemongrass necessitates severing the root mass at a suitable depth while preserving the clump's structure and reducing harm to the stems and roots. Consequently, harvesting systems intended for root and tuber crops are inappropriate for lemongrass because of the variations in crop morphology, root architecture, and harvesting necessities. Therefore, this research project aims to design and develop a tractor-mounted lemongrass harvester featuring a seven-blade digging system, vibrating conveyor separator and rubber-roller transport mechanism. These design features were developed to improve harvesting efficiency, reduce losses, and crop damage.

The local lemongrass growing sector can greatly benefit from the design of an economical harvester that employs the same energy source as a tractor. The structural efficiency of the designed lemongrass harvester was computationally modelled using SolidWorks for three-dimensional CAD modelling and finite element analysis (FEA) before fabrication. This method allowed for efficient design validation and cut down on

the need for redundant physical prototypes and design changes. The right material has also been chosen to guarantee the stiffness, strength, and stability of the body structure (Jamari et al., 2022). Additionally, the FEA conducted using SolidWorks simulation was used to evaluate the structural performance of the lemongrass harvester. The research was then conducted using an experimental testing design once computer simulation findings were obtained. Thus, the goal of this project was to design and develop a tractor-operated harvester for the harvesting of lemongrass. The performance of the developed harvester was assessed in the experimental field.

MATERIALS AND METHODS

The conception and preliminary design evaluations of the lemongrass harvester were performed to ascertain the viability of the machine structure. The harvester's design comprises essential components like the digger blade, three-point hitch, and body frame. Analyses of stress, strain, displacement, and factor of safety were conducted through design evaluation under various applied forces (Figure 1). Based on these assessments, essential design changes were implemented to guarantee structural stability. Upon confirmation, the fabrication of the lemongrass harvester was executed utilising suitable materials available in the local market. During evaluation, specific test factors such as depth of cut and harvesting efficiency were taken into account. Performance analysis assessed how much of crop loss or unharvested yield. Ultimately, the comprehensive performance assessment served as the foundation for endorsing the harvester for field deployment.

Design Considerations

The lemongrass harvesting machine was precisely designed, considering several criteria, to guarantee optimum efficiency. These elements included the grass uprooting system, the ease of fabrication and adjustment, and the mechanism for placing lemongrass after harvest. Moreover, the proposed harvester could harvest 73 cm of lemongrass in a single pass. Furthermore, the harvester was constructed to meet some design requirements including (i) capability to harvest different sizes of lemongrass, (ii) flexibility to accommodate different harvesting depths, and (iii) adjustable rpm of the conveyor for minimum damage to harvested lemongrass. These design requirements were evaluated through computational design analysis and considered in relation to the cultural practices for lemongrass harvesting in Malaysia.

Computational Design and Analysis

Design of Lemongrass Harvester

The design process flowchart clearly illustrates the procedure for designing the machine (Figure 1). The computational design was performed using the SolidWorks 2023 software. The harvester design underwent a design analysis to improve field capacity and usability.

Three-dimensional computer-aided design (3D-CAD) modelling of the lemongrass harvester is shown in Figure 2. Computer-aided engineering (CAE) and SolidWorks simulation tools were used to perform a static force and strength analysis (Miah et al., 2023).

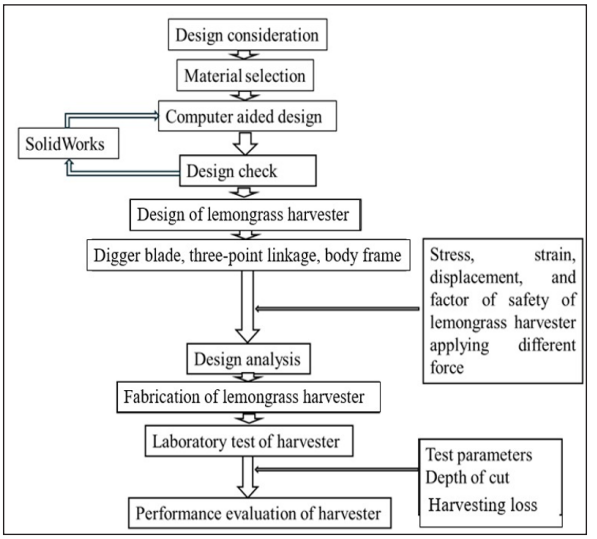


Figure 1. Design process and performance evaluation flowchart of lemongrass harvester

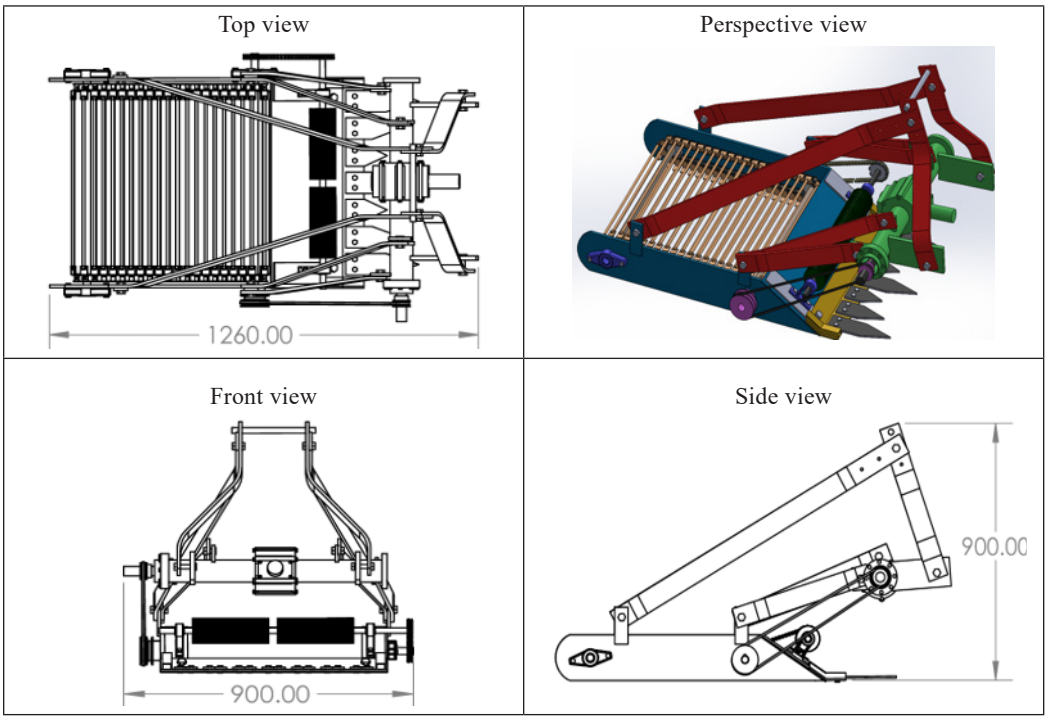


Figure 2. Different views of the lemongrass harvester

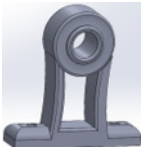
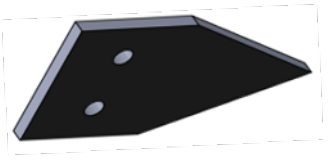
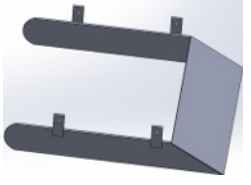
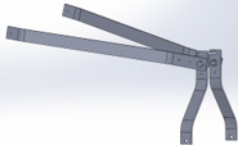
Structural Design and Description of Different Parts of Lemongrass Harvester

A tractor-operated lemongrass harvester was designed and developed at the Farm Machinery Laboratory, Department of Biological and Agricultural Engineering, Faculty of Engineering, Universiti Putra Malaysia. The main principal parts of the harvester are a digger blade, chain and sprocket, belt and pulley, conveyor belt system, support frame and rubber roller (Table 1). The blade is the main part of the digging system for uprooting lemongrass from the soil. The purpose is to harvest the lemongrass from the field while minimising soil displacement and preventing damage. The main frame serves as the foundational basis for the device, ensuring the operational components are compact. It holds all the parts of the harvester and makes an interconnection among them for easy passing of harvested lemongrass. It also protects the conveyor from foreign objects that enter during the harvesting process. The support frame is another important part that makes the connection between the harvester and the tractor. It is linked using a 3-point linkage, where the tractor can easily raise and lower the harvester and also apply draft force to move forward. The primary purpose of the rubber roller is to pull the harvested lemongrass forward to the conveyor for separating the soil from the root.

The blade is a component of the digging system used for harvesting lemongrass. This blade penetrates into the soil until it reaches the root zone of the lemongrass. The blade must penetrate the soil to a depth of 2.0 cm to 7.0 cm to reach the root zone. This blade is suitable for use on flat terrain; nevertheless, its application on uneven surfaces may result in failure. In order to provide sufficient support for the entire cutting assembly and to ensure progressive soil penetration across the working width, the digging system was built with seven blades of three different sizes. When multiple blade sizes are used instead of engaging the entire working width at once, the soil-engagement load is distributed more evenly, and the digging system encounters less initial soil resistance.

Additionally, this design minimises disturbance to the surrounding soil while facilitating the lifting of the clumps of lemongrass roots and improving soil flow around the blades. In order to promote smooth soil flow and minimise the possibility of blockage by soil clods, weeds, and crop residue, the digging system was built with a V-shaped blade arrangement (Figure 3) and suitable spacing between the seven blades. The blade spacing allows sufficient space for weeds and plant residues to move through the digging system, while the V-shaped design guides the soil laterally from the centre of the blade unit. The V-shaped digger blade is a crucial element of root digger harvesting equipment, facilitating the efficient and precise extraction of root crops from the soil during harvesting. A support frame with three predetermined nut-and-bolt mounting positions was used to modify the digger blade entry angle. A fixed blade entrance angle of 15°, 20°, or 30° with respect to the horizontal ground surface was associated with each mounting position. Before each field experiment, the support frame was secured at the proper mounting position to achieve the desired angle.

Table 1
Specification of different parts of the harvester

Name of Different Parts	Schematic Drawing	Dimension, mm	Role of the Parts
Chain and sprocket		Length- 744	Transfers the power from the conveyor belt to the rubber roller shaft
UCP bearing		UCP 204	Support the rubber roller Hold the rubber roller shaft
Digger blade		(L×W): 145x75 (S) 191x75 (M) 255×75 (L)	Digging the soil to uproot the lemongrass
Rubber roller		Diameter-90 Length-245	Pull the harvested lemongrass to the conveyor
Sprocket		Diameter 82 Teeth no. 9	Rotating the conveyor belt
Main frame		Size: 1023×730 Thickness: 10	To support and protect the conveyor from foreign objects.
Support frame		Thickness: 20	Connecting between tractor and harvester.

The vibrating conveyor is an important part of the lemongrass harvester (Figure 4). During harvesting, this conveyor has many functions. The first function is to continuously carry the lemongrass from the blade to the delivery end. The secondary function of this conveyor is to clean the roots of harvested lemongrass. It will detach the dirt from the roots

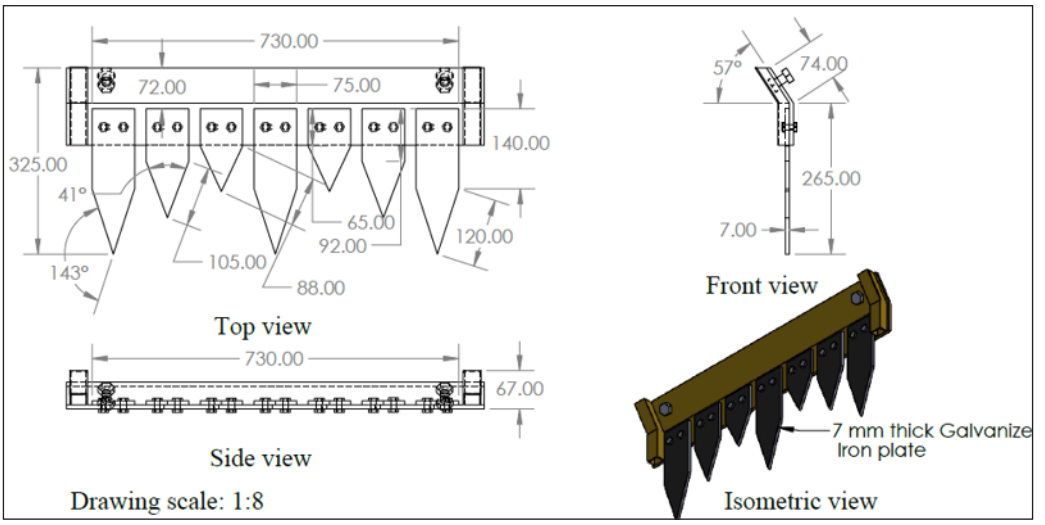


Figure 3. Different views of the digging system

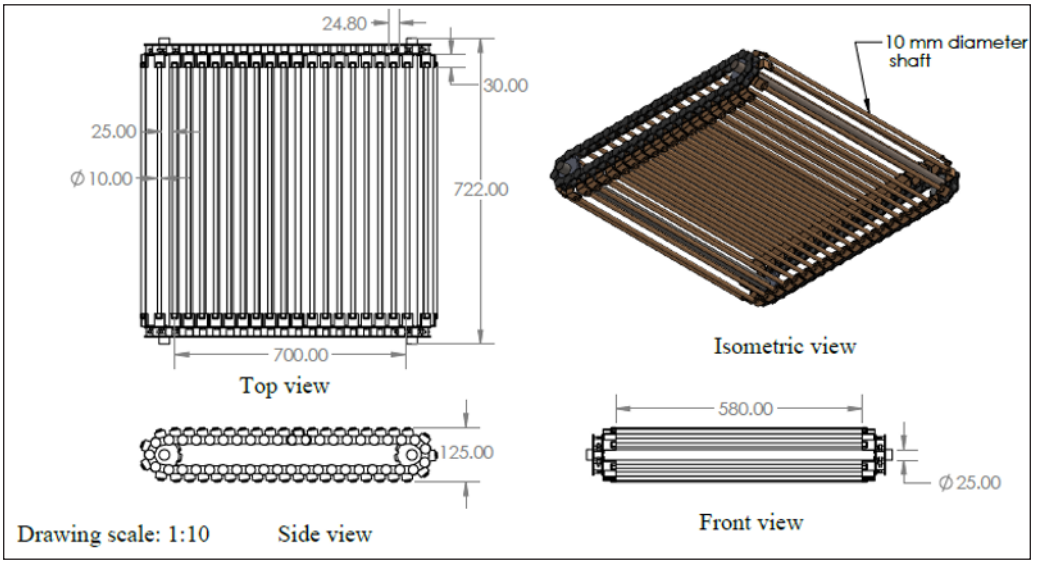


Figure 4. Different views of the conveyor on the harvester

of lemongrass; it is also known as a separator. The lemongrass becomes detached from the soil using vibration. This conveyor is designed to vibrate throughout the separating process. The chain must be adequately free, yet not excessively so, to prevent conveyor vibration that could displace the chain. The parallel rods used to make up the vibrating conveyor separator were clearly spaced apart by 25 mm. This spacing was chosen to minimise harvesting losses during conveyor operation by allowing dirt and small soil clods to pass through the separator while keeping the harvested lemongrass clumps.

Excavation Force

Loading on blades caused stress and deformation, negatively impacting the structural material. The Odey soil force model was used to calculate loads and predict total excavation forces (Odey, 2015). Figure 5 illustrates a wedge-shaped blade zone with a width w positioned in front of the tool, accompanied by an indeterminate soil failure angle. Each side features circular segments with a radius (R) that extend to the point directly opposite the bottom blade tip (S) on both sides. R and S depend upon the angle of the wedge (β). The volume of soil displaced determines the critical wedge angle, and factors such as the blade's slenderness and the necessity to convey material to the blade's slides may influence its critical wedge angle value. The angle is contingent upon two factors: blade entry angle and soil strength.

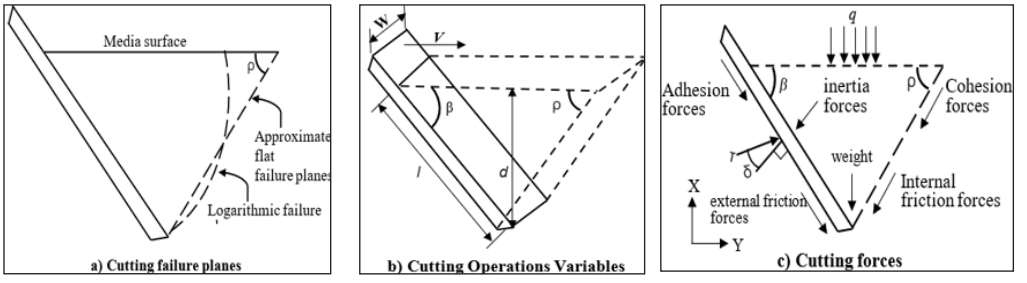


Figure 5. Odey model - three-dimensional soil cutting model (Odey, 2015)

Drag force, angle of wedge and inertia were determined for the blade according to Equations 1, 2, and 3, respectively (Odey, 2015).

$$Total\ Force(P) = \left(\Upsilon g d^2 N_\Upsilon + cdNN_c + C_a dN_{ca} + qdN_q + \Upsilon v^2 dN_a\right)W \quad [1]$$

$$[Angle\ of\ wedge\ (\beta) = \arctan\left(\frac{1}{10.255(130-2\Theta)^{(-0.4316)}}\right) - \left(\frac{1}{\tan(130-2\Theta)(\frac{180}{3.4150})}\right) \quad [2]$$

$$Inertia\ (N_a) = \frac{tan\beta + \cot(\beta+\Theta)}{[\cos(\alpha+\delta) + sin(\alpha+\delta)\cot(\beta+\Theta)][1+tan\beta\cot\alpha} \quad [3]$$

Equation 1 define P as the total force in kN, γ as the soil specific weight in kN/m^3, d as the tool working depth in m, Nγ as the dimensionless gravity coefficient, c as the soil cohesion in kPa, Nc as the dimensionless cohesion coefficient, ca as the soil-tool adhesion

in kPa, Nca as the dimensionless adhesion coefficient, q as the surface surcharge pressure in kPa, Nq as the dimensionless surcharge pressure coefficient, v as the tool speed in m/s, Na as the dimensionless inertial coefficient, and w as the tool width in m. The inertia coefficient γ, along with Nc, Nq, and Nca, are variables influenced by both the frictional strength of the soil and the geometric characteristics of the blade, as well as the strength qualities between the blade and the soil. The values of the gravity coefficient (Nγ), cohesion coefficient (Nc), and surcharge pressure coefficient (Nq) were 1.05, 1.38, and 0, respectively. These parameters are essential for the determination of draft forces in sandy soil. The values of different factors (θ (30º), γ (15 kN/m^3), c (10 kN/m^2), δ (22º), Ca (0 kN/m^2), and q (0 kPa)) are determined according to the slope of the harvester's blade and soil properties. These equations estimate the draft force exerted on the digger blade by considering the soil characteristics, blade design, and operational parameters.

Design Analysis of Lemongrass Harvester

In order to handle different loads placed on the machine, the simulation procedure must guarantee the proper safety factor, stress, and strain of the materials. In order to measure the failure of the materials in a uniaxial tensile test, the Huber-Mises-Hencky theory was used in this research (Ammarullah et al., 2023). The materials in the current computer simulation model are assumed to be consistent, isotropic, and linearly elastic (Ammarullah et al., 2021). Huber-Mises-Hencky's theory was used to compute and lower the stress, strain, displacement, and factor of safety for the harvester's most important components, including the big blade, digger blade assembly, and three-point hitch, using SolidWorks simulation (Dudda, 2018; Miah et al., 2022, 2023).

Additionally, in the design analysis, the geometric model and other relevant design parameters are taken into account to address the stress, strain, displacement, and factor of safety of various elements, as these factors are utilised in many mechanical components and would affect the overall performance of the machine (Jamari et al., 2021; Tauviqirrahman et al., 2023). Except for a portion of the chain, sprocket, and bearing, which are constructed of mild steel, most of the harvester is made of ASTM A36 steel, and mechanical properties are given in Table 2. ASTM A36 was selected due to its optimal combination of mechanical strength, weldability, accessibility, and cost-effectiveness, rendering it one of the most popular structural steels for agricultural machinery. Nevertheless, Figures 2a, 3 and 4, as well as Table 3, display the dimensions and specifications of the machine's various parts together with their typical viewpoints. However, stress analysis was carried out utilising SolidWorks software in order to enhance usability and expand the field capacity of the suggested harvester. For safety concerns, the big blade, digger blade assembly, and three-point hitch were the primary components examined. The Huber-Mises-Hencky theory was applied in this analysis to reduce displacement and stress (Dudda, 2018).

Table 2
Mechanical properties of ASTM A36 steel

Property	Value	Units
Elastic Modulus	2e+11	N/m^2
Poisson's Ratio	0.26	-
Shear Modulus	7.93e+10	N/m^2
Mass Density	7850	Kg/m^3
Tensile Strength	400000000	N/m^2
Yield Strength	250000000	N/m^2

Table 3
Technical specifications of the lemongrass harvesting machine

Characteristic	Description
Machine Dimension, cm (length × height × width)	126.00 × 90.00 × 90.00
Connection Method	3-point linkage
Working Width, cm	73.0
Excavation Depth, cm	5.0
Weight, kg	200

Fabrication of the Lemongrass Harvester

After the CAD design and computer-aided engineering (CAE) processes, the proposed design was fabricated utilising locally sourced materials (Figure 6). The overall dimensions are 1260 mm × 900 mm x 900 mm (Table 3). The fabrication expense for the harvester was USD 1500.

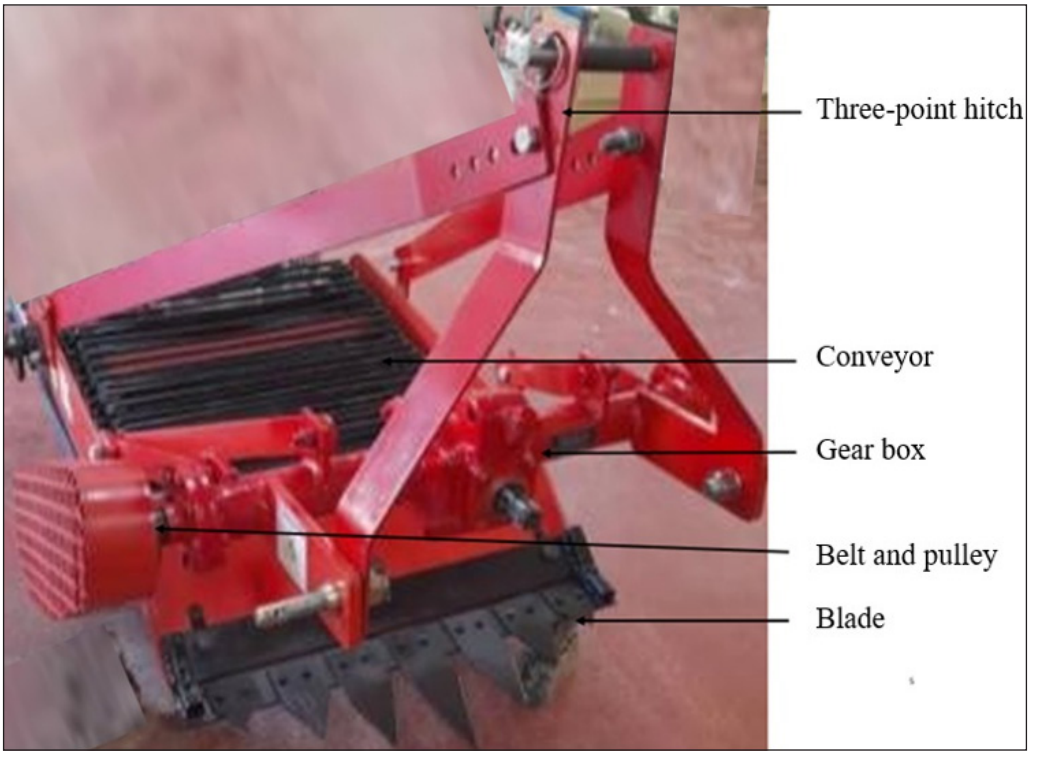


Figure 6. Structure of lemongrass harvesting machine

Working Principle of the Lemongrass Harvester

The harvester has to be connected to a tractor in order to operate correctly. Because the harvester's belt and pulley were connected to a PTO (power take-off) shaft, the conveyor and rubber roller must likewise revolve in the same direction as the PTO shaft. Power was transferred from the tractor PTO shaft to the conveyor shaft through a pulley and belt. Another side of the conveyor shaft was connected to the rubber roller shaft through a chain and sprocket. When the tractor moves forward, the digger blade enters the soil due to its inclination. The blade would uproot the lemongrass and pass it to the rubber roller; some soil would drop due to the action of the rubber roller. Then, the harvested lemongrass would come onto the conveyor vibration belt, and the soil from the root was removed due to the vibration and biting of the conveyor rod. To minimise the crop rollback toward the blade assembly and enable a smooth passage of the harvested lemongrass from the digging unit to the vibrating conveyor, these comparatively low inclination angles were chosen. Additionally, the pulley transmission system altered the conveyor's rotational speed by 1.8 times, enabling the harvested crop to be smoothly transported and minimising the risk of crop rollback and clogging.

Experiment Site and Field Test

The field experiment was conducted at Unit Sayuran, Universiti Putra Malaysia (UPM), and the plot size was 20 × 20 m. The harvester was set to run about 14.7 m in length; each entry angle was repeated three times. The experimental arrangement consisted of a Kubota M6040 tractor, with a rated power of 62 hp and a PTO rotational speed of 540 rpm (Figure 7). The conveyor speed was kept at 135 rpm, the rubber roller speed at



Figure 7. Lemongrass harvester operates in the field

220 rpm and the transmission ratio was fixed at 1:4. The experiment was arranged with three digger entry angles (15º, 20º, and 30º), and these data were analysed using SPSS Statistics 25. The criteria evaluated in the field test included the quantity of unharvested lemongrass, the cutting depth, and the field capacity. This experiment utilised sandy loam soil with a bulk density of 1420 kg/m³ and moisture content of 22.12%. To measure the corresponding performance characteristics, the equipment comprised a digital weighing balance, measuring tape, stopwatch, tachometer, moisture meter, and digital angle finder, which were used in this study. The age of lemongrass at harvest was 205 days, and the chump population was 18060 per hectare. The planting and line-to-line spacing were 60 × 60 cm, and the average root depth was 7.56 cm.

Harvesting Loss and Crop Damage

Each time that harvest was carried out, the harvested area was inspected to assess the damage to the lemongrass and to measure the harvesting loss. The total number of lemongrass clumps in the experimental area was counted. Clumps with clear mechanical damage from the harvesting operation were considered damaged (Equation 5), while clumps left in the field after harvest were considered unharvested. In the experiment, harvesting loss was defined as the percentage of lemongrass remaining in the field after harvesting, as shown in Equation 4:

$$Harvesting\ loss\ (\%) = \frac{NMHL}{TNL} \times 100 \quad [4]$$

Where NMHL is the number of unharvested lemongrass, and TNL is the total number of lemongrass in the unit area.

$$\text{Damage } (\%) = \frac{MD}{TNL} \times 100 \quad [5]$$

Where MD is the number of mechanically damaged lemongrass

Cutting Depth

It is a very important parameter of a lemongrass harvesting machine because the harvester needs to cut the soil and uproot the lemongrass. Machine performance depends on the cutting depth of the harvester; otherwise, the chance of damage will increase. So, the machine should be set at the proper depth for accurate harvesting. It is very important to know the maximum and minimum depth of cutting of the harvester. The maximum and minimum cutting depths were measured in the field after each lemongrass harvester ran. The cutting depth was measured using a measuring tape from the original soil surface to the bottom of the cut after the places corresponding to the deepest and shallowest cuts were

initially determined by eye inspection. Thirty measurements of the highest cutting depth and thirty measurements of the minimum cutting depth were taken for every treatment. The data from the three repetitions of the best treatment were utilised for statistical analysis and the creation of Kernel Density Estimation (KDE) curves.

Forward Speed

A timer and a measuring tape were utilised to quantify the time taken to travel a predetermined distance. The time required to go this distance was measured with a stopwatch. The method was conducted three times, and the average forward speed was computed according to Equation 6.

$$S = \frac{d}{t} \quad [6]$$

Where S is speed (km/h), d is driven length (km), and t is driven time period (h).

Field Capacity

Field capacity refers to the rate at which an agricultural machine performs tasks in a field within a specified timeframe. It is commonly expressed in hectares per hour (ha/h). Field capacity (FC) comprises theoretical field capacity (TFC) and effective field capacity (EFC). The TFC represents the actual rate of field coverage attained during a certain duration of harvester operation. During the operation of the harvester, EFC can be defined as the actual field rate achieved during a specified duration. The study seeks to enhance harvesting efficiency relative to conventional harvesting. The TFC and EFC were computed according to Equations 7 and 8, respectively (Hoque & Miah, 2015).

$$\text{TFC } (\text{hah}^{-1}) = \frac{SW}{10} \quad [7]$$

Where W is the width of coverage (m), and S is the forward speed (km/h)

$$\text{EFC } (\text{hah}^{-1}) = \frac{Actual\ \ field\ \ coverage\ \ (ha)}{Actual\ \ time\ \ of\ \ operation\ \ (h)} \quad [8]$$

Generally, the field efficiency of the harvester was calculated using TFC and EFC as shown in Equation 9.

$$\text{Field efficiency } (\%) = \frac{EFC}{TFC} \times 100 \quad [9]$$

Cost Calculation

The financial analysis of the developed lemongrass harvester was conducted in accordance with the established protocols for agricultural machinery management outlined by Hunt (2008). The formulas and assumptions employed to calculate the fixed costs, variable costs, yearly gross income, benefit-cost ratio (BCR), and payback period are outlined below. The cost calculation was based on the fixed and variable costs of the lemongrass harvester. The associated cost parameters were as follows.

i. Purchase cost of the harvester
ii. Salvage value of the harvester
iii. Machine life, years
iv. Bank interest rate, %
v. Annual usage of harvester, h
vi. Operator fee, USD/ha
vii. Fuel consumption, L/h
viii. Repair and maintenance expenses; and tractor rental cost (considering Malaysian conditions). The total operating cost of the developed lemongrass harvester depends on its fixed and variable costs. Fixed costs remain constant regardless of machine use, whereas variable costs occur only when the harvester is operated, as shown in Equation 10 (Hunt, 2008).

$$AC = FC + VC \quad [10]$$

The detailed cost calculation for the developed harvester is given in Table 7. Net benefit was also calculated by deducting cost from total benefit.

Fixed Cost

Fixed costs are constant and exist regardless of the utilisation of the harvester. The cost of the harvester was assessed on a yearly basis. The fixed cost of the harvester was determined using the capital consumption (CC) approach as shown in Equation 11. A capital recovery factor (CRF) consolidates total depreciation and interest fluctuations into a series of uniform annual payments at compound interest, as shown in Equation 12. This payment, along with the interest on the undervalued amount, is utilised to assess the capital consumption of agricultural machinery (Hunt, 2008).

$$\text{CC} = (P - S)CRF + S \times i \quad [11]$$

$$CRF=\frac{i(1+i)^{L}}{(1+i)^{L}-1} \quad [12]$$

Where P is the purchase price of the harvester (USD, L is the life of the harvester (yr, i is the bank interest rate (%, and S is the salvage value of the harvester (10% of P).

Variable Costs (VC)

Variable costs are associated with the operation of the lemongrass harvester, and they occur only when the harvester is used. Variable costs of the harvester are usually expressed on an hourly basis.

Break-Even point (BEP)

In the context of agricultural equipment, the break-even point (BEP) represents the least yearly utilisation of the machinery (hours/year) necessary to recoup all ownership and operational expenses, as shown in Equation 13.

$$BEP=\frac{FC}{(R-VC)}\times 100 \quad [13]$$

Where FC is an annual fixed cost (USD/year), R is a custom hiring charge or service rate (USD/h), and VC is a variable operating cost (USD/h).

RESULT AND DISCUSSION

Excavation Force Relation with Entry Angle

Odey model predicts that the excavation force of a tractor-operated lemongrass harvesting machine will increase with an increase in the entry angle (Table 4). At a penetration depth of 0.12 m and a tractor speed of 0.27 m/s, the excavation force incrementally increased from 3.056 kN at an entrance angle of 15° to 3.188 kN at 20°, ultimately attaining 3.398 kN at 30°. This pattern indicates that elevated entrance angles necessitate greater power, probably because of increased soil resistance and an expanded contact area during penetration. The

Table 4
Excavation force values of different entry angles

Depth Penetration (m)	Tractor Speed (m/s)	Entry angle (°)	Excavation force (kN)
0.12	0.27	15	3.056
		20	3.188
		30	3.398

identified correlation emphasises the impact of geometric features on excavation mechanics, essential for enhancing machine design and performance. This soil resistance force will help in the design analysis of different parts of the lemongrass harvester.

Design Analysis Results.

The design analysis outcomes for the big blade, digger blade assembly, and three-point hitch of the lemongrass harvester are presented in Figure 8, Figure 9, and Figure 10, respectively. The colours red, green, and blue in the figures represent the highest, medium, and lowest magnitudes, respectively. The design analyses were conducted based on the loads applied to certain components of the harvester. Accordingly, forces of 160 N, 400 N, and 4000 N were considered for the big blade, digger blade assembly, and three-point hitch, respectively, as these represent the maximum forces applied to the relevant components.

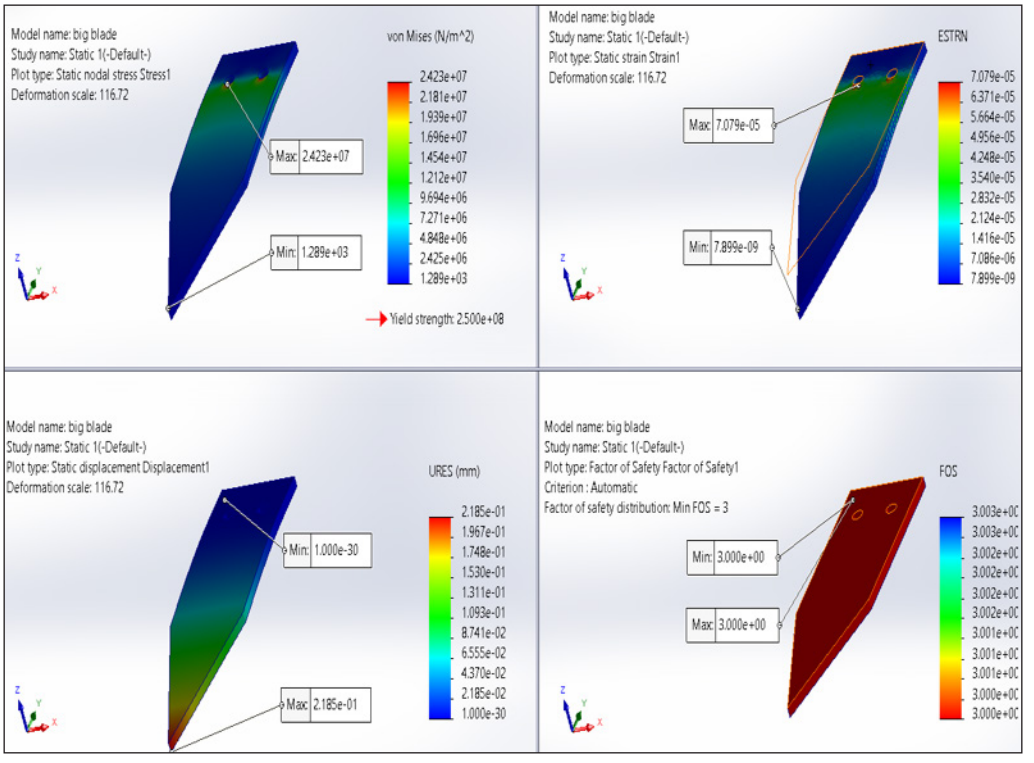


Figure 8. Big blade analysis utilising a force of 160 N for: (a) stress; (b) strain; (c) displacement; and (d) factor of safety

A safety factor of 1.0 indicates that the applied stress is equal to the material strength, and if the material is starting to deform at a specific location, there is no margin of safety (Burdekin, 2007). Figure 8 illustrates the distribution of the factor of safety, revealing that

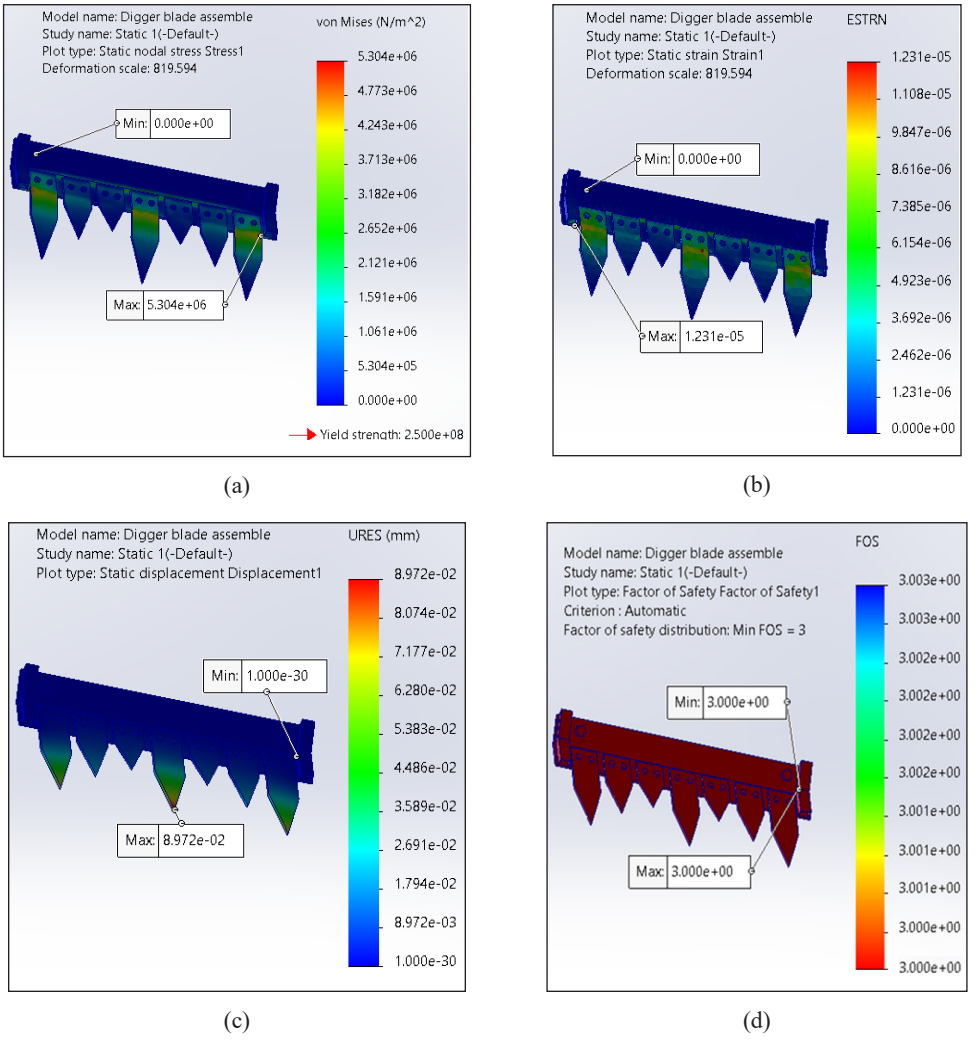


Figure 9. Digger blade analysis utilising a force of 400 N for: (a) stress; (b) strain; (c) displacement; and (d) factor of safety

the minimum factor of safety (FOS) recorded was 3. This shows that the material would begin to yield if the force is nearly tripled. The findings indicated that the yield strength of the big blade was 2.5×10^8 N/m^2, indicating that the big blade of the digging system will begin to deflect in the opposite direction when the strength exceeds this threshold (Figure 8). Miah et al. (2023) designed the furrow opener of a vegetable transplanter at FOS 1.9; however, for this digging blade, FOS was 3.0. This material commenced yielding when the von Mises stress neared the yield strength of 2.5×10^8 N/m^2. The maximum stress, strain, and displacement recorded were 2.423×10^6 N/m^2, 7.079×10^{-5}, and 0.2185 mm, respectively.

Conversely, the minimum stress, strain, and displacement were 1.289×10^4 N/m^2, 7.899×10^{-9} N/m^2, and 1.00×10^{-30} mm, respectively. The connection between the big

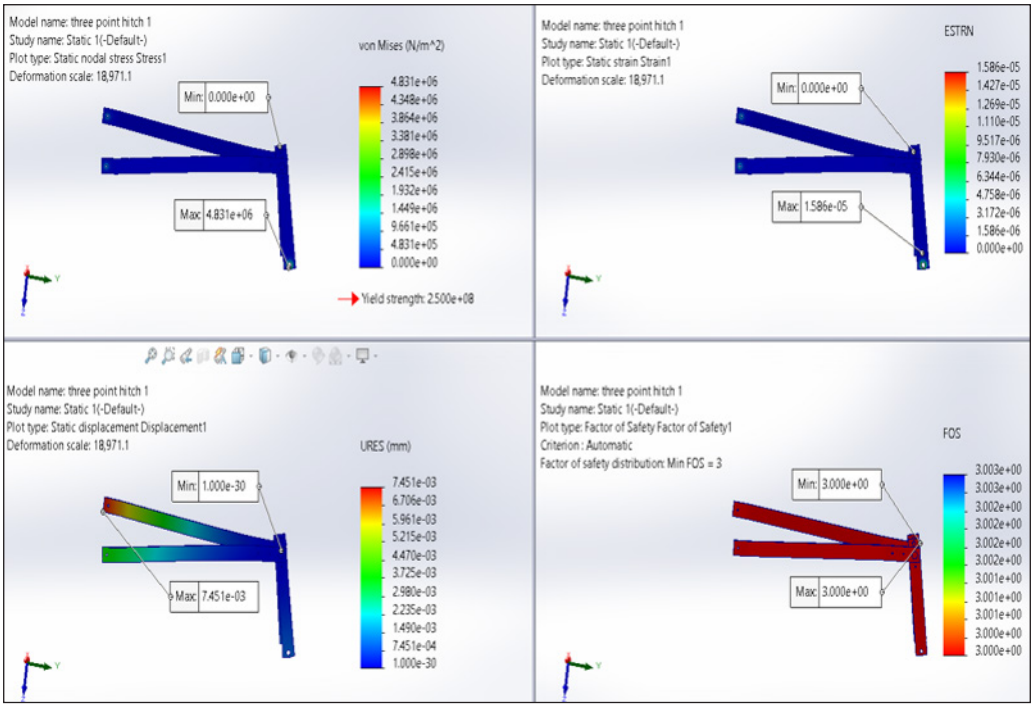


Figure 10. Three-point hitch analysis utilising a force of 400 N for (a) stress, (b) strain, (c) displacement, and (d) factor of safety

blade and the digger blade assembly was identified as the site of maximum stress and strain, which decreased progressively towards the front and rear sides. Furthermore, it was determined that the displacement was maximal near the tips of the large blades. It is important to operate the machine for at least 100 hours to find malfunctions in the different parts after fabrication (Miah et al., 2023). The developed lemongrass harvester was operated for a total period of about 100 hours over several testing days in multiple field performance evaluations conducted under normal field conditions. The machine did not undergo any systematic evaluation of durability or fatigue. During its operation, however, it was subjected to routine examination to determine the state of its main components. During the whole operating time, no substantial mechanical defects or malfunctions were found. The identical design analysis was likewise done to the digger blade assembly and the three-point hitch of the harvester, as depicted in Figures 9 and 10, respectively. Table 5 shows the results of the finite element investigation of the main structure components for the lemongrass harvester. Maximum stresses obtained in the large blade, digger blade assembly, and three-point hitch were well below the yield strength of ASTM A36 steel (2.50×10^8 N/m^2). Also, the maximum displacement was negligible, and the safety factor was 3 for all elements, indicating that the designed framework can successfully withstand the imposed stress conditions during harvesting.

Table 5
Finite element analysis results of different parts of the harvester

Component	Applied Load (N)	Maximum Stress (N/m^2)	Maximum Displacement (mm)	ASTM A36 Yield Strength (N/m^2)	Status
Big blade	160	2.42×10^{6}	2.19×10^{-1}	2.50×10^{8}	safe
Digger blade assembly	400	5.30×10^{6}	8.97×10^{-2}		safe
Three-point hitch	4000	4.83×10^{6}	7.45×10^{-3}		safe

Performance Test Results

Table 6 exhibits the effective field capacity (EFC), theoretical field capacity (TFC), and efficiency at various entry angles for the lemongrass harvesting machine. The machine underwent testing at two forward velocities (S1= 2 km/h and S2= 3 km/h) and three distinct entry angles (15º, 20º, and 30º). As the entry angle increases, the lemongrass harvesting equipment experiences higher resistance from the soil. The additional resistance comes from the machine's excavation or cutting activity at higher angles, necessitating greater energy to extract and elevate the lemongrass from the soil. As a result, the machine's efficiency is hindered, necessitating increased time and effort to cover the same area, hence diminishing its effective field capacity. The data indicates that the lemongrass harvesting machine operates most efficiently at an entry angle of 15° and a forward speed of 2 km/h, resulting in optimal field efficiency. This entry angle and forward speed allow the harvester to efficiently cover a substantial area while also making efficient use of its capacity. On the other hand, an entry angle 30º tends to result in the lowest EFC and field efficiency, making it a less favourable choice.

Field Performance at Entry Angle of 15º and Forward Speed of 2 km/h

The actual field performance of the tractor-operated lemongrass harvester and how efficient and precise the harvesting process of the harvester at an entry angle of 15º and a forward speed of 2 km/h is shown in Figure 11. Here, three graphs describe three important parameters of the harvester: successful harvesting, unharvested and damage percentage. The harvested yield remains consistently high and it is ranging from 80% to nearly 90%. This means that the harvester's performance is almost satisfactory, but there are still some challenges to improving the harvesting efficiency. On the other hand, lemongrass damage percentage was very low, indicating minimal injury occurred during harvesting. There were a few problems, such as undulation of the experimental field, varying root zone depth, and weed infestation. However, this pattern suggests that there is a need to optimise the design and control of the cutting depth and forward speed of the harvester.

Table 6
Field capacity and field efficiency at different entry angles and tractor forward speeds

Digger entry angle	Effective width (m)	Time required (h)		Theoretical field capacity (ha/h)		Effective field capacity (ha/h)		Efficiency (%)		Harvesting, %		Damage, %	
		S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
15°	0.73	0.014	0.014	0.147	0.221	0.065	0.067	44.52	30.27	85.61	81.35	5.81	8.96
20°	0.73	0.016	0.015	0.147	0.221	0.059	0.061	39.99	27.43	81.32	79.36	6.28	12.51
30°	0.73	0.016	0.016	0.147	0.221	0.056	0.058	37.96	26.36	76.57	68.24	10.37	15.24
Mean	0.73	0.015	0.015	0.147	0.221	0.060	0.062	40.82	28.02	81.17	76.32	7.49	12.24
SD	0	0.001	0.001	0.000	0.000	0.005	0.004	3.36	2.02	4.52	7.07	2.51	3.15
CV (%)	0	7.97	6.92	0.00	0.00	8.19	7.19	8.23	7.21	5.57	9.26	33.50	25.73
LSD (0.05)	-	*	*	-	-	*	*	*	*	*	*	*	*

*Significant at a 5% level of significance

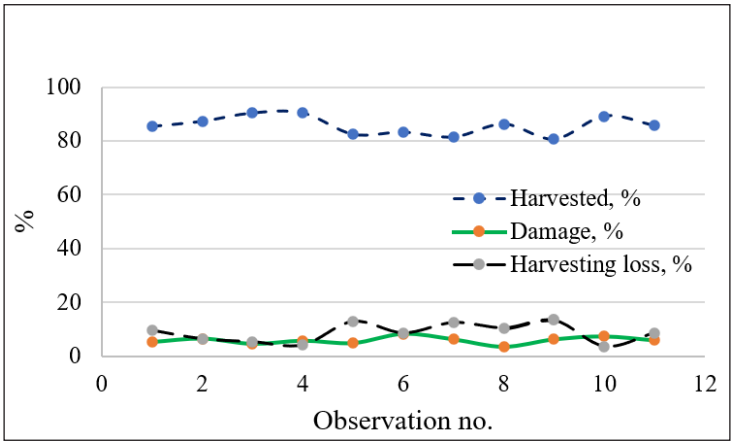


Figure 11. Field performance data of lemongrass harvester

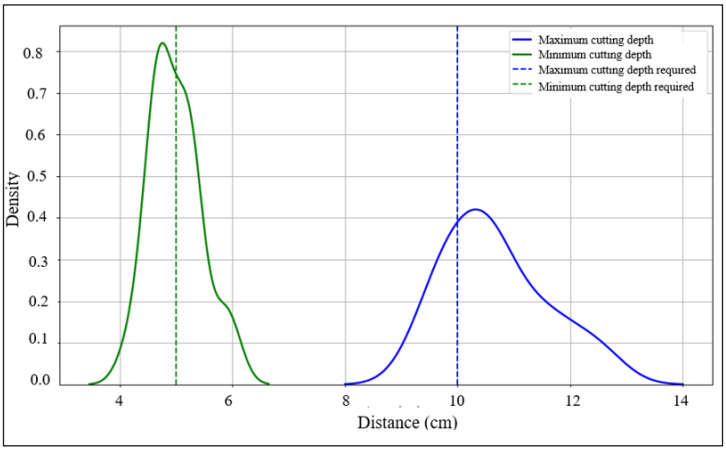


Figure 12. Lemongrass harvester cutting depth (minimum and maximum) uniformity

Minimum and Maximum Cutting Depth

Kernel density estimation (KDE) of the minimum and maximum cutting depths for a lemongrass harvester at an entry angle 15º and a forward speed of 2 km/h, showing the consistency of its cutting blade performance, can penetrate the root zone for uprooting lemongrass (Figure 12). The blue graph illustrates the distribution of maximum cutting depths. At the same time, the green curve indicates the minimum cutting depths observed during harvesting. Vertical dashed lines represent the theoretical maximum (blue) and minimum (green) cutting depths for reference purposes. It is important to know whether the cutting blade can reach up to the root zone or not. The figure shows that the density peaks for minimum cutting depth are more distinct and acute, centred at 4.8 cm. So, it is very close to the minimum cutting depth required for lemongrass uprooting.

The position of the effective rootzone of lemongrass in the soil subsurface is within 5 cm (Singh et al., 2000). The distribution of maximum cutting depth is wider and peaks at around 10.6 cm, and the required maximum cutting depth is 10 cm, which means there is no problem in terms of cutting depth. The divergence of both actual distributions from their corresponding required values indicates the developed machine can harvest lemongrass with minimal difficulty. The harvester attains consistently minimal cuts, although exhibits inconsistency at greater cutting depths. This analysis is essential for enhancing cutting methods and increasing operational efficiency.

Financial Analysis

The estimated cost to fabricate the lemongrass harvester in this project was USD 1,500. This value was used as the initial purchase cost for the financial analysis and considers an economic life of 12 years. Its typical annual use would be 720 h, assuming the bank interest is 10%, and the harvester's salvage value is 10% of the original price. Annual depreciation is calculated at USD 112.5 with a Capital Recovery Factor (CRF) of 0.147 (Table 7). The fixed cost includes capital consumption and shelter cost; if the machine did not operate for the whole year, this cost would be continuous and is USD 313.45 annually. At the same time, variable costs included fuel costs, operator wages, tractor hiring costs, and repair and maintenance costs. It depends on the machine's operating time. Here, the variable cost is USD 5690.80 annually. It was assumed that the charge for harvesting lemongrass using this harvester is USD 153/ha, and then the annual gross income reaches USD 7204.46. The benefit-cost ratio (BCR) and investment payback periods of the harvester are 1.20 and 1.25 years, respectively, indicating strong financial viability. The harvester BCR is low, and the payback period is very quick because the total cost (fixed and variable) is very high compared to gross income, but it would be profitable because the harvesting period is long (720 h/yr).

Break-Even Analysis

The break-even analysis graph shows the relationship between annual hours the harvester operates and the corresponding annual cost and returns. The X-axis represents the machine's operating hours, and the Y-axis represents the associated cost and return. There are two lines in the graph: the total cost line, which includes fixed and variable costs, and the return line, which indicates revenue from the lemongrass harvester. The break-even point is 150 hours, and the annual cost is USD 1500, where the two lines intersect (Figure 13). This means the harvester must operate at least 150 hours to cover all costs. It cannot be profitable if the machine operates below 150 hours annually. It will help the owner of the harvester to justify whether their investment will be profitable or not.

Table 7
Financial analysis of lemongrass harvester

Cost items	Estimated Value
Price of lemongrass harvester (USD)	1500
Economic life of harvester	12
Depreciation (USD/yr)	112.5
Capital Recovery Factor (CRF)	0.147
Fixed cost	
1. Capital consumption (CC), USD/yr	213.45
2. Shelter cost, USD/yr	100
Subtotal fixed cost, USD/yr	313.45
variable cost	
1. Effective operating time per day (h)	6
2. Average operation time per year (day)	120
Average operation time per year (h)	720
Fuel consumption per hour (L)	5
Diesel price in Malaysia, USD/L	0.51
Fuel cost USD/yr	1836
Repair and maintenance cost (USD/yr)	100
Operator cost in Malaysia (USD/day)	16.29
Operator cost (USD/yr)	1954.8
Tractor hiring cost in Malaysia (USD/day)	15
Tractor hiring cost (USD/yr)	1800
Variable cost (USD/yr)	**5690.8**
Total cost (USD. /yr)	**6004.25**
Field capacity (ha/h)	0.0654
Harvesting charge (USD/ha)	153
Gross income (USD/yr)	**7204.46**
Net income (USD/yr)	1200.21
Benefit cost ratio (BCR)	1.20
Payback period (yr)	1.25

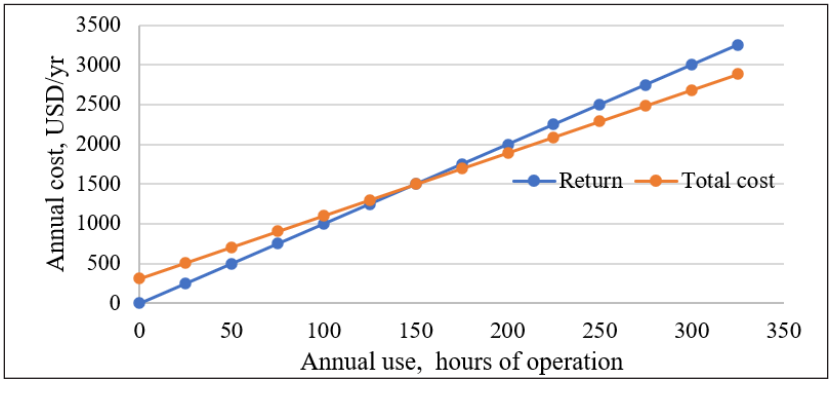


Figure 13. Break-even analysis of the lemongrass harvester

CONCLUSION

The development and evaluation of a tractor-mounted lemongrass harvesting machine showed high potential for harvesting lemongrass in a mechanised way. Through careful design and structural analysis of different parts, optimum performance was ensured with minimum harvesting loss or damage to the crop. The effective design of the V-shaped digger blade, rubber roller, supporting frame, and vibrating conveyor of the harvester ensured a desired uniform cutting depth and reliable uprooting. The blade entry angle of 15° at a forward speed of 2 km/h demonstrated the best harvesting outcomes. The harvester's economic analysis strongly supported its viability because the BCR is 1.20, and the payback period is just over one year. The field efficiency of the harvester is 45%, which means there are many challenges that need to be improved to increase the harvesting performance, such as enhancing harvesting efficiency and reducing crop damage. The lemongrass harvesting machine demonstrates potential as a practical and effective substitute for manual techniques. Its capacity to attain enhanced productivity, superior cutting precision, and less manpower demands renders it an attractive option for lemongrass harvesting operations. The harvester was developed for small to medium lemongrass producers, agricultural machinery manufacturers, and the regional lemongrass sector in Malaysia. The developed harvester was tested in particular agricultural field and crop-specific characteristics and its performance may vary due to different soil types, moisture levels and weather conditions. Additional research and development is recommended to enhance harvesting efficiency and reduce crop damage

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