

Assessment of operating parameters and economic viability of a mechanized oil palm harvester using experimental design

Frederick Abangba Akendola*, Clement Adekunle Komolafe, Abdulai Ayirebi Ankrah and Obed Ofori Yemoh

Department of Mechanical Engineering, Faculty of Engineering, University of Mines and Technology, Tarkwa, Ghana

Received: 30-July-2024; Revised: 18-February-2025; Accepted: 22-February-2025

©2025 Frederick Abangba Akendola et al. This is an open access article distributed under the Creative Commons Attribution (CC BY) License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Abstract

The labour-intensive nature of conventional (manual) oil palm harvesting necessitates the adoption of mechanized harvesters. This study employs an experimental, observational, and evaluative approach, utilizing multiple testing procedures in alignment with grounded theory. This methodology is crucial for minimizing errors. The study assesses the impact of operating parameters on the performance metrics of mechanized oil palm harvesters, with a particular emphasis on the influence of operators' skill sets, distinguishing this work from previous studies. The findings highlight the delicate balance between maximizing economic gains and addressing labour-related challenges. While mechanization promises improved sustainability and efficiency, the results indicate that operator proficiency is critical in unlocking its full potential. Despite the limitations, the mechanized oil palm harvester portrays transformative potential. Testing the study's hypothesis shows a 67% reduction in the labour force, which highlights the machine's efficiency and potential to alleviate labour stresses and risks, particularly in the landscape of African agriculture, where mechanized practices are still gaining attention.

Keywords

Mechanized oil palm harvesting, Economic analysis, Operating parameters, Labour efficiency, Operator skill impact, Sustainable agriculture.

1. Introduction

Oil palm (*Elaeis guineensis*) is a very important crop in global agriculture. The crop provides significant economic value due to its high oil yield per hectare relative to other oilseed crops. Oil palm production is mainly concentrated in tropical regions, including West Africa, Southeast Asia, and Central America. However, less developed areas in these regions have relied on manual approaches, with few embracing mechanized agriculture. The labor-intensive characteristic of oil palm harvesting poses several challenges including significant physical strain on workers, inconsistent harvest quality, and high labor costs [1].

The use of fundamental tools such as sickles and chisels to harvest the fruit bunches from relatively taller palm trees constitutes manual harvesting and often requires considerable physical effort and skill [2]. The characteristic difficulties of the manual process have necessitated the development and adoption of mechanical oil palm harvesters to enhance efficiency and reduce intrinsic dependence on labor. Mechanized harvesting systems provide the potential to improve productivity, reduce labor costs, and enhance the consistency of harvest quality [3].

Despite the great benefits of mechanization, many challenges have been identified in the adoption and optimization of mechanical oil palm harvesters. The variability in performance owing to different operating conditions and the skill levels of operators is one of the major challenges associated with mechanical oil palm harvesting [4]. Studies have demonstrated that operator proficiency greatly

*Author for correspondence

influences the effectiveness of mechanized harvesters, affecting both the speed and quality of harvesting operations [4, 5]. Also, mechanical harvesters usually encounter issues related to high initial investment costs, machine maintenance, and adaptability to various field conditions [6].

However, the transition from manual to mechanical harvesting carries significant socio-economic implications. The displacement of manual labour by machines, which sometimes faces strong opposition can lead to unemployment and socio-economic disruptions, especially in regions where agriculture is a major source of employment [7]. Hence, while mechanization promises economic and operational benefits, it also necessitates careful consideration of its broader impacts on rural communities and agricultural workers.

The motivation for this study stems from the need to address the persistent challenges of manual oil palm harvesting and to explore the potential of mechanical solutions in improving agricultural productivity and sustainability, particularly in regions where mechanized agriculture is still emerging. Given the significant role of operator skill in determining the success of mechanized harvesters, this study aims to evaluate the performance of mechanical oil palm harvesters, with a specific focus on the financial implications related to operational costs.

However, there has been limited research on the operating parameters of the harvesting equipment, creating a gap in the literature that this study aims to fill. Another research gap addressed by this work is the influence of the machine operator's skill set on performance metrics and the overall output of the machine, thus distinguishing this study from previous ones.

The objectives of this study are to determine the operating parameters of the mechanized oil palm harvester, assess the economic implications of its use, and test the hypotheses formulated for the study.

The study is structured according to the following order. Section 2 is a thorough literature review of oil palm harvesting methods and existing mechanization technologies. Section 3 outlines the methodology used in the design and fabrication of the mechanized harvester. The fourth section contains the results of the study, while Section 5 represents a discussion of the findings, highlighting their implications for further studies. Finally, Section 6 is a conclusion of

the entire study, which also offers a direction for future studies.

2.Literature review

Oil palm production is a vital component of global agriculture, contributing significantly to the economies of tropical countries [8, 9]. With the growing demand for palm oil, the adoption of efficient harvesting methods is essential. Mechanical oil palm harvesting has emerged as a promising solution, offering labour efficiency, cost-effectiveness, and operational advantages [10]. These modern harvesting machines provide precise trimming, resulting in higher yields and quality [11]. However, issues such as machine operating parameters and cost remain the focus of ongoing research to ensure the adoption and efficiency of harvesting machines [12]. Again, the next phase of development can develop sustainable practices, such as precision farming and artificial intelligence (AI)-guided harvesting techniques [13, 14]. Understanding the importance of technology is essential to meet the global demand for palm oil, reduce environmental concerns, and ensure that farmers earn a living in this important industry [15].

The research on the operating parameters of mechanical oil palm harvesters is pivotal in optimizing the efficiency of palm oil production, a cornerstone of the global edible oil industry [16, 17]. Mechanical harvesters have emerged as a vital tool to replace labour-intensive manual harvesting [18]. The effectiveness of these machines is contingent upon various operational factors [19, 20]. Firstly, the harvester's cutting height significantly influences yield and tree health [21].

Maintaining an optimal height ensures maximum fruit recovery while minimizing damage to the palm canopy [22]. Furthermore, the harvester's ground speed and forward movement play a crucial role in productivity [23]. Balancing speed with precision is imperative to avoid tree stress and losses due to unripe fruit detachment [24, 25]. The type and sharpness of cutting implements are also vital factors affecting the efficiency of mechanical harvesters [26]. Blade design and maintenance impact both fruit detachment and tree health [27].

The economics of mechanical oil palm harvesters have gained significant attention in recent years due to their potential to revolutionize the palm oil industry [28]. Traditional manual harvesting methods are labour-intensive and costly, contributing to rising

production expenses. Mechanization offers a promising solution to these challenges [22]. Studies by Jelani et al. [1] and Roles et al. [29] highlighted the efficiency gains achieved through the adoption of mechanical harvesters. They reported substantial reductions in labour costs, resulting in increased profitability for oil palm plantations.

Additionally, mechanical harvesters exhibit higher operational speeds and improved precision compared to manual labour, leading to higher yields and product quality [30]. However, initial capital investment remains a crucial consideration. Research by Akinyi [31] emphasizes the need for careful cost-benefit analysis when transitioning to mechanized harvesting. Factors such as plantation size, terrain, and maintenance expenses must be considered to ensure a favourable return on investment.

Numerous studies have adopted diverse methodologies to evaluate the performance and efficiency of mechanized oil palm harvesters. A next-generation motorized oil palm cutter was developed and evaluated using both experimental and observational approaches to assess performance metrics, including fuel efficiency and cutting speed [32]. The equipment enhanced harvesting rates by 35% relative to manual methods and significantly reduced the physical exertion required by workers. A cutting efficiency of 95% for palm trees under 6 meters but exhibited reduced effectiveness for relatively taller trees due to significant vibration. Affordability, ergonomic friendliness and enhanced worker safety stemming from reduced direct interaction with trees are the major advantages of this study. However, limitations such as fatigue during extended use are caused by vibration, and also the contribution of the gasoline engine to noise pollution and emissions.

Similarly, other researchers investigated the effect of the design of harvesting tools on work-oriented musculoskeletal disorders through ergonomic assessments and field experiments. The studies were conducted using ergonomic tool evaluation, surveys and field experiments. The outcomes of the studies revealed that tools with telescopic poles and ergonomic grips significantly minimized awkward postures, such as excessive reaching or bending. This finding was obtained by [33], where ergonomic modifications decreased shoulder and back strain by 30%. Electromyographic (EMG) analyses also demonstrated that redesigned mechanical harvesting tools reduced muscle activation in high-stress areas,

particularly the upper arms and shoulders. For instance, [34] obtained a 20% reduction in deltoid muscle activation with curved blade designs. Ergonomically enhanced mechanical harvesting tools led to faster harvesting times and reduced fatigue. Tools with telescopic poles, as per the findings of [35], significantly enhanced productivity by 15%. While the advantages of the studies include user-centred design, enhanced worker health and increased operational efficiency, they had the following overall limitations: high cost of execution, short-term assessment and the studies could not be generalized beyond the experimental setting.

Other studies have concentrated on the integration of advanced technologies into harvesting machines. Ahmada et al. [36] assessed two oil palm harvesting tools on a technical and economic perspective using a comparative analysis approach to assess and evaluate cost-effectiveness and operational efficiency. The outcome showed that conventional sickle-based tools are efficient for young palms up to 4 meters in height, allowing for high fruit recovery rates with reduced injury to the fruit or palm trees. Also, conventional sickle tools have low acquisition and maintenance costs, making them suitable for small-scale farmers. The merits include lightweight and easy-to-handle equipment, minimal training requirements, and relatively low upfront investment. Nonetheless, this harvesting approach has its limitations. These include excessive worker fatigue over extended periods, low efficiency for palms taller than 4 meters due to the need for alternative tools, and variable productivity depending on operator skill and physical fitness. Conversely, mechanical harvesting equipment enhanced harvesting speed by 20-30% relative to sickle-based tools, especially for palm trees taller than 4 meters. However, they are less effective for palms under 3 meters due to challenges faced by machine operators when manoeuvring. Again, whereas mechanical harvesting equipment involves higher initial investment and maintenance costs, their efficiency in large-scale operations reduces the overall labour cost per ton of fresh fruit bunches (FFB) harvested. With high initial and maintenance costs that make them less accessible for small-scale farmers, increased operational costs and adverse environmental concerns due to fossil fuel consumption, and operator training that serves as an adoption barrier being the major limitations encountered, the advantages are faster harvesting with less operator fatigue, their suitability for taller palms (3-6 meters), offering a broader operational

range and a reduced labour dependency in regions with limited workforce.

Chikelu [35] designed and made a telescopic palm fruit harvester and demonstrated its effectiveness in bringing down harvesting time by 50% compared to conventional methods. Anuar and Jaafar [37] evaluated oil palm operations, where much focus was placed on mechanized FFB harvesting, and found a significant increase in harvesting efficiency and a reduction in labour costs. Mechanized harvesting offers increased efficiency, reduced labour costs, and improved worker safety. Mechanized harvesters like the ones studied by Chikelu [35] enable faster and more consistent harvesting operations. Additionally, the ergonomic improvements discussed by Anuar and Jaafar [37] enhance workplace safety, reducing the risk of accidents associated with conventional manual harvesting. Furthermore, mechanization helps mitigate labour shortages that are prevalent in many oil palm-growing regions. Despite the benefits involved, mechanized harvesting also presents critical limitations and challenges. The initial investment cost for mechanized equipment can present a hindrance for smallholder farmers, as highlighted by Gai et al. [30], who highlighted the need for affordable and accessible mechanical solutions. Again, the proficiency of operators plays a crucial role in realizing the full benefit of mechanical harvesters. Studies by Ramasubramanian et al. and Pakeerathan [10, 13] highlighted the merits of training and skill development to maximize the efficiency and effectiveness of mechanical oil palm harvesting. Another limitation is the adaptability of mechanized harvesters to different terrains and palm tree heights. Certain mechanized tools may not be suitable for uneven or steep terrains, potentially limiting their applicability across diverse agricultural landscapes [35, 38].

Mechanized oil palm harvesting has the potential to greatly enhance harvesting efficiency, improve worker safety and minimize labour costs. However, the overall success of mechanization heavily relies on the proficiency of operators and the adaptability of equipment to different agricultural environments. Whereas recent advancements in smart farming and renewable energy integration offer promising prospects, challenges such as high starting costs and the need for skilled labour must be addressed to fully realize the benefits of mechanized harvesting.

Mechanized oil palm harvesting provides a transformative approach to addressing the labour-

intensive nature of conventional harvesting methods. The balance between economic gains and labour-related challenges indicates the importance of continued research and innovation in this field.

3. Methods

3.1 Experimental Setting

This research was conducted in Kwaebibirem Municipality, located in Ghana. This part of the country is recognized as one of Ghana's key hubs for oil palm cultivation. It has the biggest processing plant for oil palm in Ghana. Spatial maps (shown in *Figure 1*) of palm plantations in which all relevant data for this research was collected were obtained using ArcGIS version 10.2. Ghana Oil Palm Development Company (GOPDC) confirmed that Kwaebibirem Municipal leads in producing oil palm, which influenced its selection as the study area. Kwaebibirem was chosen over other locations, such as Ejisu-Juaben Municipality, which shares similar characteristics, due to its relatively high concentration of plantations with diverse management practices. This diversity made it the most suitable location to pilot and validate the mechanical oil palm harvester under various conditions.

Additionally, the proximity to Asuom and other adjoining communities, along with logistical support from GOPDC, facilitated data acquisition, operator training, and consistent monitoring during the experiments. Furthermore, oil palm cultivation is integral to the livelihoods of the local population, ensuring that the results from this research have direct relevance and realistic benefits for stakeholders both within and beyond the experimental setting.

3.2 Systematic approach

The study employed experimental and observational approaches within a novel theoretical framework, specifically grounded theory. This theory is a qualitative research method, which generates systematic theories from data, making it the most suitable approach for exploring emerging phenomena and refining operational processes. Grounded theory was selected for this study because of its iterative nature, which allows for an unending refinement of both the experimental design and theoretical implications based on empirical observations in an inductive approach, unlike deductive research, which tests pre-existing hypotheses. This approach was utilized in the study by guiding the exploration of mechanical oil palm harvesting practices and enabling the integration of observed patterns into a

conceptual framework of the study in line with its iterative and inductive characteristics.

Initially, the mechanical harvesting equipment was examined to understand its operating principle before being assembled again. The transmission shaft (part 6) transmits the power generated by the prime mover to the cutting head (part 8) as illustrated in *Figure 3*. The angular velocity is converted into linear velocity through a slider-crank mechanism and a gear train, enabling to-and-fro motion of the cutting blade for harvesting.

The equipment was piloted through a random sample of two plantations in Abaam and Twapease. The substantive research took place in Kwaebibirem, where plantations (with a 4.8m mean tree height) were chosen using a random sampling technique for harvesting. These plantations were located in Twapease, Abaam, Mampong, Asuom, and Abenanso, following Equation 1, as the total number of commercial plantations feeding directly into GOPDC within the demarcated area in *Figure 1* is five. The selected plantations have approximately flat

topography, where palm trees have a planting distance of 8 meters between rows and 9 meters between columns, which creates a shady canopy and provides a conducive environment and favorable conditions for the harvesting tools operators. Harvesting tool operators were also selected at random from among residents of Asuom, having one year of experience at least, in the harvest of oil palm and between the ages of 25-40 years. These criteria were applied so that the selection of operators with the necessary skills and fitness to effectively perform the job could be done. A rest period was allowed for harvesting tool operators (manual and mechanical) to replenish lost energy. The variables measured during the harvesting process included equipment capacity, cutting duration per frond and FFB for both mechanical and manual tools, fuel consumption, machine temperature under maximum and no-load conditions, dimensions of palm fronds and FFB stalk cross-sections, and the operating costs associated with both harvesting tools, as illustrated in *Tables 4, 7, and 8*. The study methodology is summarized in the block diagram shown in *Figure 2*.

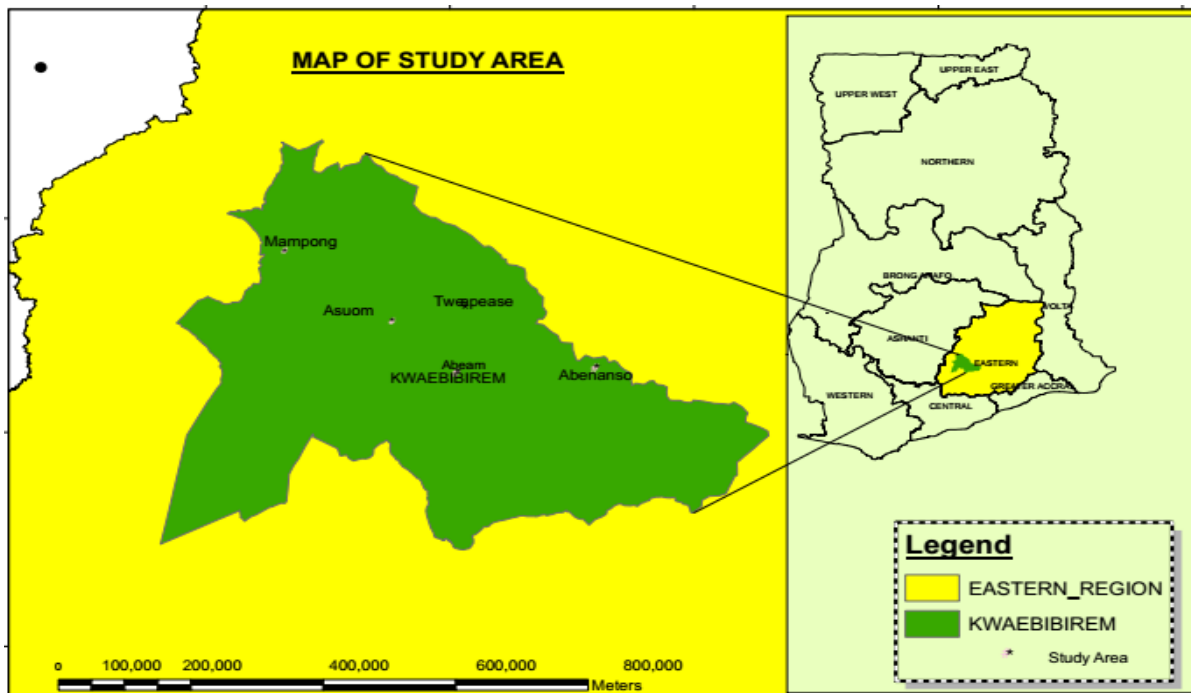


Figure 1 Map of the study area

$$n = \frac{N}{1+N(\alpha^2)} \quad (1)$$

Where N is the total population (total number of commercial plantations that feed directly into the

GOPDC in the demarcated area in *Figure 1*, that is 5), n is the sample size, and α = significance level (0.05).

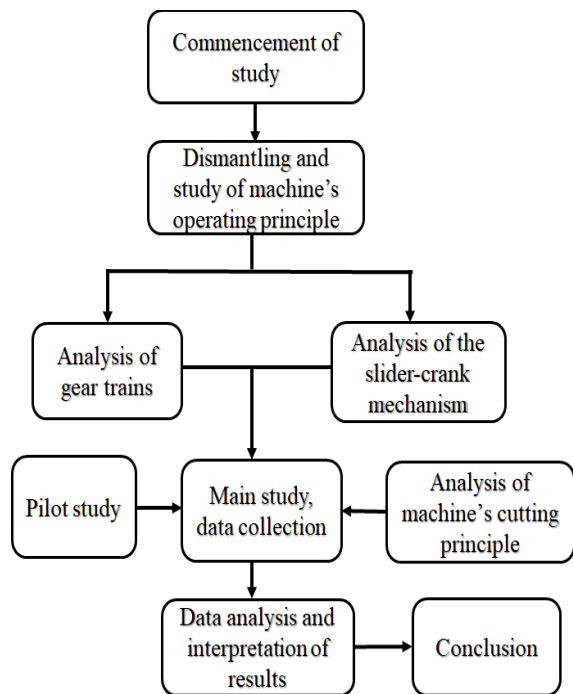


Figure 2 Flow chart showing the study approach

3.3 Manual and mechanical oil palm harvesting

A group of four labourers was assembled to carry out the harvesting of FFB using a sickle-pole combination. Two were tasked with FFB and palm fronds cutting, while the other two handled loose fruit collection, stacking palm fronds, and gathering FFB in one place. The two operators of the sickle and pole were paid an amount of GH¢ 70.00 for every 1000 kg of harvested fruit bunches for equal division between them. In mechanical harvesting, a group of 3 workers was assembled to carry out FFB harvesting activities. Photograph of a 2-stroke engine powering the mechanical equipment *Figure 4*.

One team member was responsible for cutting fronds and FFB using the mechanical oil palm harvesting machine, as illustrated in *Figure 5*. The machine was powered by high-quality fuel, approved by the Quality Assurance Unit of the National Petroleum Authority of Ghana. Meanwhile, the other team members handled loose fruit collection, palm frond stacking, and gathering the bunches at a central point. The machine operator was paid an amount of GH¢ 70.00 per 1000 kg of harvested FFB. The harvesting took place for 8 hours per day (9 am - 4 pm) over 5 days. *Table 1* [4] illustrates a summary of the environmental conditions recorded during the harvesting periods. To ensure consistency, the harvesting tool operators (manual and mechanical)

worked within the same time interval and had equal rest periods during the harvesting process.

Table 1 Environmental conditions recorded during the harvesting periods

Parameter	Value
Sunlight	Partly cloudy (solar radiation peaks within 12-1 pm)
Relative humidity (%)	46-75
Wind speed (km/h)	5-8
Rainfall (mm)	0
Temperature (°C)	27-34

3.4 Tools used

The harvesting tools that were used during this study were the mechanical oil palm harvester and the sickle-pole harvester, which tools were compared by conducting harvesting activities. The tool that was used to analyse the data collected was Microsoft Excel. *Table 2* shows the dimensions of the harvesting tools.

Table 2 Dimensions of the harvesting equipment

Qty	Manual equipment	Mechanical equipment
Length (m)	3.4	5.2
Mass (kg)	1.8	9

3.5 Instruments used

The instruments that were used for the study include a digital tachometer, which is calibrated to measure speed up to 10000 rpm ($\pm 0.01\% \pm 1$ digit rpm including tolerance of conversion), an infrared thermometer, which is calibrated to measure temperatures up to $3600\text{ }^{\circ}\text{C} \pm 0.3$, surveyor's tape (50 m), vernier calliper, weighing scale, stopwatch.

3.6 Selection of harvesting equipment

Both manual and mechanical harvesters were utilized in the experiments. The manual harvester consisted of a sickle and pole securely attached. The mechanical equipment was composed of 5 main parts: an engine, a shaft, a pole (telescopic), a slider-crank mechanism (speed converter), and a cutter. This particular equipment was chosen for the research because of its straightforward design and the availability of resources for maintenance. No other mechanized alternatives were available for this machine in Ghana's agricultural sector at the time of the study. The dimensions of the selected tools are shown in *Table 2*, while the parts list for the mechanical harvester is provided in *Table 3*.

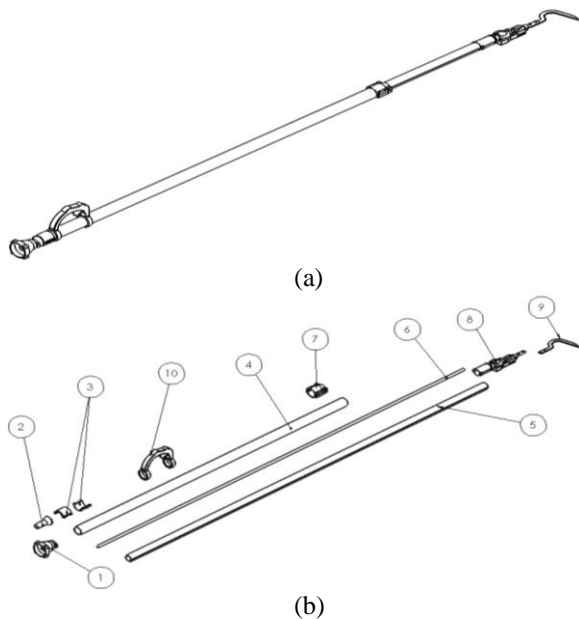


Figure 3 (a) Assembly drawing of the mechanical oil palm harvester (b) Mechanical oil palm harvester's components [4]

Table 3 Parts: mechanical harvester

Part number	Part name	Quantity
1	Engine holder	1
2	Shaft seat	1
3	Cover	1
4	Outer shaft	1
5	Inner shaft	1
6	Transmission shaft	1
7	Holding plate	1
8	Cutting head	1
9	Cutting blade	1
10	Handle	1



Figure 4 Photograph of a 2-stroke engine powering the mechanical equipment

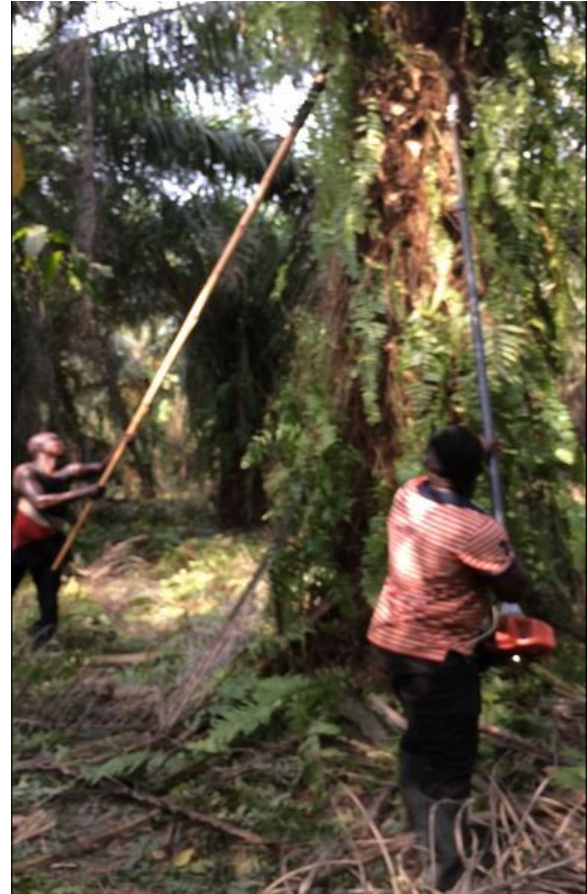


Figure 5 Mechanical and manual harvesting

3.7 Determination of operating parameters

Operating parameters are the set of specific variables and conditions under which a machine, system, process, or equipment functions optimally and within the desired performance limits. These parameters are very critical for controlling, monitoring, and ensuring the effective operation of various systems in fields such as engineering, manufacturing, and technology [38, 39]. The following operating parameters were determined using Equation 2-10. Applied pressure, power output, cutting force, cutting time, fuel consumption, and heat energy emitted.

$$F_c = \frac{m_b v}{t} \tag{2}$$

where; m_b = Mass of cutting blade (kg), v = Linear velocity of the cutting blade (ms^{-1}), F_c = Cutting force (N), t = Mean time for cutting frond/FFB (seconds).

$$P_a = \frac{F}{A} \tag{3}$$

$$A = \frac{A_f + A_s}{2} \tag{4}$$

$$A_s = \frac{\pi d^2}{4} \quad (5)$$

$$A_f = \frac{\sum_{i=0}^n A_{fi}}{n} \quad (6)$$

$$A_{fi} = \frac{1}{2}bh \quad (7)$$

where; P_a = Applied pressure in cutting (Nm^{-2}), A = Average cross-sectional area (m^2), A_{fi} = Average cross-sectional area of the frond, A_s = Average cross-sectional area of bunch stalk, d = Average diameter, b = Based of frond cross-section (m), h = Height of frond cross-section (m).

$$P_o = \omega T_o = \frac{2\pi NT_o}{60} \quad (8)$$

Where; P_o = Output power of the machine (W), N = Rotational speed of the transmission shaft of the machine (rpm), ω = Angular velocity of the transmission shaft of the machine (rad.s^{-1}), T_o = Operating torque (Nm).

$$Q = mc_p\Delta T \quad (9)$$

$$C_f = \frac{v_f}{t} \quad (10)$$

Where; Q = Heat emitted by the machine (kJ), c_p = Fuel specific heat capacity (kJ/kg.K), ΔT = Change in temperature ($^{\circ}\text{C}$), C_f = Fuel consumption (l/hr), v_f = Volume of fuel consumed (l), t = Period for which v_f Was consumed (h).

3.8Economic analysis

The costs of operating the mechanical and manual harvesting tools were analyzed and compared. The annual cost per kilogram of harvesting FFB and the cost-benefit ratio for the machine and manual tools were respectively computed using Equations 11 and 12 respectively [40]. Also, a One-Way sensitivity analysis was performed on the input parameters to determine how changes in input costs (e.g., fuel prices, maintenance costs and labour costs) affect the results. The justification is that the variations of these parameters are mutually exclusive.

$$C.kg^{-1} = \frac{C_t}{m_t} \quad (11)$$

$$CB \text{ ratio} = \frac{Cost}{Benefit} \quad (12)$$

Where; $C.kg^{-1}$ = Cost per kg of harvested FFB ($\text{GH}\text{¢.kg}^{-1}$), C_t = Total expenditure ($\text{GH}\text{¢}$), m_t = Total mass of FFB (kg), $CB \text{ ratio}$ = Cost-Benefit ratio ($\text{GH}\text{¢.t}^{-1}$).

3.9Hypothesis testing

Some researchers, such as Escallón-barrios et al. [41] and Jelani et al. [1], in the field of agricultural machinery, claim that the mechanized oil palm

harvester is economically efficient in terms of labour requirements compared to conventional manual harvesting tools. This is because harvesting the same quantity of FFB per day with manual tools requires between two and three operators, whereas a single mechanized harvester can achieve the same output. Thus, by a hypothetical inference, the use of the mechanized oil palm harvester reduces labour by at least 50% in contrast with that for manual harvesting. A random sample of 3 oil palm harvesting equipment operators to harvest FFB using mechanical and manual harvesting tools on 8.09 hectares of palm plantation produced the following outcome. In testing the hypothesis above (one-tailed) in a statistical approach, the alternative (H_a) and null (H_0) hypotheses are formulated as follows [42].

- i. H_0 : the use of the mechanized oil palm harvester reduces the labour by at least 50%.
- ii. H_a : the use of the mechanized oil palm harvester reduces the labour by less than 50%.

Mathematical expressions for the alternative and null hypotheses are shown in Equation 13.

$$\begin{aligned} H_0: p &\geq 0.5 \\ H_a: p &< 0.5 \end{aligned} \quad (13)$$

The hypothesis represented in Equation 13 was tested by computing the Z-score (standard score) using Equation 15. The Z-score (z_p) is standard deviations that a raw score's value deviates above or below the observed or measured value. The standard error of the proportion is calculated first, as shown in Equation 14:

$$\sigma_p = \sqrt{\frac{p(1-p)}{n}} \quad (14)$$

Substituting the values:

$$\sigma_p = \sqrt{\frac{0.5(1-0.5)}{3}} = 0.28868$$

Then, using Equation 15, the Z-score is computed as follows:

$$z_p = \frac{p_s - p}{\sigma_p} \quad (15)$$

Substituting the calculated values:

$$z_p = \frac{0.709 - 0.5}{0.28868} = 0.724$$

Where; p is the population proportion, p_s is the proportion of successes, σ_p is the standard error of the proportion, and n is the sample size.

3.10 Data analysis

Data collected from the field was cleaned by inspection to remove outliers and analyzed by use of the statistical analysis tool pack in Microsoft Excel, with a 5% significance level, by adopting the Multiple Testing procedure. No supplementary software was used in addition to Microsoft Excel for the statistical analysis.

4. Results

4.1 Harvesting equipment performance

Table 4 displays the mean daily capacity and duration for cutting both the mechanical and manual harvesters. Duration for cutting and capacity are the primary factors that influence the efficiency of the harvesting equipment. The findings showed that the mechanical harvester has a mean capacity of 239 FFB/day, while the manual equipment achieves 192

FFB/day. This aligns with the results reported by Jelani et al. [43], which ranged from 498-561 FFB (mechanical equipment) and 214–238 FFB for the sickle-pole harvester. This suggests that farmers are not well-acquainted with the mechanical oil palm harvester and lack sufficient skills due to its unavailability and the absence of training. Additionally, although the mechanical harvester outperforms the manual version, the data indicate a significant decrease in its capacity by 43-48%, which contrasts with the anticipated improvement as suggested by Mohamaddan et al. [5] and Ruiz et al. [6]. This decrease is likely due to the operators' unfamiliarity with the equipment. The significance of this finding highlights the need for engagement with stakeholders to create and implement policies that encourage farmers to embrace mechanized agriculture in Ghana's agricultural sector.

Table 4 Sickle-pole and mechanical palm harvesting equipment' daily output

Day/Parameter	Mechanical equipment			Conventional (manual) equipment		
	Number of FFB harvested	Duration (hr)		Number of FFB harvested	Duration (hr)	
		Total duration	Effective duration		Total duration	Effective duration
1	213	8	6.32	203	8	3.97
2	239	8	6.01	198	8	5.55
3	264	8	6.22	202	8	4.67
4	219	8	6.24	167	8	4.59
5	258	8	6.31	189	8	4.57
Total	1193	40	31.1	959	40	23.35
Average	239	-	6.22	192	-	4.67
Standard Deviation	22.70	-	0.13	14.92	-	0.57
Coefficient of Variation	0.09	-	0.02	0.08	-	0.12
Mass (kg)	16912	-	-	13987	-	-
Average mass	3382.2	-	-	2797.4	-	-

Figure 6 presents a graph of the mean time spent in harvesting FFB using both manual and mechanical harvesters. The findings indicated that, for manual harvesting, the average time to harvest a fruit bunch was 1.68 minutes, compared to 1.39 minutes for mechanized harvesting. This suggests that the mechanical harvester is approximately 22% faster than the manual sickle-pole harvester. These results are consistent with the 0.8 and 1.23 minutes for mechanical and manual harvesting, respectively, reported by Jelani et al. [43], where the time to cut FFB using the mechanized harvesting equipment was shorter than with the sickle-pole harvester.

Cantas = mechanical oil palm harvester

Avg-C = Average harvesting time for the mechanical oil palm harvester

Avg-M = Average harvesting time for the manual oil palm harvester

Figure 7 depicts the rate of harvesting for both mechanical and manual harvesting methods of oil palm. In both cases, the number of FFB harvested surged upward with time. Moreover, while there is a strong correlation ($0.9 \leq R \leq 1$) between the number of FFB harvested and the time spent, the mechanical harvester shows an even stronger correlation ($R = 0.997$) compared to the sick-pole harvester ($R = 0.986$). This suggests that for any timeframe, the mechanized harvester produces a higher output than the manual harvester. These results are consistent with those of Oyedeji et al. [2] and Mohamaddan et al. [5], who found that the mechanical harvester

achieved over 90% of the manual harvester's average harvesting capacity.

At first, the performance of the manual equipment in terms of the amount of FFB cut per unit of time, appeared to be better than that of the mechanical harvester. However, after 120 minutes of continuous harvesting, the quantity of FFB cut per unit of time using the mechanized equipment considerably surpassed that of the sickle and pole, as shown in Figure 7.

This suggests that the adoption of an improved alternative for oil palm harvesting can be readily embraced in the landscape of agriculture where mechanized farming is emerging. However, Khor et al. [44] describe this gradual adaptation as a potential limitation. As operators become more familiar with the mechanical harvester, their performance improves. The increase in operator proficiency, attributed to the training intervention provided during the initial phase of the study, results in more effective FFB harvesting [45].

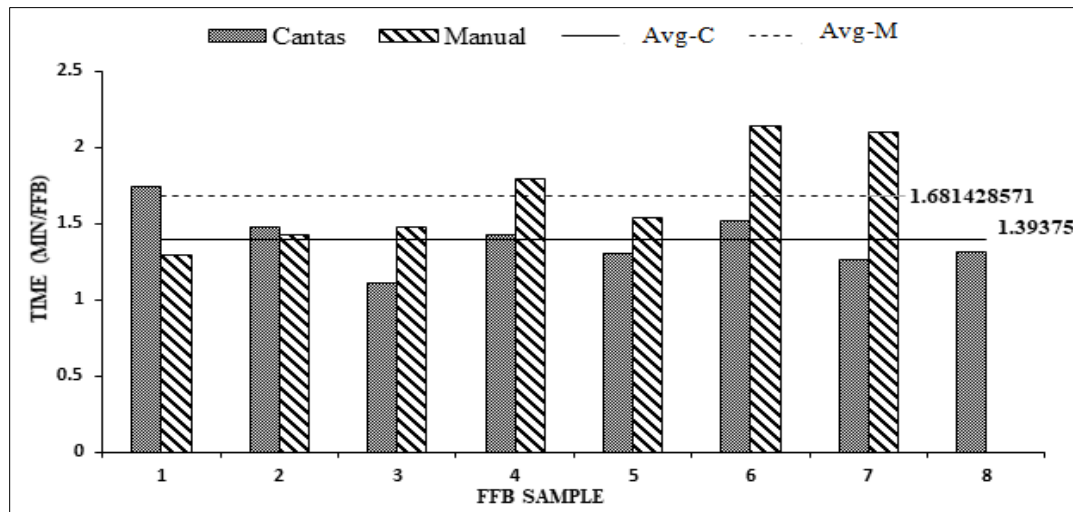


Figure 6 Mean cutting times for the mechanical and manual harvester

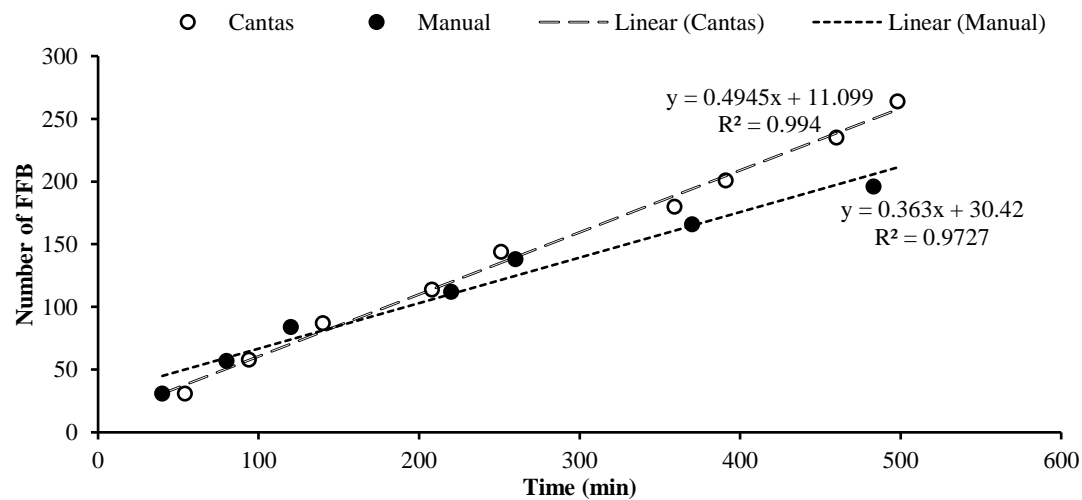


Figure 7 Relationship between the number of FFB harvested and time

The model derived from analysing the data collected from mechanical harvesting is $y = 29.672x + 11.099$, which means the number of **FFB** = **29.67 [Time]** + **11.099**. This model estimates the “capacity of the mechanical oil palm harvester” within a specified

period [45]. On the other hand, the model based on the manual harvesting data is $y = 21.782x + 30.42$, which translates to Quantity of **FFB** = **21.78 [Time]** + **30.42**. This model can also be applied to predict the “capacity of the sickle-pole harvester” within a

specified period [45]. These models allow for forecasting, suggesting that after 8 hours of operation, the mechanical harvester can collect around 249 FFB, while the manual equipment is expected to gather approximately 205 FFB. This implies that, in 8 hours, the mechanized equipment can achieve 22% greater productivity relative to the sickle-pole counterpart. This enhancement is smaller than the 43-48% increase Mohamaddan et al. [5] and Ruiz et al. [6] proposed.

The accuracy of the predictions made by these models is established by the coefficient of determination (R^2) for both equipment, showing the confidence level of forecasting based on the models developed for each piece of equipment [35]. The R^2 value for the mechanical harvester is 0.994, while for the manual harvester it is 0.9727. This indicates that the predictions made for the mechanical and manual harvesters are accurate to 99.4% and 97.27%, respectively. Farmers in Ghana have not yet adopted the mechanical harvester as their primary harvesting tool due to its unavailability and higher associated costs [37]. The scholarly input lies in the creation of a predictive model for enhancing precision agriculture, supporting more efficient, data-driven decision-making in oil palm harvesting.

4.2 Performance metrics of the mechanical and manual harvesters

Table 5 illustrates the comparative performance of the manually operated sickle-pole harvester and the mechanized harvester. The percentage differences for the daily capacity of the mechanical harvester, daily

capacity of the machine operator, and labour-to-land ratio for the mechanical harvester are 24.45%, 5.26%, and 100%, respectively, higher than those for the sickle-pole harvester. This is similar to the reports of Ismail et al. [46], Jelani et al. [1], and Sowat et al. [3], who reported similar results of 9%, 55%, and 155%, respectively. With higher effective working time, increased daily capacity, and less drudgery, the mechanized harvester operators conserved energy and worked significantly longer than the operators of the sickle-pole harvester. The implication is that the harvesting machine exhibits a higher performance rate compared to the sickle-pole harvester.

Figure 8 illustrates the mean daily and hourly capacities of both the mechanical and manual harvesters. The closeness in the capacities of the manual and mechanical harvesters in Figure 8 is caused by the inadequate skill set of the machine operators since the machine operator had no thorough training in mechanical oil palm harvesting until the execution of this study, contrary to the operator output presented by Ismail et al. [46]; Escallón-barrios et al. [41], Sowat et al. [3]. A new observation from this study is that the proficiency of the machine operator significantly influences both the performance metrics and the overall output of the mechanical harvester. In other words, the more proficient the operator, the better the performance metrics and the higher the overall output of the machine. However, the significant 24.4% improvement in efficiency during the harvesting period is solely attributed to the training intervention provided at the beginning of the study.

Table 5 Comparison between performance metrics of the mechanical and manual harvesters

Item Description	Mechanized	Manual	Diff. (Δ)	Percent. Diff. ($\% \Delta$)
Acreage	20	20	-	-
Number of workers	3	4	-1	-33.33
Worker-land ratio	1:20	1:10	1:10	+100
Mass per day ($\text{kg} \cdot \text{day}^{-1}$)	3382.2	2797.4	584.8	+20.91
Acreage	20	20	-	-
Number of days used	5	5	-	-
Working period per day (hr)	8	8	-	-
Effective period per day (hr)	6	5	1	+20
Total FFB harvested	1193	959	234	+24.40
Total mass (kg)	16912	13987	2925	+20.91
Avg. mass day^{-1}	3382.2	2797.4	584.8	+20.91
Avg. FFB $\cdot \text{day}^{-1}$ harvested	239	192	47	+24.45
Avg. FFB $\cdot \text{hr}^{-1} \cdot \text{group}^{-1}$ harvested	40	38	2	5.26
Cost per mass ($\text{GH} \cdot \text{kg}^{-1}$)	2.33	4.01		

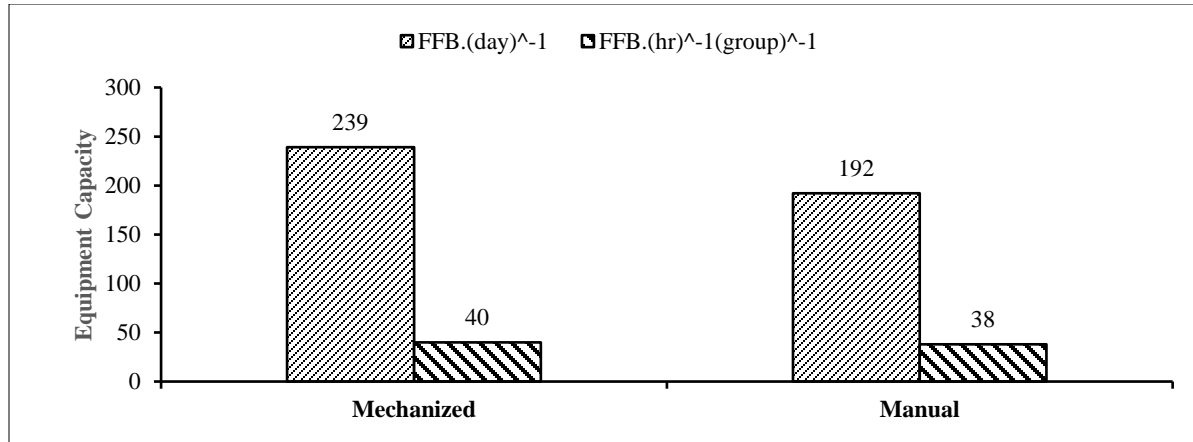


Figure 8 Average capacity of the mechanical and manual oil palm harvesters

4.3 Functional specification of the mechanical oil palm harvester

Table 7 presents the functional specifications of the mechanical harvester. The cutting force, applied

pressure, output power, heat energy emitted, and fuel consumption were respectively determined using Equations 1, 2, 7, 8 and 13 according to Table 6.

Table 6 Measured parameters for determining the operating parameters

Measured quantities	Value
Rotational speed (N)	6222 rpm
The radius of the rotating shaft (r)	0.004 m
Mass of the cutting blade (m_b)	0.5 kg
The average diameter of bunch stalk (d)	0.01 m
Avg. cross-sectional area of bunch stalk (A_s)	$7.85 \times 10^{-5} \text{ m}^2$
Avg. cross-sectional area of frond base (A_f)	$4.97 \times 10^{-4} \text{ m}^2$
Effective cross-sectional area (A)	$2.88 \times 10^{-4} \text{ m}^2$
Distance between the axis of rotation and cutting region of the blade (s)	0.3 m
Mass of fuel contained at a time (m)	0.75 kg
Initial machine temperature (T_1)	27.86 °C
Final machine temperature (T_2)	56.11 °C
Specific heat capacity of gasoline (c_p)	2.22 kJ/kg.K

Table 7 Operating parameters of the mechanical oil palm harvester

Operating parameter	Value
Output power	50.822 W
Applied pressure	905.647 Nm^{-2}
Cutting force	0.2606 N
Mean (FFB/frond) cutting time	5 s
Fuel consumption (no load)	0.1875 l/hr
Fuel consumption (on load)	0.84 l/hr
Heat energy emitted	46.986 kJ

The operating parameters determined are the key variables influencing the operational efficiency of the mechanical harvester [38, 39]. From the study, it was determined that the machine operator's effort in cutting FFB or fronds is limited to gently guiding the cutting blade through the bunch stalk or frond cross-section, as the required power (50.822 W) is supplied by the machine's prime mover. This is in line with the

observations and findings of Cengel [47] Benjan [48]. But the operators of the sickle-pole harvester needed to apply an average pressure of 904.861 Nm^{-2} to cut a FFB or frond by their strength equivalent to (50.822 W), and a cutting force of 0.2606 N to complete the cutting process. A toggle between the output torque and rotational speed of the slider-crank mechanism that produces the work output maintains

this power. Any effect that reduces the power also impacts the work output, preventing the machine from achieving its ultimate objective of cutting FFB and fronds. The heat produced by the mechanical harvester (46.986 kJ) results from an open system exothermic reaction in the two-stroke engine. However, this heat is not sufficient to cause significant discomfort or fatigue during the harvesting process, as the temperature gradient (28.25 °C) does not reach the dangerous heat index of 39.44 °C [49].

4.4 Economic analysis

Table 8 compares the cost incurred in the use of the manual and mechanical harvesters, whereas Table 9 illustrates the projected annual expenditures on the use of the manual and mechanical harvesters.

Based on the number of FFBs that can be harvested annually by each harvesting mechanism, as shown in Table 9, the annual operating cost of the manual harvester is GH¢56,026.67, whereas that of the mechanical harvester is GH¢39,426. This indicates

that operating the manual harvester is less economical compared to the mechanical harvester. This finding aligns with previous studies [50, 51], reinforcing that mechanizing the harvesting process maximizes economic returns while minimizing stress, fatigue, and labour intensity [26].

Additionally, the cost-benefit ratio of the mechanical oil palm harvester and the sickle-pole harvester was determined using Equation 11 to be 0.354 and 0.200, respectively. The results indicate that the cost-benefit ratio of the manual harvester is higher than the mechanical harvester, implying that adopting the mechanical harvester as the primary harvesting mechanism is more economical.

A sensitivity analysis revealed that a 10-20% variation in fuel prices and a 20-50% variation in maintenance costs had a minimal impact on the total expenditure of the mechanical oil palm harvester, with variations of 0.235-0.245% and 0.16-1.16% respectively.

Table 8 Comparative analysis of cost and performance of manual and mechanized oil palm harvesting tools

Description	Manual	Mechanized
Price	GH¢480	GH¢4500
Lifespan	6 months	2 years
Capacity/day	192 FFBs	239 FFBs
Labour cost	GH¢70 t^{-1}	GH¢70. t^{-1}
Working days/week	5	5

Table 9 Annual expenditure on the use of the manual and mechanical palm harvester

Description	Amount/period/quantity	
	Manual	Mechanical
Annual working days	130	130
The annual number of bunches	49920	62140
Total mass (ton)	792	986
Selling price per tone	GH¢200	GH¢200
Depreciated cost of the machine	-GH¢560	-GH¢2250
Fuel cost	GH¢0	-GH¢464
Maintenance cost	GH¢0	-GH¢312
Labour cost	-GH¢55466.67	-GH¢36400
Total revenue	GH¢158400	GH¢197200
Total Expenditure/cost incurred	-GH¢56026.67	-GH¢39426

4.5 Hypothesis testing

The hypothesis deals with the statistical analysis of labor requirement of the manual and mechanical oil palm harvester. To determine the statistical relevance of the labor requirement of the manual oil palm harvester relative to that for mechanical harvesting machine, the concept of hypothesis testing presented in Section 3.9 was applied to the data obtained through the experiment. Table 10 simplifies the

outcome of the statistical analysis at a significance level of 5%.

The critical Z value for a left-tailed test is $Z_c = -1.642$ according to statistical tables. The region of rejection in this left-tailed test is thus $\{Z: Z < -1.645\}$. From Table 10 since the calculated Z value for the labour requirement is $Z_p = 0.724 > Z_c = -1.645$, the conclusion is that the test failed to reject H_0 .

Similarly, since the P-value = 0.4428, which is larger than the significance level ($P=0.4428>0.05$), the test failed to reject the H_0 .

The outcome of the test implies that the alternate hypothesis that “the use of the mechanized oil palm

harvester reduces the labor force by less than 50%” is rejected, whereas H_0 , which states that “the use of the mechanized oil palm harvester reduces the labor force by at least 50%” is accepted.

Table 10 Labor requirement of the manual and mechanical oil palm harvester

Harvesting mechanism	Number of workers (labour)	Quantity of FFB Harvested	Statistical analysis	
Manual	2	13987	Sample size	3
Mechanized	1	16912	Calculated Z-score	0.724
			Critical Z-score	-1.645
			Calculated p-value	$P = 0.7278 > 0.05$
			Population proportion	0.5

5. Discussion

The study assessed the performance of manual and mechanical oil palm harvesters, revealing significant differences in their efficiency and economic viability. The mechanical harvester exhibited a higher average daily capacity (239 FFB/day) relative to the manual sickle-pole harvester (192 FFB/day). The mechanical oil palm harvester attained a 22% improvement in the mean cutting time, requiring 1.39 minutes per fruit bunch compared to 1.68 minutes for the conventional manual method and harvested 24.4% more FFB daily. Although these findings indicate a substantial improvement in the harvesting efficiency of the mechanical harvester, they align with similar studies by Jelani et al. [43] in the same direction. Nonetheless, the study revealed a significant reduction (43-48%) in the capacity of the mechanized harvester relative to the expected improvement, despite the improvements relative to Jelani et al. [1]. This drop is mainly due to the operators' unfamiliarity with the machinery, underscoring the need for proper training and adaptation. The proficiency of machine operators plays a critical role in obtaining optimal performance, as demonstrated by the enhanced metrics with increased familiarity. The implications of the higher performance and efficiency of the mechanical harvester are that it can significantly improve productivity, reduce labour costs, and reduce physical strain on workers. The shortfall is attributed to operator unfamiliarity, emphasizing the critical and inevitable role of training in optimizing the harvester's efficiency.

The increase in efficiency of the mechanical harvester can be attributed to its design and operating parameters such as higher output power and cutting force, which reduce the physical effort required from

oil palm plantation operators in line with the findings of Abangba et al. [4], Oyediji et al. [2], and Thaddeus et al. [52]. Predictive models developed for both the mechanical harvesting machine ($y=29.672x+11.099$) and conventional manual harvester ($y=21.782x+30.42$) predict a higher harvesting capacity over time compared to the conventional manual method and demonstrate high reliability. Coefficients of determination (R^2) of 99.4% and 97.27% for mechanical and manual harvesters respectively were obtained whilst enabling precise forecasts of harvesting capacities. These results emphasize the mechanical harvester's potential to improve agricultural productivity in operations involving commercial quantities subject to appropriate operator training and stakeholder engagement. These predictive models for oil palm harvesting are a novel development that characterizes this study.

The economic analysis further supports the cost-effectiveness of the mechanical harvester, with lower annual operating costs (GH¢39,426) compared to the manual method (GH¢56,026.67). The cost-benefit ratio additionally favours the mechanical harvester, making it a more economical choice in the long run, which is consistent with the conclusion of Abangba et al. [4], Oyediji et al. [2] and Thaddeus et al. [52].

The comparison of performance metrics between the manual and mechanical harvesters further emphasizes the advantages of mechanization. The mechanical harvester required three operators, compared to four for the conventional method, achieved a 20.91% increase in mass harvested per day, and demonstrated a 100% higher worker-to-land ratio efficiency. Economically, the mechanical harvester's lower cost per kilogram of harvested fruit and reduced labour

requirements contributed to a more favourable cost-benefit ratio (0.354) relative to the manual harvester (0.200). Also, the mechanical harvester's higher efficiency and reduced drudgery allowed operators to work longer hours with less fatigue. These advantages align with findings in other studies asserting that mechanization improves both productivity and operator well-being, despite initial challenges with operator proficiency.

Operator unfamiliarity with the mechanical harvester was a significant factor, reducing its potential performance advantage. While the training intervention improved efficiency over time, the short study duration may have limited the observation of long-term improvements. Economic analysis revealed that, although the mechanical harvester has higher upfront and maintenance costs, its long-term cost-effectiveness is superior. However, sensitivity to fuel price variations and maintenance costs was minimal, indicating robust economic viability. Additionally, the study was conducted over a limited period and in a specific geographical area, which may not fully capture the variability in field conditions and operator skills across different regions. These limitations introduce a margin of error in attempting to generalize the findings beyond the experimental setting. Therefore, to maximize the benefits of mechanical oil palm harvesters, it is essential to provide comprehensive and regular training for operators to familiarize them with the machinery and improve their proficiency, involve stakeholders in developing and implementing policies that promote the adoption of mechanized agriculture, including subsidies and financial incentives for purchasing machinery to enhance mechanized agriculture, and finally, to conduct long-term studies across different regions to validate the findings and refine the predictive models for broader applicability.

This is very necessary because the mechanical harvesting machine reduces labour intensity and health risks since conventional methods involve climbing tall trees and exposing workers to injuries, whereas mechanical harvesting machines eliminate conventional techniques, reducing occupational health hazards and improving the overall well-being of farm labourers. Additionally, postharvest losses are significantly minimized with the adoption of the mechanical harvesting machine as harvesting is done at a relatively rapid rate. Beyond these environmental impacts, the social impact of the mechanical oil palm harvesting machine ensures regular capacity building of tool operators, labour versatility and gender

inclusivity. These social and environmental impacts add to the overall benefits of adopting the mechanical harvesting machine in the Ghanaian agricultural economy. These benefits, such as increased productivity, reduced postharvest losses, job creation in machinery fabrication and servicing, and making Ghana's palm oil more competitive in both local and international markets, potentially increasing export revenue, make it compelling for all stakeholders to fast-track policies toward implementing mechanized agricultural sustainably in Ghana.

The limitations encountered during the study were that the height of palm trees was not measured directly without first using a wooden pole to mark the height, after which it could be measured with a tape measure. Additionally, the angle of pole inclination, the cross-sectional area of the palm frond (cut surface), and the bunch stalk required arithmetic calculations.

A complete list of abbreviations is listed in *Appendix I*.

6. Conclusion and future work

The study established that operating parameters significantly influence performance metrics, which are further constrained by the skill set of machinery operators. This limitation reduces the expected economic gains, despite the mechanized harvester offering a more sustainable and efficient solution that helps minimize labour-related stress, fatigue, and risks. Testing the study's hypothesis revealed a 67% reduction in labour force requirements, exceeding the estimated 50%. This further highlights the transformative potential and efficiency of the mechanized oil palm harvester. This is particularly relevant in the African context, where mechanized agriculture is still in the early stages of adoption.

Based on the study, it is recommended that future research focus on developing cost-effective mechanized solutions, enhancing operator training programs, and exploring sustainable energy sources for powering harvesting equipment. By addressing these challenges, mechanized harvesting can play a crucial role in improving the sustainability and productivity of oil palm cultivation, particularly in regions where labour shortages are a significant concern. Additionally, modifying the mechanical oil palm harvester to include a user-friendly control interface and displays, while exploring alternative materials to reduce its weight, is recommended.

Acknowledgment

This study was supported by funding from Desert Lion Company Ltd., one of the leading suppliers of agro-products in Ghana. The authors sincerely appreciate the company's assistance in connecting them with farmers and providing mechanical oil palm harvesters for the study.

Conflicts of interest

The authors have no conflicts of interest to declare.

Data availability

None.

Author's contribution statement

Frederick Abangba Akendola: Conceptualization, modelling, testing and evaluation, data analysis, writing – original drafting, review and proofreading. **Clement Adekunle Komolafe:** Writing – review, editing and proofreading. **Abdulai Ayirebi Ankrah:** CAD modelling and simulation. **Obed Ofori Yemoh:** CAD modelling and simulation.

References

- [1] Jelani AR, Ahmad MR, Azaman MI, Gono Y, Mohamed Z, Sukawai S, et al. Development and evaluation of a new generation oil palm motorised cutter. *Journal of Oil Palm Research*. 2018; 30(2):276-88.
- [2] Oyedeji A, Umar A, Kuburi L, Apeh I. Trend of harvesting of oil palm fruit; the mechanisms, and challenges. *International Journal of Scientific Research and Engineering Development*. 2020; 3(3):1053-63.
- [3] Sowat SN, Ismail WI, Mahadi MR, Bejo SK, Kassim MS. Trend in the development of oil palm fruit harvesting technologies in Malaysia. *Jurnal Teknologi (Sciences & Engineering)*. 2018; 80(2):83-91.
- [4] Abangba AF, Adekunle KC, Ayirebi AA, Ofori YO. Performance evaluation, machine parameters and ergonomic aspects of palm fruit harvesters. *Journal of Advanced Research in Applied Mechanics*. 2024; 122(1):14-31.
- [5] Mohamaddan S, Rahman MA, Andrew_munot M, Tanjong SJ, Deros BM, Dawal SM, et al. Investigation of oil palm harvesting tools design and technique on work-related musculoskeletal disorders of the upper body. *International Journal of Industrial Ergonomics*. 2021; 86:103226.
- [6] Ruiz ÁE, Banguera J, Pérez TW, Hernández HJ, Arévalo J, Mosquera MM. Technical and economic assessment of two harvesting tools for young *elaeis oleifera* x *E. guineensis* oil palms. *Agronomia Colombiana*. 2020; 38(3):418-28.
- [7] Gathala MK, Laing AM, Tiwari TP, Timsina J, Rolarubzen F, Islam S, et al. Improving smallholder farmers' gross margins and labor-use efficiency across a range of cropping systems in the eastern Gangetic plains. *World Development*. 2021; 138:105266.
- [8] Chiriaco MV, Bellotta M, Jusić J, Perugini L. Palm oil's contribution to the United Nations sustainable development goals: outcomes of a review of socio-economic aspects. *Environmental Research Letters*. 2022; 17(6):1-22.
- [9] Nair KP. *Tree crops. Harvesting Cash from the World's Important Cash Crops*, 1st ed.; Springer Nature: Cham, Switzerland. 2021: 249-85.
- [10] Ramasubramanian B, Sundarajan S, Rao RP, Reddy MV, Chellappan V, Ramakrishna S. Novel low-carbon energy solutions for powering emerging wearables, smart textiles, and medical devices. *Energy & Environmental Science*. 2022; 15(12):4928-81.
- [11] Karunathilake EM, Le AT, Heo S, Chung YS, Mansoor S. The path to smart farming: innovations and opportunities in precision agriculture. *Agriculture*. 2023; 13(8):1-26.
- [12] Xue H, Gong H, Yamauchi Y, Sasaki T, Ma R. Photo-enhanced rechargeable high-energy-density metal batteries for solar energy conversion and storage. *Nano Research Energy*. 2022; 1(1):1-21.
- [13] Pakeerathan K. Smart agriculture: special challenges and strategies for island states. In *smart agriculture for developing nations: status, perspectives and challenges 2023* (pp. 251-8). Singapore: Springer Nature Singapore.
- [14] Sharma A, Sharma A, Tselykh A, Bozhenyuk A, Choudhury T, Alomar MA, et al. Artificial intelligence and internet of things oriented sustainable precision farming: towards modern agriculture. *Open Life Sciences*. 2023; 18(1):20220713.
- [15] Kahar P, Rachmadona N, Pangestu R, Palar R, Adi DT, Juansilfero AB, et al. An integrated biorefinery stratilization of palm-oil wastes. *Bioresource Technology*. 2022; 344:126266.
- [16] Deb N, Alam MZ, Rahman T, Al-khatib MA, Jami MS, Mansor MF. Acid–base pretreatment and enzymatic hydrolysis of palm oil mill effluent in a single reactor system for production of fermentable sugars. *International Journal of Polymer Science*. 2023; 2023(1):1-15.
- [17] Binti SA, Binti JSH, Binti RSN, Binti AH. Redefining biofuels: investigating oil palm biomass as a promising cellulose feedstock for nitrocellulose-based propellant production. *Defence Technology*. 2024; 37:111-32.
- [18] Baur P, Iles A. Replacing humans with machines: a historical look at technology politics in California agriculture. *Agriculture and Human Values*. 2023; 40(1):113-40.
- [19] Szász L, Demeter K, Rácz BG, Losonci D. Industry 4.0: a review and analysis of contingency and performance effects. *Journal of Manufacturing Technology Management*. 2021; 32(3):667-94.
- [20] Felipe CM, Leidner DE, Roldán JL, Leal-rodríguez AL. Impact of IS capabilities on firm performance: the roles of organizational agility and industry technology intensity. *Decision Sciences*. 2020; 51(3):575-619.
- [21] Lee AT, Mcgregor G, Coetzee A. Correlates of yield, fecundity and survival of a wild harvested cyclopia intermedia (honeybush) population. *Agroecology and Sustainable Food Systems*. 2023; 47(5):646-67.

- [22] Lodolini EM, Polverigiani S, Giorgi V, Famiani F, Neri D. Time and type of pruning affect tree growth and yield in high-density olive orchards. *Scientia Horticulturae*. 2023; 311:111831.
- [23] Ghaziani S, Dehbozorgi G, Bakhshoodeh M, Doluschitz R. Unraveling on-farm wheat loss in fars province, Iran: a qualitative analysis and exploration of potential solutions with emphasis on agricultural cooperatives. *Sustainability*. 2023; 15(16):1-24.
- [24] Afsah-hejri L, Homayouni T, Toudeshki A, Ehsani R, Ferguson L, Castro-garcía S. Mechanical harvesting of selected temperate and tropical fruit and nut trees. *Horticultural Reviews*. 2022; 49:171-242.
- [25] Li M, Nangong Z. Precision trunk injection technology for treatment of huanglongbing (HLB)-affected citrus trees—a review. *Journal of Plant Diseases and Protection*. 2022; 129(1):15-34.
- [26] Yezekyan T, Marinello F, Armentano G, Trestini S, Sartori L. Modelling of harvesting machines' technical parameters and prices. *Agriculture*. 2020; 10(6):1-12.
- [27] Pulingam T, Lakshmanan M, Chuah JA, Surendran A, Zainab-I I, Foroozandeh P, et al. Oil palm trunk waste: environmental impacts and management strategies. *Industrial Crops and Products*. 2022; 189:115827.
- [28] Foong SY, Chan YH, Lock SS, Chin BL, Yiin CL, Cheah KW, et al. Microwave processing of oil palm wastes for bioenergy production and circular economy: recent advancements, challenges, and future prospects. *Bioresource Technology*. 2023; 369:128478.
- [29] Roles J, Yarnold J, Hussey K, Hankamer B. Techno-economic evaluation of microalgae high-density liquid fuel production at 12 international locations. *Biotechnology for Biofuels*. 2021; 14(1):1-19.
- [30] Gai R, Chen N, Yuan H. A detection algorithm for cherry fruits based on the improved YOLO-v4 model. *Neural Computing and Applications*. 2023; 35(19):13895-906.
- [31] Akinyi D. Cost-benefit analysis of prioritized climate-smart agricultural practices and innovations among smallholder farmers a case of selected value-chains in Sub-Saharan Africa. Doctoral Dissertation, Egerton University. 2022.
- [32] Nichenametla PKCK. A multi-criteria assessment of the impact of previous land use and current management practices on the performance of oil palm on smallholders' plots in the southern Thailand. Master's Thesis, Norwegian University of Life Sciences. 2023.
- [33] Anwar A, Murugan AS, Recchia A, Kim E, Urbanic J. Investigating musculoskeletal risks in manual mushroom harvesting: an ergonomic field study in Canadian farms. *Social Sciences & Humanities Open*. 2024; 10:1-7.
- [34] Seo M, Kim H, Jung W. Ergonomic improvements to agricultural harvest baskets to reduce the risk of musculoskeletal disorders among farmers. *International Journal of Environmental Research and Public Health*. 2022; 19(17):1-12.
- [35] Chikelu PO. Model design and development of a telescopic palm fruit harvester. *Modern Mechanical Engineering*. 2023; 13(1):1-20.
- [36] Ahmada MR, Radzia MK, Ramlia AS, Bakria MA, Hafizi MI, Azamana AI, et al. Evaluation and comparison of the ergonomics, performance and economics of battery-powered and engine-powered palm oil harvesting tools: Cantas Elektro. *Jurnal Kejuruteraan*. 2023; 35(4):811-21.
- [37] Anuar MM, Jaafar SB. Evaluation on TVET assessment in oil palm operation focuses on mechanized FFB harvesting and collecting. *Advances in Agricultural and Food Research Journal*. 2022; 3(1):1-10.
- [38] Akhtar J, Amin NS. A review on operating parameters for optimum liquid oil yield in biomass pyrolysis. *Renewable and Sustainable Energy Reviews*. 2012; 16(7):5101-9.
- [39] Jung GB, Su A, Tu CH, Weng FB. Effect of operating parameters on the DMFC performance. *Journal of Fuel Cell Science and Technology*. 2005; 2(2):81-5.
- [40] Bertola NJ, Bayane I, Brühwiler E. Cost-benefit evaluation of a monitoring system for structural identification of existing bridges. In *bridge safety, maintenance, management, life-cycle, resilience and sustainability 2022* (pp. 394-400). CRC Press.
- [41] Escallón-barrios M, Castillo-gomez D, Leal J, Montenegro C, Medaglia AL. Improving harvesting operations in an oil palm plantation. *Annals of Operations Research*. 2022; 314(2):411-49.
- [42] Lehmann EL, Romano JP. *Testing statistical hypotheses*. New York: Springer; 1986.
- [43] Jelani AR, Hitam A, Jamak J, Noor M, Gono Y, Ariffin O. Cantas TM—a tool for the efficient harvesting of oil palm fresh fruit bunches. *Journal of Oil Palm Research*. 2008; 20:548-58.
- [44] Khor JF, Ling L, Yusop Z, Tan WL, Ling JL, Soo EZ. Impact of El Niño on oil palm yield in Malaysia. *Agronomy*. 2021; 11(11):1-22.
- [45] Chicco D, Warrens MJ, Jurman G. The coefficient of determination R-squared is more informative than SMAPE, MAE, MAPE, MSE and RMSE in regression analysis evaluation. *Peerj Computer Science*. 2021; 7:1-24.
- [46] Ismail A, Ahmad SM, Sharudin Z. Labour productivity in the Malaysian oil palm plantation sector. *Oil Palm Industry Economic Journal*. 2015; 15(2):1-10.
- [47] Çengel YA. *Green thermodynamics*. *International Journal of Energy Research*. 2007; 31(12):1088-104.
- [48] Bejan A. *Advanced engineering thermodynamics*. John Wiley & Sons; 2016.
- [49] Carlson JM, Zanolotti A, De CSE, Poblacion AP, Fabian PM, Carnes F, et al. Critical windows of susceptibility for the effects of prenatal exposure to heat and heat variability on gestational growth. *Environmental Research*. 2023; 216:114607.
- [50] Levin HM, Mcewan PJ. *Cost-effectiveness analysis: methods and applications*. Sage; 2001.

- [51] Neumann PJ, Sanders GD. Cost-effectiveness analysis 2.0. *New England Journal of Medicine*. 2017; 376(3):203-5.
- [52] Thaddeus DJ, Bakri MA, Khalid MR, Ahmad MR, Azaman MI, Mustaffa NK, et al. An overview of the benefits and advantages of implementing mechanisation in the oil palm plantation: a look at fresh fruit bunch (FFB) evacuation. *Advances in Agricultural and Food Research Journal*. 2023; 4(2):1-13.



Frederick Abangba Akendola is a lecturer and Ph.D. candidate in Mechanical Engineering at the University of Mines and Technology, Tarkwa, Ghana. He holds a BSc in Agricultural Engineering and an MPhil in Mechanical Engineering, both from Kwame Nkrumah University of Science and Technology, Kumasi, Ghana. His expertise lies in design and manufacturing, hydraulics, and renewable energy technology. Currently, his research focuses on the application of artificial intelligence to mechanical systems for performance improvement. He is a member of the Ghana Institution of Engineering (GHIE) and the Ghana Society of Agricultural Engineering (GSAE).
Email: faakendola@umat.edu.gh



Clement Adekunle Komolafe is a Senior Lecturer in the Department of Mechanical Engineering at the University of Mines and Technology, Tarkwa, Ghana. He holds a Ph.D. in Mechanical Engineering (Thermofluids) from the Federal University of Agriculture, Abeokuta, Nigeria. His research interests include thermal engineering, encompassing thermodynamics, fluid mechanics, and heat and mass transfer, as well as energy technologies and machine design. Dr. Komolafe is a certified Mechanical Engineer by the Council for the Regulation of Engineering in Nigeria (COREN). He is also a member of the Nigerian Society of Engineers (MNSE) and the Nigerian Institution of Mechanical Engineering (MNImechE).
Email: cakomolafe@umat.edu.gh



Abdulai Ayirebi Ankrah is a Lecturer and Ph.D. candidate in the Department of Mechanical Engineering at the University of Mines and Technology. He holds an MSc in Mechanical Engineering from the Pan African University Institute and a BSc in Mechanical Engineering from the University of Mines and Technology. His specialization includes Design and Manufacturing, Modeling, Fault Detection, Condition Monitoring, Diagnosis, and Prognostics.
Email: aaankrah@umat.edu.gh



Obed Ofori Yemoh was born on January 13, 1988, in Accra, Ghana. He holds a Higher National Diploma in Plant Engineering from Accra Technical University, a Bachelor's degree in Mechanical Engineering (Design and Manufacturing) from KAAF University College, and a Master of Philosophy in Mechanical Engineering (Design and Manufacturing) from Kwame Nkrumah University of Science and Technology (KNUST). He is a member of the National Association of Black Engineers and currently serves as an Assistant Lecturer in the Department of Mechanical Engineering at the University of Mines and Technology. With a strong background in design, manufacturing, and plant engineering, his research interests include the design and manufacturing of plant and industrial equipment, product design and development, sustainability, and green building technology. In addition to his academic career, he is a professional Design Engineer with over 10 years of experience in engineering design and detailing.
Email: ooyemoh@umat.edu.gh

Appendix I

S. No.	Abbreviation	Description
1	AI	Artificial Intelligence
2	FFB	Fresh Fruit Bunch
3	EMG	Electromyographic
4	GOPDC	Ghana Oil Palm Development Company