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Article

Design and Performance Evaluation of a Low-Cost Portable Rotary Cutting Machine for Sugar Palm Inflorescence Stalk Trimming

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Abstract

Sugar palm (*Arenga pinnata*) sap tapping still relies on manual trimming of the inflorescence stalk surface using a machete. Although rotary cutting devices have been studied for several agricultural materials, quantitative evidence for a low-cost handheld machine specifically designed for sugar palm inflorescence stalk trimming is still limited. This study designed, fabricated, and evaluated a portable low-energy rotary cutting machine that integrates a rotary disc blade, DC worm gear motor, worm gearbox, rechargeable lithium battery, and protective blade cover. The novelty of the study is the task-specific evaluation of cutting time, operational capacity, energy consumption, battery-based trimming capacity, and prototype cost for smallholder sap tapping. Manual and machine-assisted trimming were compared using 20 repetitions for each method. The average cutting time decreased from 22.4 ± 1.1 to 6.8 ± 0.6 s/stalk, corresponding to a 69.64% reduction and 3.29 times faster operation than manual trimming. Operational capacity increased from 160.7 to 529.4 stalks/hour. The machine operated at 10.8 V and 0.95 A, requiring 10.26 W and 0.0194 Wh/stalk. A fully charged 10.8 V, 4.8 Ah battery can theoretically support approximately 2675 trimming operations before complete drainage. The prototype material cost was Rp 433,000, equivalent to approximately USD 24.25 using an exchange rate of Rp 17,856/USD. The results indicate that the developed device is a feasible low-cost and low-energy mechanization option for repetitive sugar palm inflorescence stalk trimming.

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1. Introduction

Sugar palm (*Arenga pinnata*) is an important multipurpose plantation crop in Indonesia and other tropical regions. It produces valuable products, including sap, palm sugar, starch, fiber, and construction materials, and contributes directly to rural livelihoods and smallholder agroindustry. Among these products, palm sap is particularly important because it is the main raw material for traditional palm sugar production. Recent studies have shown that sugar palm sap quality varies with production center and handling conditions; for example, total sugar content in palm sap from several production centers in West Sumatra was reported in the range of 7.00-15.73%, while total polyphenol content varied from 46.32 to 499.32 mg GAE/g [1]-[3]. These variations indicate that sugar palm production is influenced by both biological and processing factors, and therefore improvements in tapping practice are relevant to product quality and smallholder productivity.

In conventional sugar palm sap tapping, farmers perform several sequential activities, including ladder installation, tree climbing, sap collection from previous tapping, cleaning of the tapping area, trimming of the inflorescence stalk surface, wick installation, collection container installation, and descending from the tree. Among these activities, trimming the inflorescence stalk surface is a critical repetitive operation because it is directly related to reopening sap channels and maintaining continuous sap flow. This operation is commonly performed manually using a machete or similar hand tool. Although the method is simple and widely practiced, it requires physical effort, depends strongly on operator skill, and may produce inconsistent cutting quality.

Manual trimming also presents practical limitations in rural production systems. The operation is repeated during daily tapping activities and is often performed under uncomfortable working conditions, such as at elevated positions on the tree and in humid field environments. Repetitive manual cutting may increase fatigue, reduce consistency, and lengthen the time required for sap tapping, particularly when farmers handle many trees or inflorescence stalks in one working cycle. These limitations indicate the need for a simple mechanization solution that can assist the trimming operation without significantly increasing equipment cost, weight, or operational complexity.

Agricultural mechanization has been widely recognized as an important approach for improving labor efficiency, reducing physical workload, and increasing productivity in smallholder farming systems [4]-[7]. However, mechanization for small-scale agricultural operations must be adapted to the practical needs of rural users. Appropriate agricultural machines should be affordable, portable, easy to operate, easy to maintain, and suitable for field environments with limited access to electricity or fuel-powered machinery [8]. Recent developments in agricultural machinery have also shown increasing interest in electric-drive systems, battery-powered operation, and lightweight fabrication methods because these technologies can support cleaner, quieter, and more flexible field operations [9]-[11].

Cutting and size-reduction processes are important in agricultural biomass handling because they influence cutting force, energy consumption, and overall processing efficiency [12]-[17]. Quantitative studies have shown that cutting performance is strongly affected by blade geometry, cutting angle, material properties, and operating parameters. Vu et al. [15] optimized chopping of agricultural residues and reported an optimum condition with cutting force of 251.7 N and cutting power of 26.2 W. Xie et al. [18] developed a rotary cutter for golden needle mushroom root cutting and reported a 39.4% reduction in cutting force and a 24.5% reduction in unit-area power consumption compared with a conventional flat-blade rotary cutter. Chen et al. [19] optimized a rotary cutting device for safflower filament harvesting and achieved 99.97% harvesting efficiency with 1.53% damage rate under optimized conditions. These studies demonstrate that agricultural cutting devices should be evaluated using quantitative indicators, not only descriptive observations.

Rotary cutting mechanisms have also been applied to several agricultural and biomass systems because they provide continuous cutting action, improved cutting uniformity, and reduced dependence on repeated manual force [18]-[21]. Nevertheless, the reviewed studies differ substantially from sugar palm inflorescence stalk trimming in terms of crop material, working scale, cutting objective, and evaluation method. Residue chopping studies commonly emphasize cutting force, cutting power, or size-reduction energy; mushroom and safflower harvesting devices emphasize cutting force, unit-area energy, harvesting efficiency, and damage rate; rotary tillage studies emphasize soil throwing distance and plant crushing rate. These metrics are valuable, but they cannot directly answer practical questions faced by sugar palm farmers, such as cutting time per stalk, number of stalks that can be trimmed per battery charge, daily time saving, and component cost of a handheld prototype.

A critical state-of-the-art comparison therefore reveals a specific methodological and application gap. Previous studies provide quantitative evidence for cutting optimization in agricultural residues, mushrooms, safflower, oil palm fronds, and rotary tillage systems [12]-[21], but they do not report a direct manual-versus-machine comparison for sugar palm inflorescence stalk trimming under the same field task. In particular, previous works generally do not provide sugar-palm-specific trimming time, daily stalk capacity, battery-based trimming capacity, low-cost component breakdown, or the practical time saving for a representative smallholder workload. Therefore, a direct claim that a sugar palm trimming device is faster than previous machines would be inappropriate because the tasks and metrics are different. In this manuscript, the term faster is used only in relation to the conventional manual trimming baseline tested under the same experimental conditions.

Based on this gap, the present study aims to design, fabricate, and evaluate a low-cost portable rotary cutting machine for sugar palm inflorescence stalk trimming. The proposed device integrates a rotary disc blade, a low-power DC motor, a gearbox-based torque amplification system, a rechargeable lithium battery, and a protective blade cover within a compact handheld structure. The novelty of this study is the task-specific quantitative evaluation of a

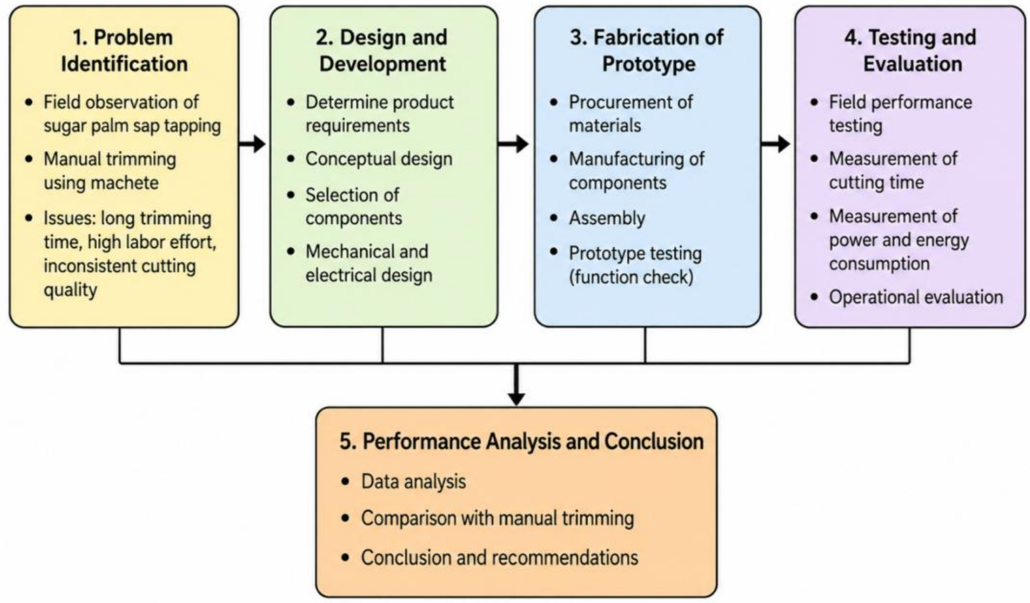

Figure 1. Research framework for the design, fabrication, and performance evaluation of the portable rotary cutting machine.

handheld, battery-powered rotary cutting machine for sugar palm sap tapping, including cutting time, cutting speed ratio relative to manual trimming, operational capacity, daily time saving, electrical power consumption, energy consumption, estimated torque, battery operating capacity, component cost, and operational consistency. The findings are expected to contribute to appropriate agricultural mechanization for smallholder sugar palm production systems.

2. Methods

This study employed an engineering design and experimental evaluation approach to develop and assess a low-cost portable rotary cutting machine for sugar palm (Arenga pinnata) inflorescence stalk trimming. The research procedure consisted of five stages: problem identification, design and development, prototype fabrication, testing and evaluation, and performance analysis. This framework was used to ensure that the developed machine was not only mechanically functional but also suitable for small-scale field operation in rural sugar palm production systems.

The problem identification stage focused on conventional sugar palm sap tapping practices, particularly the repetitive trimming of the inflorescence stalk surface using a machete. The main limitations identified were long trimming time, high physical effort, dependence on operator skill, and inconsistent cutting quality. Based on these problems, the design requirements were formulated, including portability, low energy consumption, cutting effectiveness, operational safety, ease of operation, low production cost, and ease of maintenance.

The experimental boundary of this study was limited to the inflorescence stalk trimming operation. In a complete sugar palm sap tapping cycle, farmers usually perform ladder installation, tree climbing, collecting sap from previous tapping, cleaning of the tapping area, trimming of the inflorescence stalk surface, wick installation, collection container installation, and descending from the tree. However, this study only evaluated the trimming stage because this is the specific activity replaced by the developed rotary cutting machine. The experimental boundary is illustrated in Figure 2.

The developed machine consisted of four main subsystems: rotary cutting unit, power transmission system, electrical power supply, and handheld structural frame. The rotary cutting unit used a circular disc blade to remove a thin layer of the sugar palm inflorescence stalk surface. The power transmission system consisted of a DC worm gear motor and worm gearbox, which reduced rotational speed and increased output torque at the cutting shaft. The electrical system consisted of a rechargeable lithium battery, battery management system, wiring, and power switch. The overall configuration and main components of the prototype are shown in Figure 3.

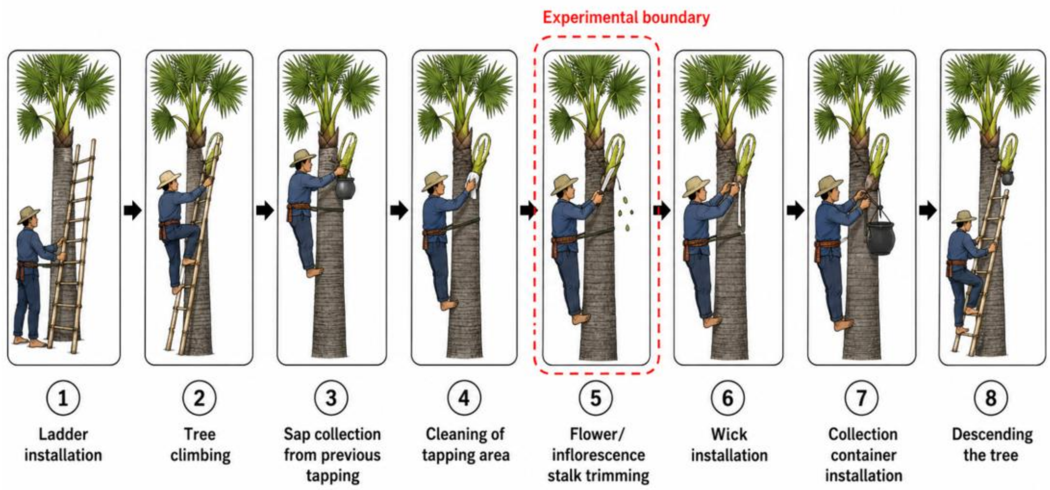

Figure 2. Typical sugar palm sap tapping workflow and experimental boundary considered in this study.

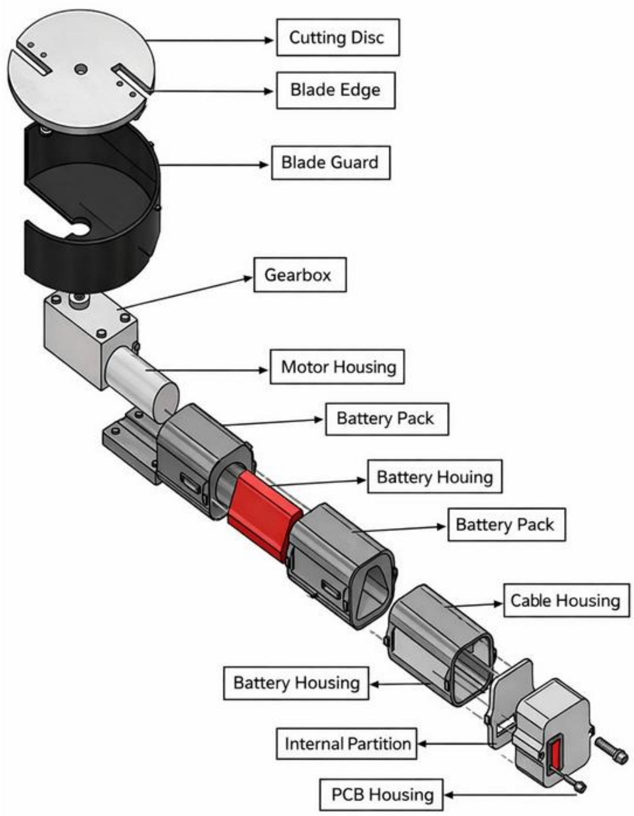

Figure 3. Overall configuration and main components of the portable rotary cutting machine.

The main design requirements and technical specifications of the developed prototype are summarized in Table 1. The machine used a DC worm gear motor with a rated voltage of 10.8-12 V and a rated power of approximately 10-12 W. The worm gearbox had a gear ratio of 1:200-1:250, producing an output rotational speed of 27-40 rpm and an output torque of approximately 32-46 kgf·cm. The rotary blade had a diameter of 65 mm, a thickness of 3 mm, and a cutting angle of 23°-29°. The device was powered by a rechargeable lithium battery with a capacity of 4800 mAh.

The rotary blade geometry and protective blade cover were important design elements. The blade was selected to provide sufficient cutting ability while maintaining compactness and low power demand. The protective cover was added to partially enclose the rotating

Table 1. Design requirements and technical specifications of the developed portable rotary cutting machine.

Design aspect	Design implementation	Main specification or evaluation basis
Application	Sugar palm inflorescence stalk trimming	Field trimming operation
Portability	Compact handheld structure	Suitable for field operation
Cutting mechanism	Rotary disc blade	65 mm diameter, 3 mm thickness
Cutting angle	Inclined blade edge	23°-29°
Drive system	DC worm gear motor	10.8-12 V, 10-12 W
Transmission	Worm gearbox	Gear ratio 1:200-1:250
Output speed	Low-speed rotary cutting	27-40 rpm
Output torque	Gearbox-assisted torque amplification	32-46 kgf·cm
Power source	Rechargeable lithium battery	10.8 V, 4.8 Ah
Safety feature	Protective blade cover	Reduced blade exposure
Fabrication method	Mechanical assembly and 3D-printed parts	Low-cost and modular construction
Maintenance	Replaceable blade, motor, battery, and housing	Assembly/disassembly observation

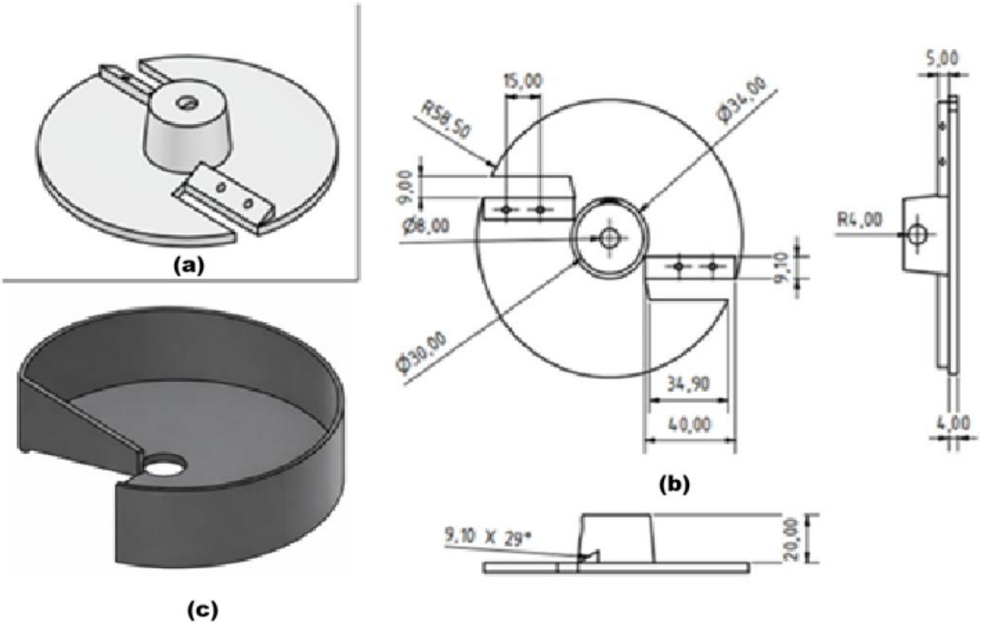

Figure 4. Geometry of the rotary cutting blade and protective blade cover: (a) blade and cover assembly, (b) blade dimensional drawing, and (c) protective cover dimensional drawing.

blade and reduce the risk of accidental contact during handheld operation. The blade geometry and protective cover are shown in Figure 4.

The structural components, including the motor housing, battery housing, switch cover, coupling cover, and blade cover, were fabricated using a combination of mechanical assembly and 3D-printed parts. In the revised manuscript, the component description that was previously presented as a figure is presented as a table because the content is tabular. The component cost list and estimated production cost are summarized in Table 3.

The USD values in Table 3 were estimated using an approximate exchange rate of Rp 17,856 per USD at the time of cost estimation. The small-batch production estimate includes assembly and testing overhead but excludes distribution, warranty, and institutional overhead costs. Experimental testing was conducted using sugar palm inflorescence stalks obtained from active sap tapping locations. The tested stalks were selected from similar field conditions to reduce variation caused by differences in maturity, moisture condition, and surface characteristics. Two trimming methods were compared: conventional manual trimming

Table 2. Performance indicators and measurement methods.

Parameter	Method	Unit
Cutting time	Digital stopwatch	s/stalk
Average cutting time	Mean of repeated trials	s/stalk
Standard deviation	Statistical calculation	s
Cutting efficiency improvement	Percentage reduction in cutting time	%
Operating voltage	Digital multimeter	V
Operating current	Digital multimeter	A
Electrical power	Voltage-current calculation	W
Energy consumption	Power-time calculation	Wh/stalk
Angular velocity	Output speed calculation	rad/s
Estimated torque	Power-angular velocity calculation	N·m
Battery operating capacity	Battery energy divided by energy per stalk	stalks/charge
Operational consistency	Coefficient of variation	%

Table 3. Component cost list and estimated production cost of the portable rotary cutting machine.

Component or cost item	Estimated cost
DC worm gear motor and gearbox	Rp 120,000 (USD 6.72)
Rechargeable lithium battery pack, 10.8 V, 4.8 Ah	Rp 100,000 (USD 5.60)
Battery management system, charger connector, and wiring	Rp 40,000 (USD 2.24)
Rotary disc blade	Rp 35,000 (USD 1.96)
Protective blade cover and mechanical fasteners	Rp 30,000 (USD 1.68)
Power switch	Rp 10,000 (USD 0.56)
3D-printed housing and handheld frame	Rp 75,000 (USD 4.20)
Miscellaneous consumables	Rp 23,000 (USD 1.29)
Total prototype material cost	Rp 433,000 (USD 24.25)
Estimated small-batch production cost with 15-25% assembly and testing overhead	Rp 498,000-541,000 (USD 27.89-30.31)

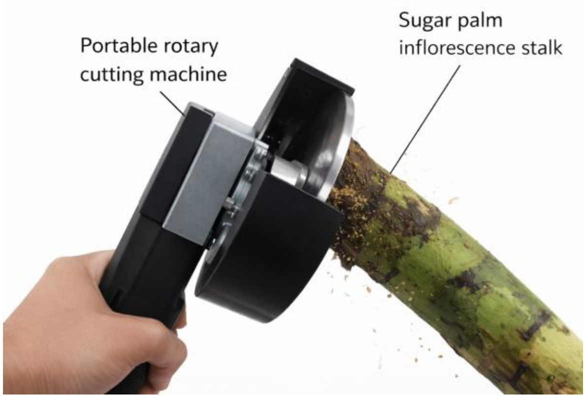

Figure 5. Experimental setup during machine-assisted trimming of sugar palm inflorescence stalk.

using a machete and machine-assisted trimming using the developed portable rotary cutting machine. Both methods were tested under comparable field conditions using the same general trimming direction and approximately similar trimming depth. The experimental setup is shown in Figure 5. Before testing, the rotary cutting machine was fully charged and checked to ensure that the blade, gearbox, battery, and switch were functioning properly. For manual trimming, the measurement started when the operator positioned the machete on the inflorescence stalk surface and ended when the trimming operation was completed. For machine-assisted trimming, the measurement started when the rotary cutting machine was activated and applied to the stalk surface and ended when the trimming operation was completed. Each method was repeated 20 times to evaluate repeatability and operational consistency.

The experimental data were analyzed quantitatively. Cutting time results are presented as mean ± standard deviation. The difference between manual trimming and machine-assisted trimming was evaluated using an independent-samples t-test at a significance level of $p < 0.05$. The coefficient of variation was also calculated to compare operational consistency between the two methods. Electrical power, energy consumption, torque, and battery operating capacity were analyzed only for the machine-assisted method because the conventional manual method does not use electrical energy. The cutting efficiency improvement was calculated using:

$$\eta = \frac{t_m - t_p}{t_m} \tag{1}$$

where η is the cutting efficiency improvement (%), t_m is the average cutting time using the manual method (s), and t_p is the average cutting time using the portable rotary cutting machine (s).

Electrical power consumption was calculated using:

$$P = V \times I \tag{2}$$

where P is electrical power consumption (W), V is operating voltage (V), and I is operating current (A). Energy consumption per trimming operation was estimated using:

$$E = P \times \frac{t}{3600} \tag{3}$$

where E is energy consumption per cutting operation (Wh/cut), P is electrical power consumption (W), and t is cutting time (s).

The angular velocity of the blade was calculated from the output rotational speed using:

$$\omega = \frac{2\pi N}{60} \tag{4}$$

where ω is angular velocity (rad/s), and N is output rotational speed (rpm). The estimated torque was then calculated using:

The estimated torque at the cutting shaft was calculated using:

$$T = \frac{P}{\omega} \tag{5}$$

where T is torque (N·m), P is electrical power consumption (W), and ω is angular velocity (rad/s). This torque estimation was used to interpret the ability of the low-power motor and gearbox system to support trimming of fibrous sugar palm inflorescence stalks.

Battery energy and battery-based trimming capacity were calculated using:

$$E_b = V_b \times Q_b \tag{6}$$

$$N_{full} = \frac{E_b}{E} \tag{7}$$

$$N_{usable} = \frac{kE_b}{E} \tag{8}$$

where E_b is nominal battery energy (Wh), V_b is nominal battery voltage (V), Q_b is battery capacity (Ah), N_{full} is the theoretical number of stalks trimmed before complete battery drainage, N_{usable} is the practical number of stalks trimmed when only a fraction k of the battery energy is used, and k is the usable battery energy factor. In this study, $k = 0.80$ was used as a conservative practical estimate.

Daily trimming time saving was calculated using:

$$\Delta t_{day} = (t_m - t_p) \times N_d \tag{9}$$

where Δt_{day} is the daily trimming time saving (s/day), and N_d is the number of stalks trimmed per day. In this study, a representative workload of 50 stalks/day was used to explain the practical meaning of the time reduction.

3. Results and Discussion

The portable rotary cutting machine was successfully fabricated and assembled according to the design requirements described in the previous section. The final prototype

Table 4. Quantitative comparison of selected previous studies and the present study.

Study	Application	Quantitative result reported	Main formulation or evaluation method	Limitation related to sugar palm tapping	Specific contribution of this study
Wilczyński et al. [12]	Biomass cutting before biofuel production	Energy consumption of biomass cutting process was quantified for size-reduction operation	Energy-consumption evaluation of biomass cutting	Not handheld and not sugar palm inflorescence trimming	Adds low-energy evaluation for handheld sugar palm trimming
Gan et al. [13]	Miscanthus mowing conditioning	Compared three blade designs and their effect on energy consumption	Blade-design comparison based on energy demand	Different crops, field operation, and cutting scale	Applies compact rotary disc blade to sugar palm stalk surface trimming
Vu et al. [15]	Chopping agricultural residues	Optimum cutting force = 251.7 N and cutting power = 26.2 W	Grey-based Taguchi multi-response optimization	Chopping process, not handheld sap tapping	Uses power and energy analysis in a portable sap-tapping tool
Xie et al. [18]	Golden needle mushroom root cutting	New slitting-angle cutter reduced cutting force by 39.4% and unit-area power consumption by 24.5%	Rotary cutter design and test analysis	Mushroom root cutting, not sugar palm trimming	Demonstrates rotary mechanism for smallholder trimming support
Chen et al. [19]	Safflower filament harvesting	Optimized device achieved 99.97% harvesting efficiency and 1.53% damage rate	Response surface optimization of rotary cutting harvester	Harvesting efficiency metric differs from trimming time per stalk	Shows that quality and damage indicators are important for plant cutting devices
Zhu et al. [21]	Bionic rotary blade for plant crushing and soil throwing	Average soil throwing distance = 632.30 mm and plant crushing rate = 81.55%	Discrete element modeling and field validation	Rotary tillage/harvesting, not handheld trimming	Supports rotary-blade relevance but highlights need for application-specific evaluation
Present study	Sugar palm inflorescence stalk trimming	Cutting time reduced from 22.4 to 6.8 s/stalk; 69.64% time reduction; power = 10.26 W; energy = 0.0194 Wh/stalk; theoretical battery capacity = 2675 stalks/charge	Direct manual-versus-machine comparison with electrical, battery, cost, and daily workload calculation	Long-term durability and ergonomic measurement not yet fully evaluated	Provides task-specific quantitative evidence for low-cost handheld sugar palm trimming

integrates a rotary disc blade, DC worm gear motor, worm gearbox, rechargeable lithium battery, switch, protective blade cover, and handheld structural frame into a compact device for field operation. The functional test showed that the rotary blade was able to remove the outer layer of the sugar palm inflorescence stalk surface without repeated chopping motion. In the machine-assisted method, the operator only guides the tool along the stalk surface while the rotating blade performs the trimming action. This mechanism reduces dependence on repeated manual force and provides more continuous cutting contact.

To strengthen the state-of-the-art discussion, selected previous studies are compared quantitatively in Table 4. The table shows that previous studies reported quantitative metrics such as cutting force, cutting power, energy consumption, harvesting efficiency, damage rate, soil throwing distance, and plant crushing rate. However, these studies were conducted on different materials and operating tasks. Therefore, the present study does not claim to be faster than previous machines. Instead, it provides a task-specific quantitative comparison between manual and machine-assisted sugar palm inflorescence stalk trimming.

Table 4 clarifies the research position of the present work. Previous studies demonstrate that cutting and rotary mechanisms can be optimized using force, power, energy, efficiency, and damage-related metrics. Nevertheless, their quantitative results cannot be directly converted into sugar palm trimming time because the material, task, machine scale, and performance metric are different. The present study therefore fills a narrower but practical gap by reporting cutting time per stalk, time ratio relative to manual trimming, daily time saving, energy consumption per stalk, estimated battery capacity, and prototype cost for a handheld device used in sugar palm sap tapping.

The comparison between manual trimming and machine-assisted trimming is presented in Table 5 and illustrated in Figure 6. The average cutting time decreased from 22.4 ± 1.1 s/stalk using the manual method to 6.8 ± 0.6 s/stalk using the developed rotary cutting machine. This represents a reduction of 15.6 s/stalk, equivalent to a cutting time improvement of 69.64%. The machine-assisted method was approximately 3.29 times faster than conventional manual trimming under the same experimental conditions.

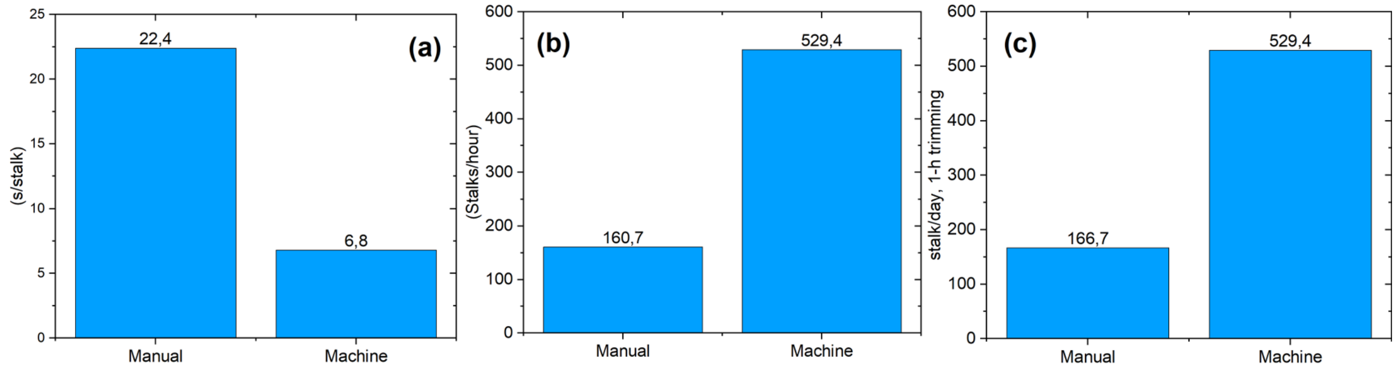

Figure 6. Comparison between manual and machine-assisted trimming: (a) average cutting time, (b) estimated number of stalks trimmed per day for 1-h active trimming, and (c) operational capacity.

Table 5. Performance, electrical, and cost characteristics of the developed rotary cutting machine.

Parameter	Manual trimming	Rotary cutting machine	Remarks
Number of repetitions	20	20	Experimental replication
Cutting time (s/stalk)	22.4 ± 1.1	6.8 ± 0.6	Mean ± standard deviation
Time reduction (%)	-	69.64	Relative to manual trimming
Time saved per stalk (s)	-	15.6	22.4 – 6.8
Time ratio	1.00	3.29	Machine was 3.29 times faster than manual trimming
Operational capacity (stalks/hour)	160.7	529.4	Calculated from 3600/t
Estimated stalks/day for 1-h active trimming	160.7	529.4	Assuming one hour of active trimming per day
Daily time saving for 50 stalks/day	-	780 s or 13 min	(22.4 – 6.8) × 50
Coefficient of variation (%)	4.91	8.82	Operational consistency indicator
Statistical significance	-	$p < 0.001$	Independent-samples t-test
Operating voltage (V)	-	10.8	Machine-assisted method only
Operating current (A)	-	0.95	Machine-assisted method only
Estimated power (W)	-	10.26	Calculated from $P = V \times I$
Estimated energy (Wh/stalk)	-	0.0194	Calculated from $E = P \times t/3600$
Estimated torque (N·m)	-	2.45-3.63	Based on output speed range
Prototype material cost	-	Rp 433,000 / USD 24.25	Based on component cost list

The reduction in cutting time is practically important because inflorescence stalk trimming is a repetitive activity in sugar palm sap tapping. If a farmer trims 50 stalks per day, the average time saving is calculated as (22.4 − 6.8) × 50 = 780 s/day, or approximately 13 min/day. This value represents only the trimming operation, not the complete tapping cycle. Therefore, it should not be interpreted as total daily labor saving for the entire sap tapping activity. Although 13 min/day may appear limited, the benefit accumulates over repeated daily operations and must be considered together with reduced manual force, improved cutting consistency, lower dependence on machete skill, reduced wrist motion, improved safety due to partial blade covering, and easier operation for less experienced users.

The statistical analysis confirmed that the difference between the two methods was significant at $p < 0.001$. This indicates that the improvement was not only descriptive but also statistically supported. The standard deviation decreased from ±1.1 s in manual trimming to ±0.6 s in machine-assisted trimming, showing a smaller absolute variation in cutting duration. However, because the machine-assisted trimming time was much shorter, its coefficient of variation was higher. This result suggests that the developed machine produced faster operation with acceptable repeatability under the tested field conditions.

The improved cutting performance can be explained by three main engineering factors. First, the rotary blade provides continuous cutting action, whereas manual trimming requires repeated repositioning and cutting motion. Second, the worm gearbox reduces rotational speed and increases torque at the cutting shaft, allowing the low-power motor to maintain cutting contact with fibrous stalk material. Third, the compact blade geometry, with a 65 mm diameter, 3 mm thickness, and 23°-29° cutting angle, supports effective trimming while maintaining low power demand. These findings are consistent with previous studies showing that cutting performance is influenced by blade design, cutting angle, cutting force, and energy consumption in fibrous agricultural materials [12]-[17].

Electrical evaluations showed that the developed machine operated at approximately 10.8 V and 0.95 A, resulting in an estimated power consumption of 10.26 W. With an average cutting time of 6.8 s/stalk, the estimated energy consumption was approximately 0.0194 Wh/stalk. This low energy requirement indicates that the machine can be operated using a compact rechargeable lithium battery, making it suitable for rural and off-grid environments. Based on the output rotational speed of 27-40 rpm, the estimated torque was approximately 2.45-3.63 N·m, which is sufficient for trimming the outer surface of the inflorescence stalk rather than cutting through the entire stalk.

Table 6 shows the estimated number of stalks that can be trimmed using a fully charged battery. The nominal battery energy was 10.8 V × 4.8 Ah = 51.84 Wh. Dividing this value by the energy consumption of 0.0194 Wh/stalk gives approximately 2675 stalks before complete battery drainage. However, complete battery drainage is not recommended for practical operation. When 80% usable battery energy is assumed, the estimated capacity remains approximately 2140 stalks per charge. This result indicates that battery endurance is not the limiting factor for typical daily smallholder trimming workloads. The actual field value may be lower because of motor start-up current, idle time, frictional losses, battery aging, and operator handling.

Table 6. Estimated battery-based trimming capacity of the developed machine.

Battery condition	Available battery energy (Wh)	Estimated stalks per charge	Interpretation
Nominal full battery, 100% discharge	51.84	2675	Theoretical value before complete battery drainage
Usable battery energy, 80%	41.47	2140	Practical conservative estimate to avoid full discharge
Usable battery energy, 70%	36.29	1872	Lower practical estimate with losses
Usable battery energy, 60%	31.10	1605	Conservative estimate under field losses
Representative workload, 50 stalks/day	0.97 Wh/day	Approximately 53.5 days at theoretical full discharge or 42.8 days at 80% usable energy	Assumes only active cutting energy and excludes idle losses

The developed machine also supports the low-cost design objective. The total prototype material cost was approximately Rp 433,000, equivalent to about USD 24.25 using an approximate exchange rate of Rp 17,856 per USD, as detailed in Table 3. The main cost components were the DC worm gear motor and gearbox, lithium battery pack, 3D-printed housing, rotary blade, battery management system, switch, blade cover, and mechanical fasteners. If assembly, testing, and small-batch production overhead are included, the estimated production cost may increase to approximately Rp 498,000-541,000, or USD 27.89-30.31. This cost remains relatively low for a battery-powered handheld agricultural device, although future work should verify the cost under larger production scale and local supply-chain conditions.

In terms of practical value, the proposed equipment should not be justified only by the 13 min/daytime saving for a 50-stalk workload. The equipment may also reduce repeated wrist and arm motion, reduce dependence on machete skill, improve cutting consistency, reduce direct exposure to manual blades, and allow less experienced users to perform a more uniform trimming operation. The protective cover partially encloses the rotating blade and reduces direct exposure to the cutting edge, while the electrical components are placed inside the housing to reduce contact with wiring and battery terminals. These potential benefits are important for user acceptance, especially in smallholder systems where safety, comfort, and ease of use are as important as speed.

Several limitations should be noted. First, the study focused only on the inflorescence stalk trimming operation and did not evaluate the complete sugar palm sap tapping cycle. Second, long-term durability of the blade, gearbox, battery, and 3D-printed components was not tested. Third, the effect of trimming quality on sap yield was not measured. Fourth, formal ergonomic evaluation, vibration measurement, and operator workload analysis were not included. Future research should include extended field testing, blade wear analysis, battery endurance validation, ergonomic assessment, vibration measurement, user acceptance analysis, and the influence of trimming consistency on sap production.

These results demonstrate that the developed low-cost portable rotary cutting machine provides a measurable improvement over conventional manual trimming. The machine reduced cutting time by 69.64%, operated with low electrical power, consumed only 0.0194 Wh/stalk, and had a prototype material cost of approximately Rp 433,000. In addition, the battery capacity calculation indicates that a fully charged battery can theoretically support approximately 2675 trimming operations before complete drainage. These findings support the feasibility of low-energy rotary cutting technology as an appropriate mechanization solution for small-scale sugar palm production systems.

4. Conclusions

This study designed, fabricated, and evaluated a low-cost portable rotary cutting machine for sugar palm (Arenga pinnata) inflorescence stalk trimming. The developed device integrates a rotary disc blade, DC worm gear motor, worm gearbox transmission, rechargeable lithium battery, and protective blade cover in a compact handheld structure suitable for smallholder field operation. Compared with conventional manual trimming, the machine reduced the average cutting time from 22.4 ± 1.1 to 6.8 ± 0.6 s/stalk, corresponding to a 69.64% reduction and 3.29 times faster operation, with a statistically significant difference at $p < 0.001$. The operational capacity increased from 160.7 to 529.4 stalks/hour, while a representative workload of 50 stalks/day produced a trimming-time saving of 780 s/day or approximately 13 min/day. The device operated at 10.8 V and 0.95 A, with estimated power and energy consumption of 10.26 W and 0.0194 Wh/stalk, respectively. The nominal battery energy of 51.84 Wh can theoretically support approximately 2675 trimming operations before complete drainage, or about 2140 operations at 80% usable battery energy. The prototype material cost was Rp 433,000, equivalent to approximately USD 24.25 using an exchange rate of Rp 17,856/USD. Although the study was limited to the trimming stage and did not yet evaluate long-term durability, vibration, ergonomics, blade wear, or the effect of trimming quality on sap yield, the results indicate that the proposed battery-powered rotary cutting machine is a feasible low-cost and low-energy mechanization option for repetitive sugar palm inflorescence stalk trimming.

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Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

The authors used ChatGPT to assist in language refinement, manuscript organization, and editorial improvements. All AI-generated content was critically reviewed, revised, and validated by the authors. The authors take full responsibility for the scientific accuracy, originality, and integrity of the manuscript, in accordance with the guidelines of the Committee on Publication Ethics (COPE).

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