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A semi-automatic prototype machine for splitting and endosperm extraction of *Nypa fruticans*: Design and experimental evaluation

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Abstract: *Nypa fruticans* is a mangrove palm whose immature fruit endosperm is widely consumed, but harvesting and extraction are still largely performed manual, resulting in low productivity and inconsistent quality. This study presents the design and experimental evaluation of a semi-automatic prototype machine for splitting nipa palm fruits and extracting the endosperm. The machine integrates a roller–blade mechanism for fruit splitting with a suction-based endosperm extraction system. To determine suitable operating conditions, the Taguchi design of experiments was applied using two independent L9 orthogonal arrays for the splitting and extraction functions. The performance was evaluated using the mean response and ANOVA analyses. The results show that the proposed mechanism achieves relatively high and stable splitting, while the extraction performance is mainly influenced by the suction flow rate. Integrated tests on 180 fruits under optimised conditions confirmed stable splitting and a practical extraction efficiency. The results demonstrate the technical feasibility of the proposed prototype and provide a basis for further improvements in robustness and processing capacity.

Keywords: agricultural machinery; nipa palm processing; suction-based harvesting; Taguchi method; vacuum-assisted separation

Nypa fruticans Wurmb., commonly known as the nipa palm, is a mangrove-associated species widely distributed in estuarine and coastal regions of Southeast Asia and the Indo–West Pacific. Unlike most palm species, it thrives in brackish environments and plays an important ecological role in shoreline stabilisation and mangrove ecosystems (Cheablam and Chanklap 2020). In addition to its ecological importance, the nipa palm is recognised as a multipurpose resource that provides food, construction materials, and other bioresources for coastal communities (Hamilton and Murphy 1988).

Among its various products, the immature fruit endosperm, often referred to as nipa flesh or aril, is of particular economic value. This endosperm exhibits a soft, jelly-like texture and mild sweetness, making it a widely consumed ingredient in traditional foods and desserts across many Asian countries (Cheablam and Chanklap 2020). Previous studies have also reported the presence of phenolic compounds and antioxidant activities in the nipa endosperm (Prasad et al. 2013), while post-harvest handling conditions have been shown to influence its physicochemical properties. These characteristics highlight the importance of appropriate extraction and processing methods to maintain product quality.

In parallel with research on endosperm utilisation, significant attention has been given to nipa sap as a renewable bioresource, particularly for bioethanol production and value-added products

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(Saengkrajang et al. 2021; Tamunaidu et al. 2013). However, despite growing interest in nipa-based applications, the existing studies have predominantly focused on biochemical processing and downstream utilisation. In contrast, relatively limited research has addressed the mechanical aspects of harvesting and fruit processing.

In practice, nipa endosperm extraction is still largely conducted manually. The fruit is typically split with knives or simple tools, and then the endosperm is manually removed. This process is labour-intensive, time-consuming, and highly dependent on operator skill, leading to low productivity and inconsistent product quality. In addition, direct manual handling may introduce contamination from plant residues and fibrous tissues, raising concerns regarding hygiene and product uniformity.

Mechanisation has been widely adopted in agricultural engineering to improve the productivity, reduce the labour dependency, and enhance the operational safety. Various machines have been developed for fruit cutting, peeling, and kernel separation in crops such as the coconut, oil palm, and walnut. For example, mechanical dehusking and deshelling systems have been proposed for coconut processing to improve the efficiency and safety (Onyenanu et al. 2025) and optimisation-based approaches have been applied to palm kernel and walnut cracking systems, where the interactions among cracking force, fruit geometry, and operating parameters govern the performance (Hussain et al. 2018; Ikubanni et al. 2025). These studies demonstrate that shell-splitting and kernel-separation technologies are well established for several crops; however, they are primarily designed for hard, rigid materials, where the mechanical force dominates the separation process. Such approaches are not suitable for the nipa fruit, which has a soft, high-moisture endosperm that is highly susceptible to deformation and damage under direct mechanical force. As a result, conventional cutting, impact, or scooping methods may lead to product loss and quality degradation. Therefore, there remains a lack of integrated mechanised systems specifically designed to split and extract soft biological materials, such as the nipa fruit.

To address this gap, the present study proposes and experimentally evaluates a semi-automatic prototype machine for nipa fruit processing. The system integrates two key functions: longitudinal fruit splitting via a roller–blade mechanism and non-contact endosperm extraction via a suction principle. This suction-based approach is specifically designed to handle soft, gelatinous materials, enabling the endosperm removal through pressure differentials rather than direct mechanical interaction.

To identify suitable operating conditions under limited experimental resources, the Taguchi design of experiments was employed. This method has been widely used for parameter optimisation in engineering systems due to its efficiency in evaluating multiple factors with a reduced number of experiments (Phokha et al. 2025). In this study, separate Taguchi L9 designs were applied to analyse the effects of key operating parameters on the fruit splitting and endosperm extraction performance.

Unlike conventional shell-breaking and kernel-separation systems developed for rigid agricultural products, such as the coconut, walnut, cocoa pod, or palm kernel, the proposed machine was specifically designed for soft, deformable, and high-moisture biological materials, where direct mechanical extraction can easily damage the product (Zhou et al. 2022; Han et al. 2023; Zhang et al. 2025a). The system combines roller-assisted splitting and non-contact suction-based extraction in a continuous processing configuration adapted for nipa palm fruits. To the authors' knowledge, no previous study has reported an integrated mechanised system based on these operating principles for nipa endosperm processing.

The present study, therefore, focuses on the design, fabrication, and experimental evaluation of a semi-automatic prototype for splitting nipa fruits and extracting the endosperm. In addition to the machine development, the study also identifies suitable operating conditions for the splitting and extraction processes using a Taguchi-based experimental approach. The findings contribute to the mechanisation of nipa fruit processing and provide a practical understanding of handling soft biological materials using combined mechanical splitting and suction-based extraction.

MATERIAL AND METHODS

Manual extraction and problem statement. Figure 1 illustrates the manual extraction of the nipa palm endosperm. The fruit is split longitudinally using a knife, and the endosperm is removed using

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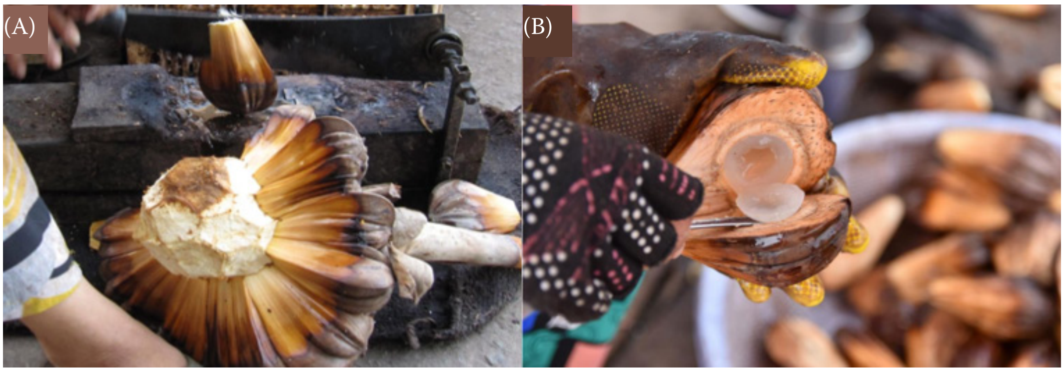

Figure 1. Manual method for extracting the nipa fruit endosperm: (A) separating the nipa fruit, (B) extracting the fruit endosperm

simple hand tools. This process is labour-intensive, time-consuming, and dependent on operator skill, resulting in low productivity and inconsistent product quality. In addition, the use of sharp tools introduces safety risks and may lead to contamination from plant residues.

Machine design and working principle. The overall working principle of the system is illustrated in Figure 2. When a nipa fruit (1) enters the machine, it is guided by positioning plates (2), which align the fruit along a nearly vertical axis. The plates form a V-shaped guiding profile and include longitudinal slots that allow roller-mounted spikes to penetrate the shell, enabling passive positioning without active control.

Fruit splitting is performed by two counter-rotating rollers (3) operating at a variable rotational speed. The spikes penetrate the shell, generating traction that pulls the fruit toward the stationary cutting blade (4), which splits it along the longitudinal axis. The blade has a V-shaped profile to facilitate self-centring.

After splitting, the fruit halves are guided along the curved chute (5) toward the suction inlet (6). A vacuum source connected to the collection container (9) generates a pressure differential that detaches the endosperm and transports it into a container. The suction inlet is configured to prevent product entry into the suction line.

The remaining shell halves are removed by a scraping plate (7), which remains in contact with the rollers by a spring mechanism (8), and discharged into the collection tray (12). This configuration enables continuous fruit splitting and endosperm extraction with minimal manual intervention.

Design basis and parameter selection. The selection of key design parameters was guided by principles of cutting mechanics and vacuum-

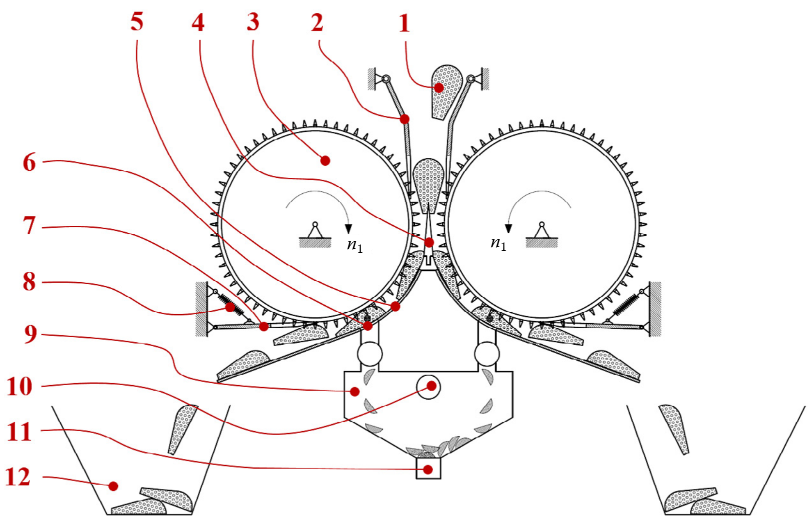

Figure 2. Schematic diagram of the machine

1 – nipa palm fruit; 2 – fruit positioning plate; 3 – rollers; 4 – cutting blade; 5 – guiding chute; 6 – suction inlet on the guiding chute; 7 – shell push-out plate; 8 – spring; 9 – endosperm collection container; 10 – suction inlet on the collection container; 11 – discharge pipe; 12 – shell collection tray; n_1 – roller speed (rpm)

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assisted material handling. Due to the heterogeneous, moisture-rich nature of biological materials, the analytical prediction of the cutting and extraction behaviour is limited; therefore, theoretical relationships were used to estimate the feasible parameter ranges, while the final values were determined experimentally. During the fruit-splitting stage, the cutting performance is primarily influenced by the blade geometry, particularly the sharpening angle. According to cutting mechanics, larger wedge angles increase the cutting force due to greater material deformation and friction (Merchant 1945), whereas sharper tools generally reduce the cutting force, but may compromise the tool durability (Dowgiallo 2005; McCarthy et al. 2007). Based on these considerations, a practical range of blade angles was selected for the experimental evaluation.

For the endosperm extraction stage, the suction force acting on the material is governed by the pressure differential generated by the vacuum system and the effective contact area:

$$F_s = \Delta P \times A_{eff} \quad (1)$$

where: F_s – the suction force (N); ΔP – the pressure difference between the ambient pressure and the suction zone (N·m^{-2}); A_{eff} – the effective suction area (m^2) (Purtov et al. 2015; Zhang et al. 2025b).

The pressure difference ΔP is related to the suction flow rate Q through standard orifice flow relationships:

$$Q = C_d \times A_0 \sqrt{\frac{2\Delta P}{\text{ñ}}} \quad (2)$$

where: C_d – the discharge coefficient (N·m^{-1}); A_0 – the inlet area (m^2); ρ – the air density (kg·m^{-3}) (Reader-Harris and Sattary 1990)

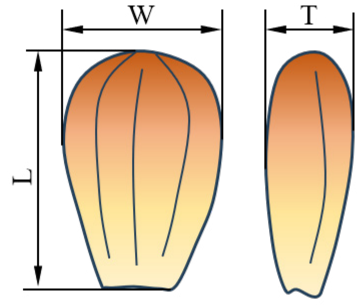

Figure 3. Nipa palm fruit dimension specifications
L – length; W – width; T – thickness

These relationships indicate that increasing the suction flow rate enhances the pressure differential and, consequently, the suction force available for the endosperm detachment. Given the variability in the fruit morphology and internal structure, these equations were used as a theoretical basis, while the parameter ranges were refined through preliminary trials and experimental evaluation.

Fruit characteristics and prototype specifications. Figure 3 presents the main dimensions of nipa palm fruits. Measurements from 100 samples showed average values of L = 133 mm, W = 83 mm, and T = 57 mm, which were used to define the machine geometry. The splitting mechanism consists of two rollers equipped with four rows of spikes arranged symmetrically around the roller axis (Figure 4). A stepped configuration improves the conformity to the curved fruit surface and enhances the traction during feeding.

Figure 5 shows the cutting blade geometry. The blade has a V-shaped profile with an included angle of approximately 100°, and three sharpening angles (15°, 20°, and 25°) were investigated.

Figure 6 presents the guiding chute and suction inlet, together with the endosperm collection

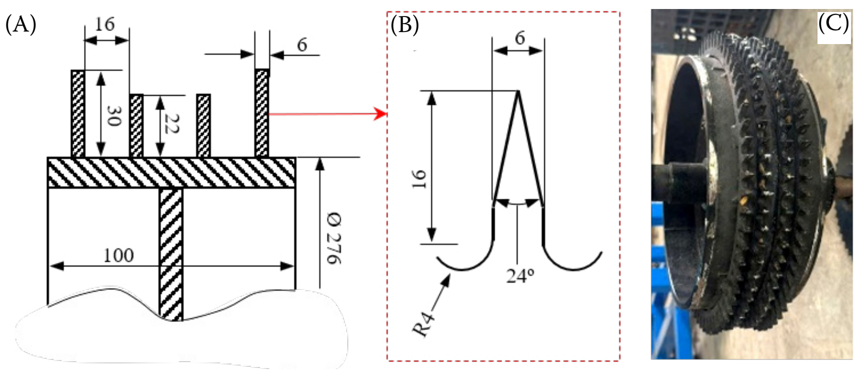

Figure 4. Geometric parameters of the rollers and spikes (A, B), real roller (C)

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Figure 5. Geometric parameters of the cutting blade: specific cutting blade dimensions (A), three cutting blades used in the study (B)

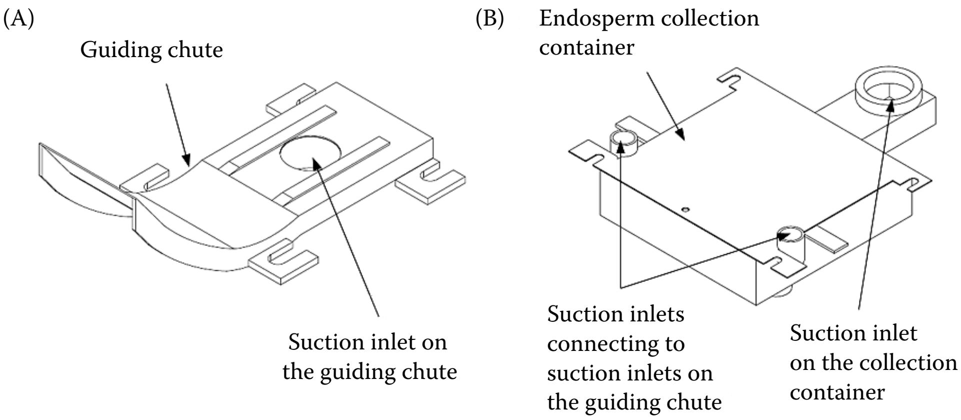

Figure 6. Geometry of the guiding chute and suction inlet (A), geometry of the endosperm collection container (B)

container. Figure 7 shows the chain drive system and the fully assembled prototype machine. The transmission system employs sprockets with tooth numbers of 26 (Z_1), 54 (Z_2), and 30 (Z_3). The machine is driven by a 1 HP motor with a 1 : 20 gearbox and a variable-frequency drive. The suction system provides a maximum flow rate of approximately 250 L·s^{-1}, with a total installed power of about 4.35 kW.

Figure 8 presents the experimental determination of the splitting force using a compression testing setup with a cutting blade having a sharpening angle of 25°. The peak load at shell fracture was recorded as the splitting force. Due to the heterogeneous nature of the fruit shell, direct measurements were adopted, as is commonly used in studies of agricultural materials (Dowgiallo 2005; Yousuf et al. 2020).

Experimental design and performance evaluation. The Taguchi method was employed to optimise the machine's operating parameters with limited experimental resources. This approach enables the efficient evaluation of multiple factors with fewer experiments and is widely used in en-

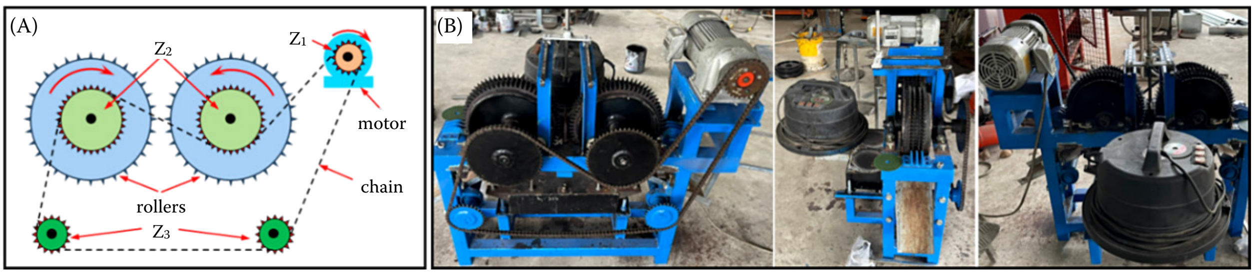

Figure 7. Chain drive system (A), fully assembled prototype machine (B)

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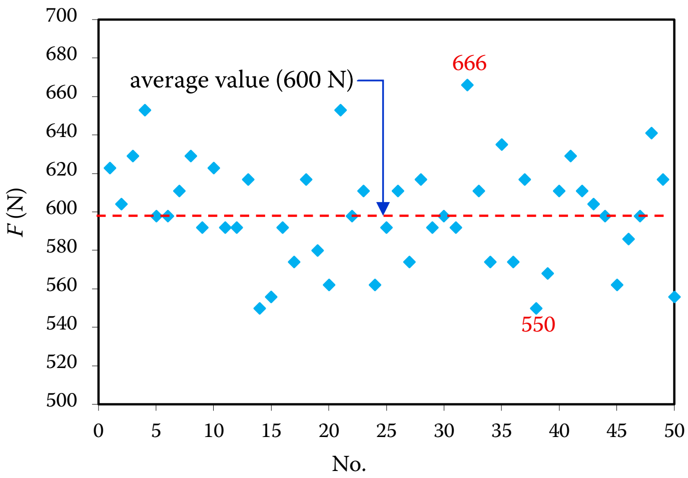

Figure 8. Experimental determination of the splitting force (F) of the nipa palm fruit

gineering optimisation studies. In this study, the two primary machine functions, fruit splitting and endosperm extraction, were analysed separately and subsequently combined.

For fruit splitting, three parameters were considered: the roller rotational speed (n, rpm), blade sharpening angle (α, °), and distance between the roller spike tips (D, mm). These parameters govern the kinematic interaction and cutting conditions during splitting.

For the endosperm extraction, the investigated parameters were the suction flow rate (Q, L·s^{-1}), the distance between the fruit and the suction inlet (t, mm) (Figure 9), and n. These parameters influence the suction behaviour and airflow interaction during extraction.

A Taguchi L9 (3^3) orthogonal array was applied for each function to evaluate the effects of the selected parameters. The factor levels are presented in Tables 1 and 2 and were determined based on the preliminary trials to ensure stable machine operation. Each experimental run used 20 nipa palm fruits, yielding a total of 180 fruits per the L9 design. The performance was evaluated using the splitting efficiency (%) and extraction success rate (%), defined as the proportions of successful outcomes.

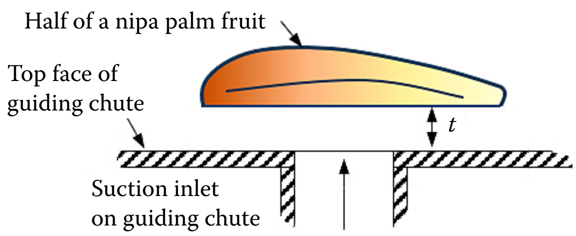

Figure 9. The distance t between the inner surface of the split fruit and the top face of the guiding chute

Statistical analysis. The mean response analysis and analysis of variance (ANOVA) were used to evaluate the effects of the operating parameters. Given the limited degrees of freedom of the Taguchi L9 design and the variability of biological materials, the statistical results were interpreted alongside engineering considerations to determine the practical operating conditions.

RESULTS AND DISCUSSION

Fruit splitting performance. Table 3 presents the results of the Taguchi L9 experiments evaluating the effects of n, α, and D on the fruit splitting per-

Table 1. Parameters and levels for the fruit splitting function

Parameters	n (rpm)	α (°)	D (mm)
Level 1	6	15	20
Level 2	8	20	25
Level 3	10	25	30

n – the roller rotational speed; α –blade sharpening angle; D – distance between the roller spike tips

Table 2. Parameters and levels for the endosperm extraction function

Parameters	Q (L·s^{-1})	t (mm)	n (rpm)
Level 1	83	1	6
Level 2	166	1.5	8
Level 3	250	2	10

Q – suction flow rate; t – the distance between the fruit and the suction inlet; n – the roller rotational speed

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Table 3. Experimental results of the nipa palm fruit splitting

No.	*n* (rpm)	α (°)	*D* (mm)	Splitting efficiency (%)
1	6	15	20	85
2	6	20	25	100
3	6	25	30	90
4	8	15	20	100
5	8	20	25	100
6	8	25	30	95
7	10	15	20	100
8	10	20	25	100
9	10	25	30	90

n – the roller rotational speed; α –blade sharpening angle; *D* – distance between the roller spike tips

formance. A total of 180 nipa palm fruits (20 fruits per run) were tested. The proposed roller–blade mechanism achieved relatively high and stable splitting efficiencies, ranging from 85% to 100%.

The mean response analysis (Figure 10) indicates that the optimal parameter combination is n = 8 rpm, α = 20°, and D = 25 mm. These results are valid within the investigated range of fruit dimensions, where natural variability influences the interaction between the fruit and the splitting mechanism.

Among the investigated parameters, α has the greatest influence, followed by n and D. The dominant role of the blade geometry stems from its direct influence on the crack initiation and propagation. Previous studies on agricultural cutting and shell-breaking systems have reported that the blade geometry strongly influences the crack initiation, cutting stability, and material separation behaviour (Han et al. 2023; Ban et al. 2024; Akendola et al. 2025). A comparable trend was observed in the present study, where the intermediate blade sharpening angle (20°) provided the most stable splitting performance.

At smaller sharpening angles, the blade becomes sharper and reduces the cutting resistance; however, excessive sharpness may lead to unstable penetration and deviation when interacting with the curved and heterogeneous fruit shell. Conversely, larger blade angles improve the mechanical robustness, but require a greater force to initiate cracking, thereby increasing the friction and reducing the splitting efficiency. Unlike rigid agricultural shells, such as the walnut or palm kernel, the Nipa fruit contains a soft, high-moisture endosperm and a more deformable shell structure. Consequently, unstable crack propagation or local shell deformation during splitting may negatively affect the subsequent extraction process. Therefore, the intermediate blade angle represents a practical balance between the penetration capability, crack stability, and overall processing reliability.

The effect of n is associated with the kinematic interaction between the fruit and the mechanism. At low speeds, feeding becomes less continuous, leading to irregular engagement and unstable alignment. At high speeds, the interaction time between the blade and the shell decreases, increasing the likelihood of misalignment or incomplete splitting. Therefore, an intermediate speed (8 rpm) provides stable feeding and sufficient interaction time.

The parameter D affects the fruit positioning and gripping. Smaller spacing improves confinement,

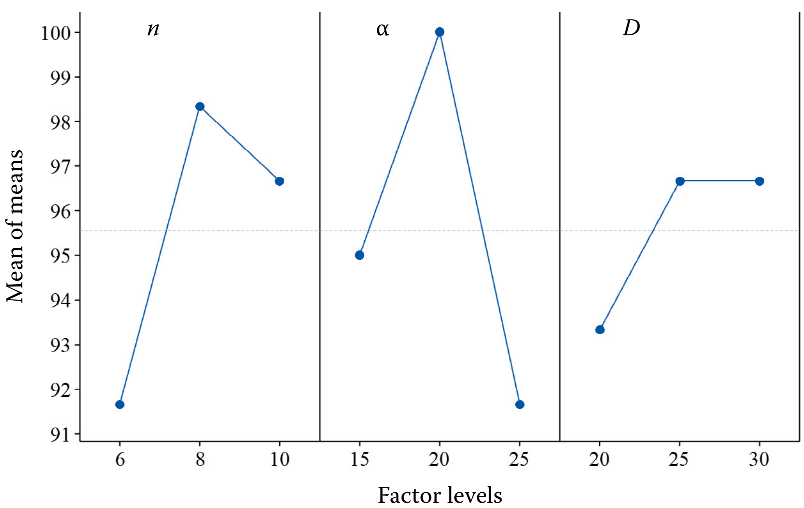

Figure 10. Mean effect plot of the nipa palm fruit splitting
n – the roller rotational speed; α –blade sharpening angle; *D* – distance between the roller spike tips

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Table 4. Analysis of variance for the means of the nipa palm fruit splitting

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P*
n	2	72.22	72.22	36.11	1.00	0.500
α	2	105.56	105.56	52.78	1.46	0.406
D	2	22.22	22.22	11.11	0.31	0.765
Residual error	2	72.22	72.22	36.11		
Total	8	272.22				

n – the roller rotational speed; α –blade sharpening angle; *D* – distance between the roller spike tips; DF – degrees of freedom; Seq SS – sequential sum of squares; Adj SS – adjusted sum of squares; Adj MS – adjusted mean square

but may restrict movement, whereas larger spacing reduces the contact stability and spike penetration. The optimal value (25 mm) represents a balance between stable gripping and smooth feeding.

Similar dependencies on geometric and kinematic parameters have been reported in shell-breaking systems for agricultural products such as the walnut and palm kernel, where the cracking efficiency depends on the contact conditions and fruit positioning (Hussain et al. 2018; Zhang et al. 2022; Ikubanni et al. 2025). However, unlike the rigid kernels of these systems, the nipa fruit contains a soft, high-moisture endosperm. Therefore, the splitting process must ensure shell rupture while avoiding excessive mechanical disturbance that could affect the subsequent extraction, highlighting the need for a crop-specific design.

The ANOVA results (Table 4) indicate that none of the factors are statistically significant at the conventional confidence level. This is mainly due to the limited degrees of freedom of the Taguchi L9 design and the narrow response range. Nevertheless, α shows the highest adjusted mean square and *F*-value, confirming its dominant influence.

Therefore, the combined interpretation of the mean response and ANOVA results provides a practical basis for parameter selection. Accordingly, the optimisation results should be interpreted as practical engineering guidance rather than strict statistical inference, particularly given the inherent variability of the biological materials. These findings are therefore valid within the investigated range of fruit dimensions.

Endosperm extraction performance. Table 5 summarises the results of the Taguchi L9 experiments evaluating the effects of *Q*, *n*, and *t* on the extraction performance. The extraction success rate ranged from 25% to 96%, indicating strong dependence on the operating parameters and airflow interaction at the endosperm–shell interface.

The mean response analysis (Figure 11) shows that the optimal parameter combination is $n = 8$ rpm, $Q = 250$ L·s^{-1}, and $t = 1.5$ mm. These results are valid within the investigated range of fruit dimensions, where the variability in size, internal structure, and endosperm distribution affects the extraction behaviour.

Among the investigated parameters, *Q* has the greatest influence. Increasing *Q* enhances the pressure differential and suction force, thereby promoting the detachment of the soft, high-moisture endosperm. Previous studies on vacuum-assisted harvesting and soft-material handling systems have shown that the suction performance strongly depends on the airflow characteristics, pressure distribution, and contact conditions between the suction inlet and the material surface (Vrochidou et al. 2022; Zhou et al. 2022; Hua et al. 2025; Zhang et al. 2025a). A comparable airflow-dependent

Table 5. Results of the nipa palm endosperm extraction experiments

No.	*n* (rpm)	*Q* (L·s^{-1})	*t* (mm)	Suction success rate (%)
1	6	83	1.0	25
2	6	166	1.5	67
3	6	250	2.0	71
4	8	83	2.0	40
5	8	166	1.0	74
6	8	250	1.5	96
7	10	83	1.5	42
8	10	166	2.0	86
9	10	250	1.0	75

n – the roller rotational speed; *Q* – suction flow rate; *t* – the distance between the fruit and the suction inlet

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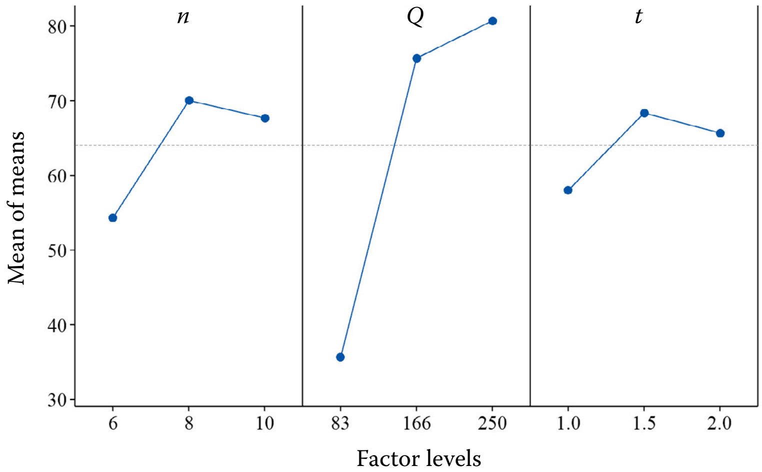

Figure 11. Mean effect plot of the nipa palm endosperm extraction
n – the roller rotational speed; *Q* – suction flow rate; *t* – the distance between the fruit and the suction inlet

trend was observed in the present study, where increasing the suction flow rate improved the endosperm detachment efficiency.

Unlike the relatively stable or uniformly shaped materials reported in previous studies, the Nipa endosperm is enclosed within an irregular biological structure and exhibits considerable variability in the position, adhesion, and moisture content. Under excessively high suction conditions, unstable local airflow and reduced sealing between the suction inlet and the fruit surface may occur, leading to non-uniform pressure distribution and less consistent detachment behaviour. Therefore, an optimal flow rate is required to balance the suction force, airflow stability, and extraction consistency.

The parameter *t* affects the local pressure gradient at the endosperm–shell interface. Smaller distances increase the suction intensity, but may restrict the airflow distribution, whereas larger distances reduce the pressure gradient and weaken the suction (Reader-Harris and Sattary 1990). The optimal value (1.5 mm) provides a balance between the suction intensity and effective airflow coverage.

The effect of *n* is associated with the interaction time between the endosperm and the suction zone. At low speeds, sufficient exposure time is available, but material transport becomes less stable; at high speeds, the interaction time is reduced, increasing the likelihood of incomplete detachment. An intermediate speed (8 rpm), therefore, provides a balance between these effects.

These findings are consistent with studies on vacuum-assisted handling systems for agricultural products, which show that the performance depends on the airflow characteristics, sealing conditions, and geometric alignment (Vrochidou et al. 2022; Goulart et al. 2023; Hua et al. 2025). However, unlike systems designed for external gripping, the present mechanism operates within a confined geometry, where the airflow must penetrate the split fruit and simultaneously detach the endosperm. This constraint is not typically addressed in conventional vacuum handling systems. In contrast, conventional extraction methods used for rigid kernels rely on cutting or impact forces, whereas suction-based approaches enable non-contact removal through pressure differentials, making them more suitable for deformable materials such as the nipa endosperm.

The ANOVA results (Table 6) indicate that *Q* has a statistically significant effect on the extraction performance, while the effects of *n* and *t* are less pronounced. This is attributed to the limited degrees of freedom of the Taguchi L9 design and the inherent variability of biological materials. Nevertheless, *n* and *t* remain practically important, as inappropriate kinematic or geometric conditions can reduce the extraction efficiency even under favourable suction flow rates.

Overall, the suction flow rate governs the detachment mechanism, while the roller motion and geometric configuration control the interaction conditions between the endosperm and the suction field. The identified optimal conditions should be interpreted within the investigated range of fruit characteristics.

Integrated machine validation and practical implications. Based on the independent optimisation of the fruit splitting and endosperm extraction functions, the optimal operating conditions for the integrated system were determined as n = 8 rpm, α = 20°, D = 25 mm, Q = 250 L·s^{-1}, and t = 1.5 mm.

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Table 6. Analysis of variance for the means of the nipa palm endosperm extraction

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P*
n	2	428.7	428.7	214.33	3.67	0.214
Q	2	3 650.0	3 650.0	1 825.00	31.29	0.031
t	2	172.7	172.7	86.33	1.48	0.403
Residual Error	2	116.7	116.7	58.33		
Total	8	4 368.0				

n – the roller rotational speed; *Q* – suction flow rate; *t* – the distance between the fruit and the suction inlet; DF – degrees of freedom; Seq SS – sequential sum of squares; Adj SS – adjusted sum of squares; Adj MS – adjusted mean square

These parameters were applied in the validation experiments to evaluate the overall machine performance.

Three confirmation tests were conducted using a total of 180 Nipa palm fruits (60 fruits per test). The results are summarised in Figure 12, with representative samples shown in Figure 13. The splitting function achieved a consistent 100% success rate across all the tests, indicating the stable operation of the roller–blade mechanism under integrated conditions.

In contrast, the extraction success rates were 75%, 83%, and 77%, respectively, showing greater variability. This variation is mainly attributed to the biological characteristics of the fruits, including the shell geometry, internal structure, moisture content, and endosperm distribution.

An analysis of the unsuccessful cases (Figure 14) revealed several recurring mechanisms. First, internal shell protrusions reduced the effective opening after splitting, in some cases making it smaller than the endosperm dimensions, which caused mechanical confinement. Second, in overmature fruits, the endosperm exhibited higher stiffness and stronger adhesion, reducing its ability to deform and detach under suction. Third, non-central splitting produced asymmetric openings, leaving part of the endosperm confined within a narrower region that could not be effectively removed.

These observations highlight that, while controllable mechanical parameters primarily govern the fruit splitting, the endosperm extraction is influenced by both the machine settings and the intrinsic variability of the raw materials. Similar limitations have been reported in vacuum-based handling systems, where the performance depends on the airflow characteristics, surface geometry, and alignment conditions (Vrochidou et al. 2022; Goulart et al. 2023).

From a practical perspective, the extraction consistency may be improved by first classifying the fruits according to the maturity level, since immature or overmature fruits exhibit different endosperm adhesion and mechanical behaviour

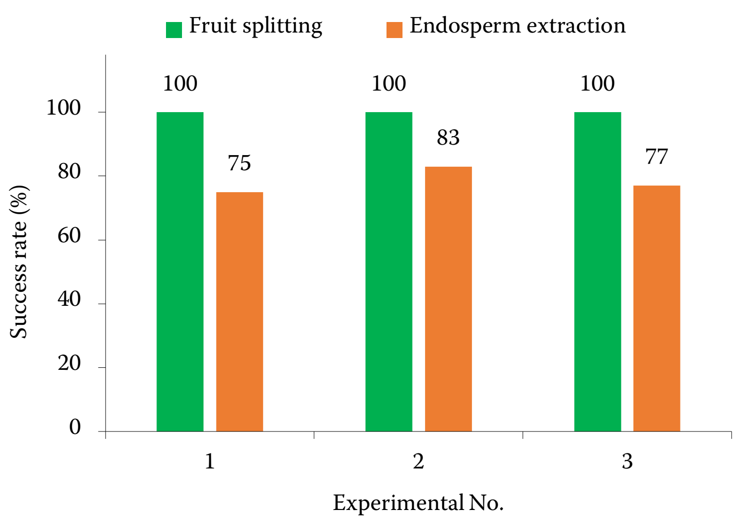

Figure 12. Experimental validation results under optimal machine parameters

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Figure 13. All the experimental samples (180 fruits): (A) first experimental set (1–60), (B) second experimental set (61–120), and (C) third experimental set (121–180)

during extraction. The post-harvest storage time should also be considered, as prolonged storage may reduce the fruit moisture content, making the shell softer and more ductile. Under such conditions, deformation of the fruit apex may occur upon contact with the cutting blade, thereby reducing the splitting stability. In addition, grouping fruits according to the external dimensions may help reduce any variability in the interaction between the fruit and the roller spikes during feeding and splitting.

Further improvements in the extraction robustness may be achieved by extending the suction inlet al.ng the fruit travel direction, thereby increasing the exposure time of the endosperm to the suction zone. This may improve detachment probability, particularly in cases of off-centre endosperms or asymmetric splitting. In addition, a simple feedback-based control strategy may be considered, in which a sensor near the extraction zone detects whether the endosperm has been successfully removed. If incomplete extraction is detected, the system could automatically increase the suction flow rate or adjust the operating conditions accordingly. Such approaches may improve the extraction consistency without requiring highly complex real-time control systems.

Compared with conventional systems for agricultural products, which typically treat shell breaking and material handling separately, the proposed machine integrates both functions into a continuous process. This is particularly important for the nipa fruit, where the soft endosperm requires immediate handling after shell opening to minimise damage and contamination.

In terms of productivity, the machine processed 60 fruits in 11–14 min, corresponding to a throughput of approximately 260–330 fruits per hour. In comparison, manual processing requires 18 to 22 s per fruit (approximately 160–200 fruits per hour per operator), representing an improvement of about 60–80% per operator under the investigated operating conditions.

It should be noted that these results are valid within the investigated range of fruit dimensions and operating conditions. Due to the natural variability of nipa palm fruits, further studies are required to evaluate the performance under broader conditions. In addition, immature fruits were not included, as their endosperm is thin and fragile, making them unsuitable for processing into final products.

Overall, the validation results confirm that the proposed system provides reliable fruit splitting and a practical level of extraction efficiency. The

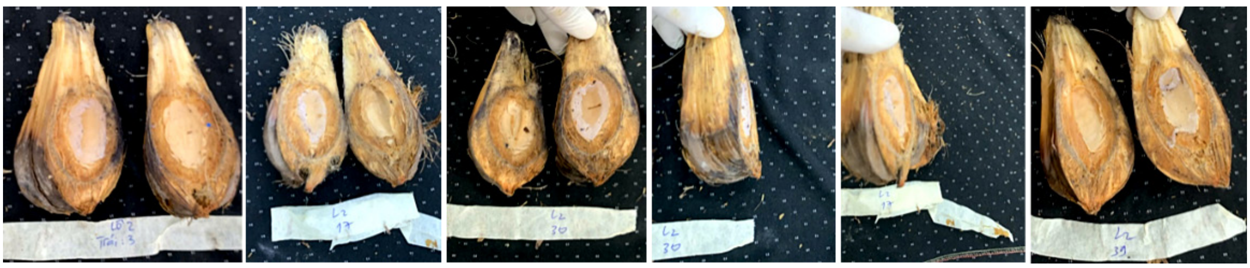

Figure 14. Several unsuccessful extraction cases

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integration of mechanical splitting and suction-based extraction represents a feasible approach for mechanising nipa fruit processing.

CONCLUSION

This study developed and experimentally evaluated a semi-automatic prototype machine for splitting Nipa palm fruits and extracting the endosperm. The proposed system integrates a rollerblade splitting mechanism with a suction-based extraction unit, enabling the continuous operation with minimal manual intervention.

The Taguchi-based optimisation showed that fruit splitting performance is mainly governed by the blade geometry and roller kinematics, resulting in relatively high and stable splitting. In contrast, the endosperm extraction is primarily influenced by the suction flow rate, while the roller speed and suction distance regulate the exposure conditions.

The integrated machine tests under optimal parameters demonstrated stable fruit splitting and a practical level of extraction efficiency. The variations in the extraction success were primarily attributed to biological factors, such as off-centre endosperms and internal shell ridges, rather than the machine settings. The additional variability may also be associated with differences in the fruit maturity; however, immature fruits were not included in the present study.

Under optimised conditions, the prototype achieved a throughput of approximately 260 to 330 fruits per hour, compared with 160–200 fruits per hour for manual processing. This productivity improvement and reduced manual handling confirm the feasibility of the mechanised processing of the Nipa palm endosperm.

Beyond developing a functional prototype, the present study also provides practical insights into handling soft biological materials by integrating mechanical splitting and suction-based extraction, which may support the future development of crop-specific processing systems for deformable agricultural products.

The future work should focus on improving the extraction robustness through adaptive suction control, improved fruit alignment mechanisms, and raw material classification, as well as increasing the system throughput for practical industrial applications.

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