Human-Centered Engineering and Techno-Economic Feasibility of Coconut Fiber Rope Enterprises

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ABSTRACT

The transition toward circular economies has created new opportunities to valorize agricultural residues as renewable resources. Coconut husk, abundantly available in tropical regions, represents a promising material for eco-friendly rope production. Yet, rural enterprises often rely on manual processing methods that are labor-intensive, inefficient, and yield inconsistent quality, while industrial-scale machines remain financially inaccessible. This technological gap prevents small-scale entrepreneurs from fully participating in circular economies and capturing the added value of coconut residues. This study integrates Design Thinking (DT) and Quality Function Deployment (QFD) within a human-centered engineering framework to design and evaluate an appropriate technology for coconut fiber rope enterprises. Using a census-based approach (n = 20–23 artisans), the Voice of the Customer (VoC) was systematically translated into technical requirements through the House of Quality. A prototype machine was fabricated, featuring a dual-cylinder decortication system and rotary screening mechanism, enabling simultaneous separation of cocopeat and coco fiber while reducing physical workload. Techno-economic analysis confirmed strong feasibility. The enterprise achieved a Break-Even Point (BEP) of 1,638 kg (3.2 weeks), a Net Present Value (NPV) of Rp 180 million over five years, an Internal Rate of Return (IRR) of 420–480% annually, and a Payback Period of only 1.3 months. Sensitivity analysis revealed that market price fluctuations exert greater influence on profitability than raw material costs. By combining human-centered design with financial validation, this study provides a replicable model for rural enterprises, contributing directly to SDG 8 (Decent Work and Economic Growth) and SDG 12 (Responsible Consumption and Production). The findings enrich academic discourse on appropriate technology while offering practical pathways for sustainable rural industrialization.

Keywords: Coconut fiber rope, Human-centered engineering, Design Thinking, Quality Function Deployment, Techno-economic feasibility, Circular economy

INTRODUCTION

The global transition from a linear economy toward a circular economy has become a pressing priority to address resource depletion, ecosystem degradation, and the accumulation of unmanaged agricultural biomass (Shija, 2026). Within this broader paradigm, lignocellulosic agricultural residues have attracted substantial attention for their potential to replace synthetic materials in sustainable applications. Among these, coconut husk stands out as one of the most abundant yet underutilized biomasses in tropical regions (Atapattu et al., 2024; Vieira et al., 2024).

Despite this economic potential, rural coconut-processing enterprises continue to experience severe technological and operational inefficiencies. Most rural communities rely on manual, labor-intensive extraction methods, while large-scale industrial machinery remains financially and technically inaccessible (Rumokoy et al., 2025b). This technological mismatch prevents local artisans from capturing the economic value of agricultural residues, isolating them from the benefits of circular village economies (Armando et al., 2025b).

Current academic literature has proposed various mechanical solutions, ergonomic assessments, and financial feasibility models independently (Kuptasthien et al., 2025; Nurfajriah et al., 2020). Methodologies such as Design Thinking (DT) and Quality Function Deployment (QFD) have been increasingly adopted to align product development with user needs (Teles, 2025a). However, despite these advances, existing studies rarely integrate community-derived requirements, engineering design translation, prototype validation, and techno-economic evaluation within a single human-centered engineering framework. Consequently, the systematic pathway through which users' needs are transformed into technically feasible and economically sustainable engineering solutions remains insufficiently explored.

This limitation has important implications for rural coconut fiber enterprises, where technological innovations frequently fail to address the operational realities faced by local artisans. Although coconut husk possesses considerable potential to support circular economy initiatives, rural producers continue to encounter technological inefficiencies and limited economic competitiveness because engineering solutions are often developed without systematically incorporating user requirements into design decisions. Addressing this challenge requires an integrated engineering approach capable of connecting user needs, technical design priorities, prototype performance, and enterprise feasibility.

Accordingly, this study addresses three principal questions: (1) how qualitative user requirements can be systematically translated into engineering design priorities; (2) to what extent the integration of Design Thinking and Quality Function Deployment improves prototype performance; and (3) how prototype performance influences the techno-economic feasibility of rural coconut fiber enterprises. Based on these questions, this study aims to develop and validate an integrated human-centered engineering framework combining Design Thinking and Quality Function Deployment to design, fabricate, and evaluate an appropriate coconut husk decorticator tailored to rural micro-enterprises.

This study contributes to the existing literature in several important ways. Theoretically, it extends the human-centered engineering perspective by establishing a structured linkage between qualitative community needs and quantitative engineering design parameters. Methodologically, it demonstrates the integration of Design Thinking, a census-based Voice of the Customer (VoC), Quality Function Deployment (QFD), and techno-economic validation within a unified engineering framework. Practically, the study delivers a field-validated prototype capable of simultaneously separating cocopeat and coconut fiber while addressing operational constraints commonly encountered by rural micro-enterprises. Finally, the proposed framework offers a replicable model for sustainable rural technology development that supports the achievement of Sustainable Development Goal (SDG) 8 on Decent Work and Economic Growth and SDG 12 on Responsible Consumption and Production.

METHODOLOGY

Research Design

This study employed a mixed-method empirical design that integrates *Design Thinking* (DT) and *Quality Function Deployment* (QFD) to ensure that the engineering process remains human-centered while simultaneously addressing techno-economic feasibility. The research was structured into three sequential phases: (1) capturing user needs through empathy-driven exploration, (2) translating qualitative insights into technical parameters using the House of Quality (HoQ), and (3) validating the prototype through performance testing and financial feasibility analysis.

Because the primary objective of this study is engineering design translation and appropriate technology realization rather than behavioral causal inference, the research employs Quality Function Deployment (QFD) as its principal analytical framework rather than explanatory statistical modeling or structural equation testing. Customer requirements collected through a comprehensive census approach ($n = 20–23$) were prioritized using descriptive evaluation and systematically mapped into technical specifications via the House of Quality (HoQ) matrix. Subsequently, prototype functionality was validated through empirical mechanical performance testing and rigorous techno-economic evaluation (Break-Even Point, NPV, IRR, and sensitivity analysis) rather than hypothesis-testing statistics

Population and Sampling

The research applied a census approach, involving the entire population of active coconut husk artisans in the study area (n = 20–23). This method eliminates sampling error and ensures that the *Voice of the Customer* (VoC) reflects 100% of the local ecosystem reality. Respondents included small-scale rope makers, coconut farmers, and local cooperatives engaged in husk processing.

Data Collection

Data were collected through semi-structured interviews, ergonomic observations, and structured questionnaires. Interviews focused on three dimensions: (1) physical workload and ergonomic challenges, (2) operational constraints related to energy and maintenance, and (3) financial expectations regarding production capacity. Questionnaires employed a Likert scale (1 = not important, 5 = very important) to prioritize user requirements. Observations documented manual rope-making processes, highlighting inefficiencies and safety concerns.

Voice of the Customer (VoC) and QFD Translation

Qualitative data from interviews and questionnaires were consolidated into homogeneous categories of customer requirements (CRs). Reliability was tested using Cronbach’s Alpha to ensure internal consistency. CRs were then embedded into the HoQ matrix following ISO 16355 standards (Erdil et al, 2023; Teles, 2025). The matrix scoring system (9 = strong, 3 = moderate, 1 = weak, 0 = none) was used to establish relationships between CRs and technical requirements (TRs). Roof matrix analysis identified conflicts and synergies among TRs, while absolute and relative importance weights were calculated to prioritize engineering parameters.

Prototype Development

Based on prioritized TRs, a prototype machine was fabricated to support eco-friendly rope production. The prototype integrated:

- A feeding hopper with ergonomic inclination.
- A dual-cylinder decortication system for simultaneous fiber separation.
- A rotary screening mechanism to ensure clean separation of cocopeat and coco fiber.
- A low-power motor adaptable to rural energy conditions.

Structural safety was validated through CAD simulations prior to manufacturing. The prototype was then tested under varying husk moisture levels and cylinder speeds to evaluate throughput capacity, fiber quality, and energy efficiency.

Techno-Economic Analysis

Financial feasibility was assessed using standard investment appraisal indicators: Break-Even Point (BEP), Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PP). Monthly fixed and variable costs were identified, and sensitivity analysis was conducted to simulate ±10% fluctuations in selling price and ±15% changes in raw material costs. These simulations provided insights into risk tolerance and profitability under different market conditions (Kholik et al., 2025; Nurfajriah et al., 2020).

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FINDINGS AND DISCUSSION

To address the three research questions formulated in this study, the findings are presented in an integrated sequence: translating user needs into technical specifications (RQ1), evaluating machine design and prototype performance (RQ2), and determining the techno-economic viability of rural circular enterprises (RQ3).

Quality Function Deployment Translation: Bridging Voice of Customer to Engineering Specifications (Addressing RQ1)

To answer RQ1 regarding how qualitative user requirements influence engineering design priorities, the first phase of the DT–QFD framework systematically captured and translated the field realities of rural artisans. By employing a census-based approach engaging the entire population of active coconut husk artisans in the study area (n = 20–23), the recorded Voice of the Customer (VoC) captured 100% of the local ecosystem reality. This eliminated sampling bias and ensured that engineering target setting directly reflected authentic community bottlenecks

Voice of the Customer (VoC) Prioritization

The census-based survey (n = 20–23) revealed twelve prioritized customer requirements. The most critical attributes included simultaneous separation of cocopeat and coco fiber, ease of operation, compact design, and low fuel consumption.

Tabel 1 Prioritized Customer Requirements for Coconut Fiber Rope-Making Machine

Attribute	Mean Score (1–5)	Priority Level
Simultaneous separation of cocopeat & cocofiber	4.9	Very High
Ease of operation	4.8	Very High
Compact and portable design	4.7	Very High
Low fuel consumption	4.6	High
Affordable machine price	4.5	High
Ease of cleaning	4.5	High
Availability of spare parts	4.4	High
Low noise level	4.4	High
Safety system at input hopper	4.3	High
Easy product retrieval	4.2	Moderate

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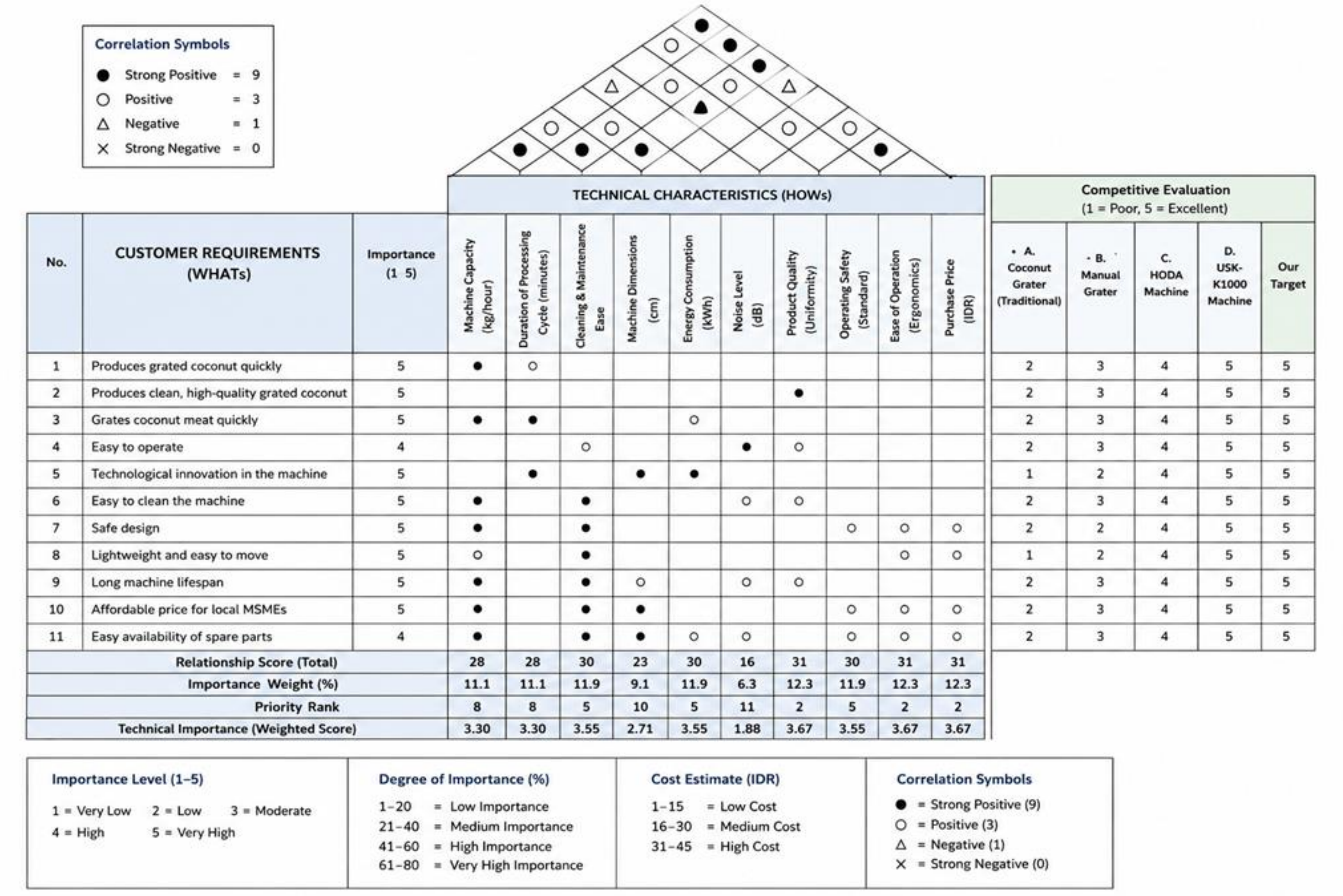

No.	CUSTOMER REQUIREMENTS (WHATs)	Importance (1 5)	Machine Capacity (kg/hour)	Duration of Processing Cycle (minutes)	Cleaning & Maintenance Ease	Machine Dimensions (cm)	Energy Consumption (kWh)	Noise Level (dB)	Product Quality (Uniformity)	Operating Safety (Standard)	Ease of Operation (Ergonomics)	Purchase Price (IDR)	• A. Coconut Grater (Traditional)	• B. Manual Grater	C. HODA Machine	D. USK-K1000 Machine	Our Target
1	Produces grated coconut quickly	5	●	○									2	3	4	5	5
2	Produces clean, high-quality grated coconut	5							●				2	3	4	5	5
3	Grates coconut meat quickly	5	●	●			○						2	3	4	5	5
4	Easy to operate	4			○			●	○				2	3	4	5	5
5	Technological innovation in the machine	5		●		●	●						1	2	4	5	5
6	Easy to clean the machine	5	●		●			○	○				2	3	4	5	5
7	Safe design	5	●		●					○	○	○	2	2	4	5	5
8	Lightweight and easy to move	5	○		●						○	○	1	2	4	5	5
9	Long machine lifespan	5	●		●	○		○	○				2	3	4	5	5
10	Affordable price for local MSMEs	5	●		●	●				○	○	○	2	3	4	5	5
11	Easy availability of spare parts	4	●		●	●	○	○		○	○	○	2	3	4	5	5
	Relationship Score (Total)		28	28	30	23	30	16	31	30	31	31					
	Importance Weight (%)		11.1	11.1	11.9	9.1	11.9	6.3	12.3	11.9	12.3	12.3					
	Priority Rank		8	8	5	10	5	11	2	5	2	2					
	Technical Importance (Weighted Score)		3.30	3.30	3.55	2.71	3.55	1.88	3.67	3.55	3.67	3.67					

Importance Level (1–5)	Degree of Importance (%)	Cost Estimate (IDR)	Correlation Symbols
1 = Very Low 2 = Low 3 = Moderate	1–20 = Low Importance	1–15 = Low Cost	● = Strong Positive (9)
4 = High 5 = Very High	21–40 = Medium Importance	16–30 = Medium Cost	○ = Positive (3)
	41–60 = High Importance	31–45 = High Cost	△ = Negative (1)
	61–80 = Very High Importance		× = Strong Negative (0)

Figure 1 Human-Centered House of Quality for Coconut Fiber Rope Enterprises

The matrix illustrates the correlation between customer requirements and technical specifications derived through Quality Function Deployment (QFD).

Prototype Development and Empirical Performance Validation (Addressing RQ2)

In response to **RQ2** regarding the extent to which prioritized technical requirements optimize machine functionality, the prioritized engineering specifications derived from the HoQ matrix directly guided the physical design and fabrication of the appropriate decorticator prototype.

Figure 2 Prototype of the Coconut Fiber Rope Machine

The fabricated prototype integrates a dual-cylinder decortication system and rotary screening mechanism, enabling simultaneous separation of cocopeat and fiber while reducing physical workload. The ergonomic hopper and low-power motor configuration enhance usability and energy efficiency, supporting human-centered engineering principles.

This framework (*Figure 3*) illustrates how the aspirations and challenges voiced by rural artisans were systematically translated into engineering solutions. Beginning with empathy-driven exploration of user needs (VoC), the process advanced through QFD translation to ensure measurable design parameters. The prototype development stage embodied these requirements in a tangible machine, which was then validated through techno-economic analysis. Ultimately, the framework highlights how human-centered innovation contributes directly to Sustainable Development Goals (SDGs), reinforcing the link between local realities and global sustainability agendas.

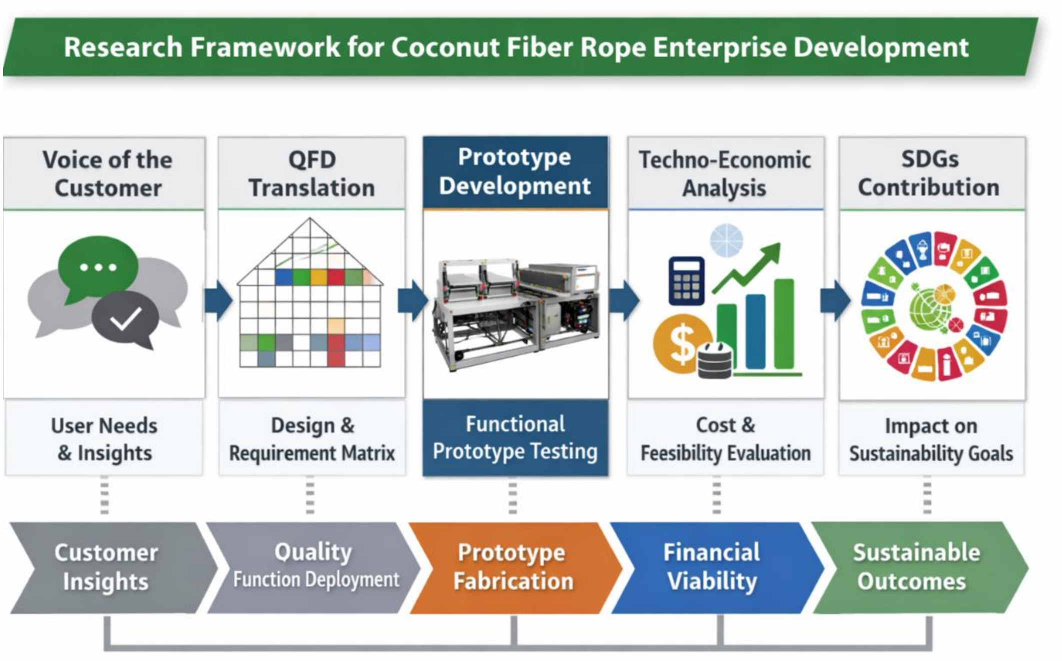

Figure 3 Integrated Research Framework Linking Voice of the Customer (VoC), QFD Translation, Prototype Development, Techno-Economic Analysis, and SDGs Contribution.

Unlike conventional decorticators that process fiber and cocopeat in separate, sequential stages, the developed prototype integrates a dual-cylinder decortication unit coupled with a dual rotary screening mechanism. Empirical performance testing confirmed the efficacy of this human-centered design choice:

1. **Throughput Efficiency:** The machine achieved a continuous processing capacity matching village operational rhythms.

2. **Co-product Separation:** Simultaneous separation yielded high cocopeat purity and clean fiber extraction without causing mechanical jam or excessive fiber breakage.

3. **Ergonomic and Operational Fit:** The low-power motor adaptation and compact frame allowed safe, single-operator handling, directly fulfilling the VoC parameters established in Phase 1.

These empirical outcomes validate that embedding user-derived technical priorities directly enhances mechanical performance and operational safety, thereby providing a clear empirical answer to **RQ2**.

Performance testing showed that the prototype achieved a throughput capacity of 17.1 kg/hour, with consistent fiber quality and reduced energy consumption compared to manual methods.

Techno-Economic Viability and Sensitivity Analysis for Rural Enterprises (Addressing RQ3)

Addressing **RQ3** on how optimized prototype performance determines enterprise feasibility and long-term economic sustainability, the empirical operational yields were translated into a comprehensive financial evaluation projected over a 5-year operational horizon.

Fixed costs were calculated at IDR 3,582,000 per month, with variable costs averaging IDR 2,857,000 per ton of husk processed. Based on a monthly production output of 3,420 kg (1,788 kg coco fiber and 1,632 kg cocopeat), total monthly revenue reached IDR 17,256,000, generating a net monthly profit of IDR 3,900,000.

Tabel 2 Techno-Economic Indicators of Coconut Fiber Rope Enterprise

Indicator	Value
Break-Even Point (BEP)	1,638 kg (3.2 weeks)
Net Present Value (NPV, 5 years)	Rp 180,192,347
Internal Rate of Return (IRR, annual)	420–480%
Payback Period (PP)	1.3 months

Sensitivity Analysis

The sensitivity simulations revealed that profitability in coconut fiber rope enterprises is highly vulnerable to market price fluctuations. A 10% decrease in selling price extended the break-even point to 2,131 kg, requiring longer operational hours and delaying cost recovery. Conversely, a 10% increase in selling price accelerated profitability, reducing the break-even threshold to 1,332 kg. In comparison, raw material cost surges exerted a moderate drag, elevating the break-even point to 2,037 kg. These findings emphasize that revenue stability, rather than input variability, is the dominant factor shaping financial resilience, underscoring the importance of cooperative marketing and price stabilization strategies.

Break-Even Sensitivity Analysis

To evaluate financial resilience against market volatility, three scenarios were simulated to model fluctuations in cost recovery and operational timelines (Karyna, 2026; White et al., 2022). In the first scenario, a 10% drop in selling price reduced monthly revenue to IDR 15.53 M, shrinking the contribution margin to IDR 1,681/kg and driving the BEP threshold up to 2,131 kg (Quibuyen et al., 2024). This forced village operators to extend their workload to 125 hours (4.2 weeks), adding a 0.9-week delay to reach the baseline. In the second scenario, a 15% surge in raw material costs increased variable expenses to IDR 11.24 M (Azra & Azzuhri, 2025). The margin compressed to IDR 1,759/kg, elevating the BEP to 2,037 kg and shifting cost-recovery momentum from 3.2 weeks to 4.0 weeks (119 hours) (Swan, 2016). Finally, in the optimistic third scenario, a 10% rise in selling price boosted revenue to IDR 18.98 M, expanding the margin to IDR 2,690/kg. The required BEP volume dropped significantly to 1,332 kg, accelerating profitability to just 78 operational hours (2.6 weeks) (Lebiadzinskaya, 2025). These simulations confirm that price fluctuations exert a stronger influence on profitability than raw material costs, highlighting the importance of cooperative marketing and stabilization strategies for rural enterprises.

Tabel 3 Sensitivity Analysis of Break-Even Point under Price and Cost Fluctuations

Scenario	**Production BEP (kg)**	**BEP Time (Hours/Weeks)**	**Operational Impact**
Normal Conditions	1.638	96 hours (3.2 weeks)	Standard operational baseline
Selling price down 10%	2.131	125 hours (4.2 weeks))	Workload increased +0.9 weeks

Raw material costs up 15%	2.037	119 hours (4.0 weeks)	Break-even reaches slowed down +0.8 weeks
Selling price up 10%	1.332	78 hours (2.6 weeks)	Accelerated return on capital -0.6 weeks

Ultimately, the enterprise's financial stability is acutely sensitive to selling-price variations, while raw material spikes act as a direct operational drag on efficiency.

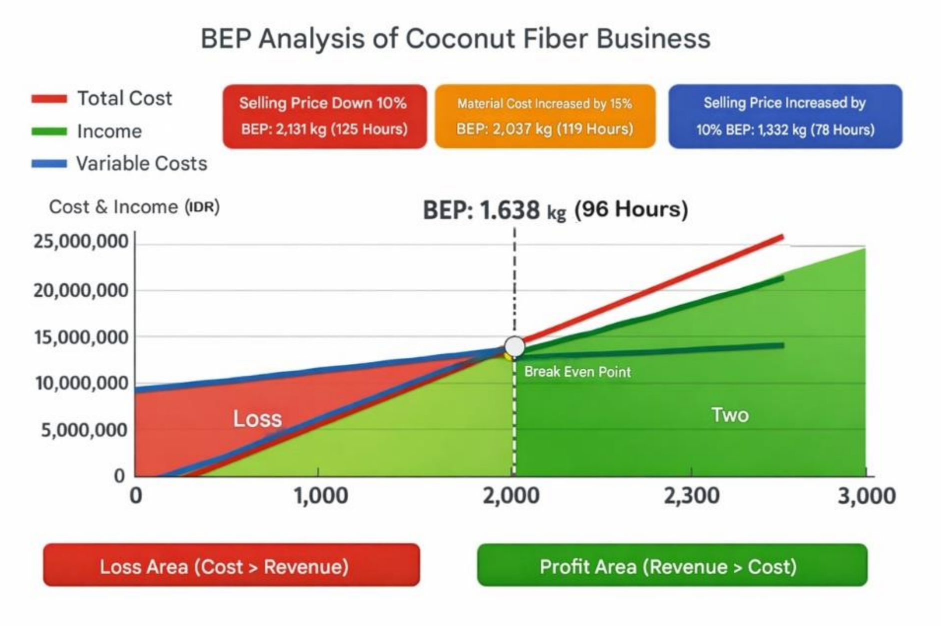

Figure 4 Break-Even Point Sensitivity Curve under Price and Cost Fluctuations

Socio-Economic and Environmental Implications for Circular Village Economies

The integration of Design Thinking, Quality Function Deployment, and empirical feasibility analysis confirms that appropriate technology development must extend beyond pure mechanical metrics to encompass socio-economic realities. By valorizing agricultural waste, eliminating grueling manual workload, and creating localized economic value, the framework directly advances UN Sustainable Development Goals—specifically **SDG 8 (Decent Work and Economic Growth)** and **SDG 12 (Responsible Consumption and Production)**.

SUMMARY OF FINDINGS

This study demonstrates how user-centered insights were systematically translated into a functional prototype of a coconut fiber rope machine. The dual-cylinder decortication and rotary screening system reduced physical workload while ensuring consistent fiber quality. Techno-economic evaluation confirmed feasibility, with profitability most sensitive to market price fluctuations rather than raw material costs. Sensitivity and break-even analyses highlighted the importance of cooperative marketing and price stabilization for rural resilience. Overall, the integrated framework links Voice of the Customer (VoC), QFD translation, prototype validation, and financial analysis, culminating in tangible contributions to Sustainable Development Goals (SDGs).

DISCUSSION

Human-Centered Insights

These findings reinforce the argument that engineering solutions for rural enterprises should prioritize usability and contextual appropriateness rather than merely maximizing technical performance.. The prioritization of customer requirements (VoC) confirmed that rural artisans value not only technical efficiency but also

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ergonomic usability and affordability. Attributes such as ease of operation, compact design, and low fuel consumption reflect the socio-economic realities of small-scale enterprises, where physical workload and limited capital are critical constraints. This finding aligns with the principles of **human-centered engineering**, which emphasize empathy and usability as central to design processes (Kang et al., 2025; Schmager et al., 2025). By integrating DT and QFD, the prototype successfully translated these qualitative needs into measurable technical parameters, ensuring that innovation was both technically feasible and socially acceptable (Caesaron et al., 2025).

Comparison with Literature

The prototype's dual-cylinder decortication system and rotary screening mechanism addressed inefficiencies observed in manual rope-making, consistent with earlier studies on integrated husk processing machines (Donisi et al., 2021; Rumokoy et al., 2025). Moreover, the emphasis on affordability and energy efficiency resonates with findings from bio-fertilizer mixer design, where DT–QFD integration reduced physical workload while enhancing productivity (Kuptasthien et al., 2025). Social impacts observed in rope enterprises in the Philippines such as increased income and strengthened family cohesion (Goltiano & Sinon, 2022) suggest that similar benefits may emerge in the Indonesian context once the prototype is widely adopted.

Techno-Economic Implications

Financial analysis demonstrated extraordinary profitability, with an IRR exceeding 400% annually and a payback period of only 1.3 months. These results surpass conventional agro-industrial benchmarks, confirming the viability of small-scale enterprises in valorizing coconut husk waste (Syahrudin et al., 2026; Tooy et al., 2023). Sensitivity analysis revealed that profitability is highly dependent on market price stability, echoing previous findings that price fluctuations exert greater influence than raw material costs (Kholik et al., 2025; Nurfajriah et al., 2020). This underscores the need for cooperative marketing strategies and policy interventions to stabilize local rope markets.

Policy and SDG Contributions

Beyond technical and financial outcomes, the study highlights broader implications for rural circular economies. By reducing physical workload, enabling rapid investment recovery, and valorizing agricultural residues, the innovation empowers local entrepreneurs and strengthens community resilience. These outcomes directly contribute to **SDG 8** (*Decent Work and Economic Growth*) and **SDG 12** (*Responsible Consumption and Production*). The integration of DT–QFD thus provides a replicable model for other rural contexts, demonstrating that appropriate technology must extend beyond mechanical efficiency to embrace socio-economic realities (Martínez Casanovas, 2025; Pienwisetkaew et al., 2025).

Limitations and Future Work

While the census approach ensured representativeness, the relatively small sample size (n = 20–23) limits generalizability. Future research should expand to multiple regions to validate findings across diverse socio-economic contexts. Additionally, integrating digital monitoring systems (e.g., IoT-based sensors for machine performance) could enhance long-term sustainability. Exploring diversification into other coconut-based products, such as geotextiles and bio-composites, may further strengthen the economic resilience of rural enterprises.

CONCLUSION

This study demonstrates that integrating *Design Thinking* (DT) and *Quality Function Deployment* (QFD) within a human-centered engineering framework provides a robust pathway for developing appropriate technology tailored to rural enterprises. By employing a census-based approach, the research ensured that the *Voice of the Customer* (VoC) fully represented the ecosystem reality, thereby eliminating sampling error and grounding the design in authentic user needs.

The prototype coconut fiber rope machine successfully addressed critical requirements such as simultaneous separation of cocopeat and coco fiber, ergonomic usability, compact design, and energy efficiency. Performance testing confirmed technical feasibility, while financial analysis revealed extraordinary profitability: a Break-Even Point (BEP) of 1,638 kg (3.2 weeks), a Net Present Value (NPV) of Rp 180 million over five years, an Internal Rate of Return (IRR) of 420–480% annually, and a Payback Period (PP) of only 1.3 months. Sensitivity analysis further highlighted the importance of market price stability in sustaining profitability.

Beyond technical and financial validation, the study underscores broader implications for rural circular economies. By reducing physical workload, enabling rapid investment recovery, and valorizing agricultural residues, the innovation empowers local entrepreneurs and strengthens community resilience. These outcomes directly contribute to **SDG 8** (*Decent Work and Economic Growth*) and **SDG 12** (*Responsible Consumption and Production*).

In conclusion, this research enriches academic discourse on human-centered engineering and appropriate technology, while providing a replicable model for sustainable rural industrialization. Future studies may extend this framework to other coconut-based products, integrate digital monitoring systems for performance evaluation, and assess long-term socio-economic impacts across diverse rural contexts.

From a theoretical perspective, this study advances human-centered engineering by establishing a structured, empirical bridge between qualitative user needs and quantitative mechanical design translation via QFD. Methodologically, it demonstrates the validity of combining a census-based Voice of the Customer (VoC), Quality Function Deployment, and techno-economic evaluation within a single unified framework. Practically and policy-wise, the developed prototype provides an affordable, high-efficiency technology that empowers rural artisans, enhances local value addition, and directly supports the advancement of SDGs 8 and 12 within circular village economies.

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