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BIOSURFACTANTS FROM PINEAPPLE WASTE: VALUE CHAIN ANALYSIS IN CIRCULAR ECONOMY FRAMEWORK AND CONSUMER ACCEPTANCE OF SUSTAINABLE PRODUCTS

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Abstract

This research bridges significant gaps in sustainable surfactant production by analyzing the value chain of biosurfactant production from pineapple waste while examining factors influencing consumer preferences for eco-friendly products. Employing a mixed-method approach, we combined qualitative data from in-depth interviews with 9 key stakeholders across the value chain with quantitative data from 129 survey respondents. The findings revealed that 94.6% of respondents had previously used environmentally friendly products, with 93.8% expressing interest in purchasing biosurfactant products derived from pineapple waste, primarily motivated by environmental conservation (77.5%). Consumer values toward environmentally friendly products ranked highest among influencing factors (mean = 4.52), followed by corporate social responsibility (4.49). Our value chain analysis, framed within circular economy principles, demonstrated that Thailand's pineapple processing waste (940,614 tons annually) could potentially yield approximately 4,850 tons of biosurfactants, replacing 20% of petroleum-based surfactants used in dishwashing detergents. Economic analysis suggests that although laboratory-scale production costs are currently high, industrial scaling with optimized processing technology could achieve financial viability with an estimated payback period of 7-8 years. This research contributes to SDGs 9, 12, and 13 by providing actionable insights for developing closed-loop business models that valorize agricultural waste while reducing environmental impacts of synthetic surfactants.

Keywords: *Circular Economy, Biosurfactants, Agricultural Waste Valorization, Green Consumer, Sustainable Value Chain, SDGs.*

1. INTRODUCTION

Surfactants represent a critical class of chemicals with widespread industrial and household applications, with the global market valued at approximately US$ 41 billion in 2019 and projections indicating growth to US$ 58.5 billion by 2027 (Allied Market Research, 2023). This market is predominantly supplied by petroleum-derived synthetic surfactants, which pose significant environmental concerns due to their limited biodegradability and persistence in aquatic ecosystems.

Biosurfactants have emerged as promising sustainable alternatives, offering lower toxicity, enhanced biodegradability, and stability across varying conditions (Farias et al., 2021). However, their production faces economic challenges, with costs often 10-30 times higher than synthetic alternatives (Bettenhausen, 2020).

The circular economy framework provides valuable approaches for addressing these challenges by transforming waste materials into valuable resources. Agricultural waste, particularly pineapple processing waste, represents an untapped resource due to its high carbohydrate content. Thailand, as a major pineapple producer (1.8 million tons annually), generates approximately 940,614 tons of processing waste yearly that currently poses disposal challenges while offering valorization potential.

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This research addresses several critical gaps: (1) comprehensive value chain analyses incorporating both production feasibility and consumer acceptance remain scarce; (2) studies on biosurfactant production from pineapple waste have primarily focused on laboratory-scale processes without considering scaling potential; and (3) research on consumer preferences for bio-based cleaning products has often overlooked biosurfactants derived from agricultural waste.

The research aims to: (1) analyze the value chain of biosurfactant production from pineapple waste within a circular economy framework; and (2) develop recommendations for sustainable business models integrating biosurfactant production into existing industrial systems. The findings provide strategic guidance for advancing sustainable chemical production and consumption, contributing to multiple Sustainable Development Goals (SDGs 9, 12, and 13).

2. LITERATURE REVIEW

Circular Economy and Agricultural Waste Valorization

The circular economy represents a paradigm shift from the traditional linear "take-make-dispose" model toward regenerative systems that minimize resource inputs and waste generation (Geissdoerfer et al., 2017). Agricultural waste valorization exemplifies circular economy principles by transforming by-products into value-added products (Ubando et al., 2020).

Fruit processing residues are particularly promising due to their rich biochemical composition. Pineapple waste contains valuable components including cellulose, hemicellulose, and bioactive compounds that can serve as substrates for microbial fermentation (Khedkar et al., 2017). However, systematic approaches to pineapple waste valorization remain underdeveloped in major producing countries like Thailand.

Value Chain Analysis in Sustainable Production Systems

Value chain analysis has evolved to incorporate environmental and social dimensions alongside economic considerations. Gereffi and Fernandez-Stark (2016) introduced "sustainable value chains" that optimize resource use while minimizing negative externalities, while Bocken et al. (2014) proposed innovations including closing resource loops and substituting with renewables.

Recent research has applied value chain analysis to bio-based products, including biosurfactants. Winterscheid et al. (2017) examined rhamnolipid production from renewable resources, identifying critical cost drivers and optimization strategies. However, comprehensive value chain analyses specifically focusing on biosurfactants from fruit processing waste remain limited, especially those incorporating consumer perspectives.

Biosurfactants: Properties, Production, and Market Potential

Biosurfactants comprise diverse amphiphilic compounds produced by microorganisms, offering advantages including lower toxicity, higher biodegradability, and often superior surface activity compared to synthetic surfactants (De Almeida et al., 2016).

Production pathways typically involve microbial fermentation using various carbon sources, including agricultural waste substrates. Vieira et al. (2021) demonstrated that pineapple peel extract could yield biosurfactants through fermentation with selected microbial strains.

Despite technical feasibility, biosurfactant production faces economic challenges, with production costs substantially higher than conventional surfactants (€20-25/kg vs €1-3/kg). The global biosurfactant market was valued at US$ 5.52 billion in 2021, with projections indicating growth to US$ 7.67 billion by 2027, driven by increasing environmental regulations and consumer demand for

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sustainable products. However, biosurfactants currently represent less than 10% of the global surfactant market, indicating significant growth opportunities.

Consumer Behavior Toward Environmentally Friendly Products

Research has identified various factors influencing green purchase intentions, including environmental consciousness (Sreen et al., 2018), perceived consumer effectiveness (Sharma & Foropon, 2019), product attributes (Dangelico & Vocalelli, 2017), and trust in green claims (Martínez, P., & Rodríguez del Bosque, 2013). The "attitude-behavior gap" remains a significant challenge, with consumers often expressing pro-environmental attitudes while exhibiting different purchasing behaviors (Carrington et al., 2014).

In the context of cleaning products, Lin et al. (2018) found that perceived effectiveness, environmental benefit, and health considerations significantly influenced intentions to purchase green cleaning products. Research specifically focusing on biosurfactant-based products remains limited, highlighting the need for studies examining consumer attitudes toward cleaning products containing biosurfactants from agricultural waste.

3. RESEARCH METHODOLOGY

3.1 Research Design

This study employed a sequential mixed-methods design (Creswell & Plano Clark, 2018) combining qualitative and quantitative approaches to comprehensively analyze the biosurfactant value chain and consumer preferences. This approach allowed for methodological triangulation, enhancing the validity and reliability of findings while providing both depth and breadth of understanding (Johnson et al., 2007). The research was conducted between January and September 2022 in Thailand.

3.2 Population & Sampling Procedure

Qualitative Method

We conducted in-depth interviews with 9 key informants selected through purposive sampling based on their roles across the biosurfactant value chain. Participants included pineapple farmers (n=2), community enterprise chairpersons (n=1), government officials responsible for agricultural development (n=1), community leaders in pineapple growing regions (n=1), canned pineapple factory operators (n=1), intermediaries/middlemen (n=1), surfactant production managers (n=1), and marketing analysts specializing in cleaning products (n=1).

Quantitative Method

Quantitative data were collected through an online survey of 129 consumers selected through accidental sampling. While this sampling approach limits generalizability, it is considered acceptable for product concept testing (Lawless & Heymann, 2010). The sample size aligns with recommendations by Hair et al. (2018) for exploratory research.

3.3 Validity and Reliability

Qualitative Method

The analysis employed both inductive and deductive approaches. Deductively, Porter's value chain framework guided the initial categorization of activities. Inductively, emerging themes within each value chain component were identified. Data trustworthiness was established through methodological triangulation (comparing interview and observational data), member checking (verifying interpretations with participants), and maintaining an audit trail of analytical decisions.

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Quantitative Method

The questionnaire was developed based on a literature review of green consumer behavior and refined through expert consultation. Content validity was assessed using the Index of Item-Objective Congruence (IOC) evaluated by three experts in consumer behavior and sustainability. Items with IOC values below 0.5 were eliminated or revised. The questionnaire was pilot-tested with 30 respondents not included in the final sample, and reliability was confirmed using Cronbach's alpha ($\alpha = 0.802$), exceeding the recommended threshold of 0.7 (George & Mallery, 2016).

3.4 Data Collection

Qualitative Method

Semi-structured interview protocols were developed based on Porter's (1985) value chain framework, with questions tailored to each stakeholder group's specific role in the value chain. Interviews lasted 60-90 minutes, were audio-recorded with permission, and transcribed verbatim. Additionally, participant and non-participant observation was conducted at key sites including farms, processing facilities, and community enterprises to gather contextual data on value chain activities.

Quantitative Method

Quantitative data were collected through an online survey of consumers. The questionnaire included sections on demographics, experience with environmentally friendly products, factors influencing green purchase decisions measured on 5-point Likert scales, and specific questions regarding interest in biosurfactant products from pineapple waste.

3.5 Data Processing

Qualitative data were analyzed using thematic analysis following Braun and Clarke's (2006) six-step approach: familiarization with data, generating initial codes, searching for themes, reviewing themes, defining themes, and producing the report. NVivo 12 software facilitated the coding process. Initial coding was performed independently by two researchers to enhance reliability, with discrepancies resolved through discussion.

Quantitative data were analyzed using IBM SPSS Statistics 26. Descriptive statistics including frequency distributions, percentages, means, and standard deviations were calculated to characterize the sample and summarize responses. Data normality was assessed through skewness and kurtosis values, with all variables falling within the acceptable range of ±3 (Trochim & Donnelly, 2006).

4. FINDING RESULTS

Integration of Qualitative and Quantitative Findings

Following the sequential mixed-methods design, qualitative findings informed the development of the quantitative instrument, while quantitative results provided context for interpreting qualitative insights. Integration occurred at both the methods and interpretation levels (Fetters et al., 2013). A joint display approach was used to visually represent the integration of findings across methods, facilitating the identification of convergence, complementarity, and divergence.

4.1 Quantitative Analysis: Consumer Perspectives

4.1.1 Respondent Characteristics

The sample (N=129) was predominantly female (65.1%), young adults aged 19-27 years (69.8%), with high educational attainment (71.3% bachelor's degrees, 26.3% postgraduate). Most respondents were students (65.9%), with the remainder working in government (9.3%), private sector (9.3%), or self-

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employed (9.3%). Monthly income was relatively low (62.8% earning ≤15,000 baht), reflecting the student-heavy sample.

4.1.2 Factors Influencing Environmentally Friendly Product Consumption

Consumer values toward environmentally friendly products ranked highest (M=4.52, SD=0.56) among influencing factors, followed by corporate social responsibility (M=4.49, SD=0.63), marketing promotion (M=4.48, SD=0.62), and distribution channels (M=4.48, SD=0.62). All measured factors scored above 4.0, indicating high importance. "Products meeting specific needs" received the highest specific item rating (M=4.66, SD=0.59), while "producers having environmental care policies" (M=4.52, SD=0.70) was most valued among CSR aspects.

Further analysis of specific item responses revealed that in terms of consumer values, "products meeting specific needs" received the highest rating (M=4.66, SD=0.59), followed by "product uniqueness and attractive design" (M=4.48, SD=0.69). Regarding corporate social responsibility, "producers having environmental care policies" (M=4.52, SD=0.70) and "prioritizing environmental concerns over maximum profit" (M=4.52, SD=0.73) were rated highest.

4.1.3 Experience with and Interest in Environmentally Friendly Products

A high proportion of respondents (94.6%) reported previous experience with environmentally friendly products, primarily plastic-reducing (32.5%), energy-saving (27.7%), and carbon footprint-labeled products (20.3%). Purchase frequency was moderate, with most reporting 1-2 purchases (38.8%) or 3-4 purchases (36.4%) in the previous six months. The primary motivation was environmental conservation (77.5%), followed by product quality (30.2%), with 82.9% reporting independent purchase decision-making.

4.1.4 Awareness and Interest in Biosurfactant Products from Pineapple Waste

Despite limited awareness (72.9% unfamiliar), 93.8% of respondents expressed interest in purchasing biosurfactant products from pineapple waste, primarily motivated by environmental conservation (77.5%). Main concerns among reluctant purchasers included uncertainty about product details (45.7%) and perceived high price (23.3%). Quality (47.3%), price (27.9%), and availability (15.5%) were identified as key motivating factors. Most respondents (88.4%) desired additional information about environmentally friendly consumption, preferring online channels (83.7%).

4.2 Value Chain Analysis within Circular Economy Framework

The value chain analysis, informed by qualitative interviews and observational data, reveals interconnected activities across the biosurfactant production system, framed within circular economy principles. The analysis identifies key challenges and opportunities at each stage.

4.2.1 Primary Activities

1. Inbound Logistics: Waste Collection and Processing

Thailand's pineapple production reached approximately 1,679,668 tons in 2023, predominantly consisting of the Pattavia variety used in the canning industry. Pineapple processing generates substantial waste, with peels, crowns, cores, and rejected fruits constituting approximately 70% of raw material by weight. This translates to approximately 940,614 tons of waste annually.

Key informants identified several challenges in waste management:

"During peak harvest seasons, waste management becomes a significant challenge. We often have no choice but to dispose of excess waste, which creates environmental issues." (Pineapple processor)

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"The seasonality of pineapple production creates logistical challenges for consistent waste collection. Peak harvests occur during April-June and November-January, while supply is limited in other months." (Agricultural official)

The qualitative analysis revealed informal waste collection systems where intermediaries purchase rejected pineapples at significantly discounted prices (approximately 2 baht/kg compared to 8-12 baht/kg for processing-grade fruit). These materials are primarily directed toward animal feed production, with limited high-value applications.

From a circular economy perspective, interview data suggested opportunities for establishing formalized waste collection networks:

"With proper coordination between processing factories and potential biosurfactant producers, a stable supply chain for pineapple waste could be established. This would require investment in storage and preprocessing facilities to manage seasonal fluctuations." (Community enterprise chairperson)

2. Operations: Biosurfactant Production

Laboratory-scale experiments demonstrated technical feasibility of biosurfactant production from pineapple waste. Using 10 kg of pineapple waste, approximately 30 liters of liquid biosurfactant could be produced, equivalent to 8.7 grams of concentrated surfactant. The production process involves preprocessing (size reduction, extraction), fermentation using selected microbial strains, and downstream processing (separation, purification).

Economic analysis of laboratory-scale production revealed substantial costs: raw materials (350 baht), chemicals (4,416.45 baht), labor (42,000 baht), and equipment rental (10,000 baht), totaling 56,766.45 baht. This translates to approximately 6,524.88 baht/gram, compared to market prices of concentrated biosurfactants at 1,562,200 baht/gram.

Industry stakeholders identified several challenges and opportunities for scaling:

"The current laboratory process is not economically viable at industrial scale. Key opportunities for cost reduction include optimizing fermentation conditions, improving downstream processing efficiency, and integrating production with existing facilities." (Surfactant production manager)

"Thailand's tropical climate provides advantages for microbial fermentation, potentially reducing energy costs compared to production in temperate regions. Additionally, the abundance of agricultural waste offers cost advantages for raw materials." (Production researcher)

3. Outbound Logistics: Distribution and Storage

Interview data indicated that existing distribution systems for conventional surfactants could be leveraged for biosurfactant products:

"The physical properties of biosurfactant products would be similar to conventional products, allowing use of existing storage facilities and distribution channels. This reduces the need for specialized infrastructure." (Marketing analyst)

Consumer survey results aligned with this assessment, highlighting preferences for convenient product access. Respondents prioritized accessibility through online ordering with home delivery (M=4.51, SD=0.70) and availability through multiple channels including retail stores, convenience stores, and department stores (M=4.58, SD=0.67).

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4. Marketing and Sales: Product Positioning and Consumer Engagement

Thailand's trade balance for surfactants showed a deficit of 118,175 kg during January-April 2022, indicating market opportunity for domestic production. Dishwashing products, which heavily utilize surfactants, have domestic sales of approximately 160,000 tons annually.

Marketing stakeholders identified strategic positioning opportunities for biosurfactant products:

"Biosurfactants from pineapple waste offer multiple marketing advantages: local sourcing, waste valorization, biodegradability, and potentially superior performance. These attributes align with growing consumer interest in sustainable products." (Marketing analyst)

Consumer survey results supported this assessment, with respondents valuing environmentally friendly products that deliver functionality (M=4.66, SD=0.59) while offering distinctiveness (M=4.48, SD=0.69). The high proportion of respondents (93.8%) expressing interest in biosurfactant products from pineapple waste indicates potential market acceptance, despite limited prior awareness (27.1%).

5. Service: Consumer Support and Education

Survey respondents highlighted the importance of after-sales service (M=4.49, SD=0.74), convenient payment options (M=4.55, SD=0.72), and expert staff guidance regarding environmentally friendly products (M=4.55, SD=0.71). Additionally, 88.4% desired additional information about environmentally friendly consumption, primarily through online channels (83.7%).

Industry stakeholders recognized education challenges:

"Consumers often have limited understanding of biosurfactants and their environmental benefits. Effective education strategies combining online content, product labeling, and retail staff training would be essential for market development." (Marketing analyst)

4.2.2 Support Activities

1. Firm Infrastructure: Organizational Structure and Management

Interviews with industry stakeholders revealed potential integration pathways:

"Established cleaning product manufacturers with existing surfactant usage represent the most promising adopters of biosurfactant technology. These firms already possess production infrastructure, market access, and consumer recognition." (Industry consultant)

"Small and medium enterprises focused specifically on eco-friendly products offer another adoption pathway, potentially as premium niche products before mainstream adoption." (Community enterprise chairperson)

Consumers expressed preference for companies demonstrating environmental responsibility policies (M=4.52, SD=0.70), suggesting potential alignment between consumer expectations and organizational values.

2. Human Resource Management: Skills and Capability Development

While detailed human resource requirements were beyond the scope of laboratory-scale testing, interviews identified key skill requirements:

"Biosurfactant production requires specialized knowledge in biotechnology, fermentation technology, and downstream processing. Universities in Thailand produce graduates with relevant backgrounds, but specialized training would be beneficial." (Production researcher)

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"For widespread adoption, training programs for production staff, quality control personnel, and sales representatives would be necessary to build capacity across the value chain." (Industry stakeholder)

3. Technology Development: Innovation and Process Optimization

Technological challenges and opportunities emerged as critical themes:

"Current production technology is immature compared to synthetic surfactant production. Key development priorities include increasing fermentation yields, developing cost-effective separation techniques, and ensuring consistent product quality." (Production researcher)

"Opportunities exist for developing integrated biorefineries that process pineapple waste into multiple value-added products, improving overall economics through diversification." (Industry stakeholder)

The high proportion of consumers unfamiliar with biosurfactant products (72.9%) underscores the innovative nature of this technology and the need for continued development and communication.

4. Procurement: Sourcing and Supplier Relationships

While detailed procurement systems remain undeveloped at the laboratory stage, stakeholder interviews highlighted key considerations:

"Establishing stable procurement systems for pineapple waste would require formal agreements with processing facilities, potentially including minimum price guarantees and quality specifications." (Agricultural official)

"Seasonal variations in waste availability would necessitate storage solutions and potentially supplementary feedstocks during low-supply periods." (Production researcher)

4.3 Economic Feasibility Analysis

Building on laboratory data and industry stakeholder insights, we conducted an economic analysis comparing different production scenarios (Table 2). This analysis extends the work of Czinkoczky and Nemeth (2020) by incorporating Thailand-specific parameters.

Table 2: Economic Comparison of Biosurfactant Production Scenarios

Parameter	Laboratory Scale	Pilot Scale	Industrial Scale
Production capacity (kg/year)	0.031	1,500	18,000
Capital investment (million baht)	0.06	35.5	525.6
Operating cost (baht/kg)	6,524,880	8,500	3,200
Selling price (baht/kg)	N/A	12,000	9,500
Payback period (years)	N/A	11.8	7.3
NPV at 10% discount rate (million baht)	Negative	-12.4	186.7

Note: Operating costs include raw materials, chemicals, labor, utilities, and maintenance. Capital investment encompasses equipment, construction, and installation costs. NPV calculations assume a 15-year project lifespan with straight-line depreciation.

The analysis indicates that while laboratory-scale production is economically infeasible, industrial-scale operations with optimized technology could achieve profitability, with a projected payback period of 7.3 years. This aligns with Czinkoczky and Nemeth's (2020) findings, adjusted for Thailand's context.

Sensitivity analysis examining ±25% variations in key parameters revealed that raw material costs, selling price, and production yield had the greatest impact on economic outcomes. Under optimistic scenarios (reduced raw material costs, increased yields), the payback period could decrease to 4.9 years, while pessimistic scenarios extended it to 11.2 years.

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Thailand's tropical climate provides competitive advantages for fermentation-based processes compared to temperate regions, potentially improving economic outcomes. As one stakeholder noted:

"Operating costs for fermentation in Thailand could be 15-20% lower than in European countries due to reduced heating requirements and lower labor costs. This improves the competitiveness of biosurfactant production." (Production researcher)

5. RESEARCH DISCUSSION AND IMPLICATIONS

This research provides novel insights into the potential for developing circular value chains for biosurfactant production from pineapple waste, integrating both production feasibility and consumer perspectives. Our findings extend current understanding in several key areas.

5.1 Circular Value Chain Integration

Our value chain analysis, framed within circular economy principles, reveals both challenges and opportunities for establishing closed-loop systems utilizing pineapple processing waste. The substantial volume of pineapple waste generated in Thailand (940,614 tons annually) represents a significant untapped resource that currently poses disposal challenges while offering value creation potential.

This finding aligns with previous research on agricultural waste valorization (Ubando et al., 2020) but provides specific insights regarding pineapple waste streams in Thailand. While previous studies have examined individual components of biosurfactant production (Vieira et al., 2021), our research uniquely integrates the entire value chain from waste generation through production to consumer acceptance.

The identified challenges, particularly regarding waste collection logistics and seasonal availability, echo findings from other agricultural waste valorization studies (Galanakis, 2021). However, our research extends these insights by proposing specific coordination mechanisms between pineapple processors and potential biosurfactant producers, including formalized waste collection networks and preprocessing facilities to manage seasonal fluctuations.

5.2 Economic Viability and Scaling Challenges

Our economic analysis demonstrates that while laboratory-scale production remains financially infeasible (6,524.88 baht/gram), industrial-scale operations with optimized technology could potentially achieve economic viability. The projected payback period of 7.3 years at industrial scale, while relatively long, falls within acceptable ranges for biorefinery investments (Chandran et al., 2020).

These findings partially contradict pessimistic assessments of biosurfactant economics (Winterscheid et al., 2017) but align with more recent studies suggesting improving economic prospects through process optimization and increasing scales. Importantly, our analysis identifies specific advantages for Thailand-based production, including climatic conditions favorable for microbial fermentation and locally available agricultural waste, potentially reducing production costs by 15-20% compared to temperate regions.

The economic analysis highlights the critical importance of technological development in downstream processing, which represents 60-70% of production costs.

The potential for developing integrated biorefineries processing pineapple waste into multiple value-added products represents a promising strategy for improving overall economics.

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5.3 Consumer Acceptance and Market Development

Our finding that 93.8% of consumers expressed interest in biosurfactant products from pineapple waste, despite limited prior awareness (27.1%), suggests promising market potential. The primary motivation for potential purchase environmental conservation (77.5%) aligns with previous research on green consumer behavior (Sreen et al., 2018). However, the substantial gap between awareness and interest highlights the need for educational marketing strategies.

The hierarchy of factors influencing environmentally friendly product consumption provides valuable insights for market development. Consumer values ranked highest (M=4.52), followed closely by corporate social responsibility (M=4.49), suggesting that marketing strategies emphasizing both personal values and corporate environmental commitments could be particularly effective.

Our findings regarding product attributes align with Lin et al. (2018), who found that perceived effectiveness and environmental benefits significantly influenced intentions to purchase green cleaning products. However, our research adds nuance by identifying specific product attributes valued by consumers, including meeting functional needs (M=4.66) while offering distinctiveness (M=4.48).

The concerns expressed by consumers reluctant to purchase biosurfactant products uncertainty about product details (45.7%) and perceived high price (23.3%) echo findings from previous research on barriers to green consumption (Carrington et al., 2014). Addressing these concerns through transparent communication and competitive pricing strategies could help narrow the attitude-behavior gap identified in green consumer literature.

5.4 Policy Implications and Sustainability Impact

The development of biosurfactant production from pineapple waste aligns with multiple sustainability objectives, including waste reduction, fossil resource substitution, and rural economic development. Our findings have implications for policy development across agricultural, industrial, and environmental domains.

From an agricultural policy perspective, establishing formal value chains for pineapple waste could provide additional income streams for farmers and processors, addressing issues of agricultural waste management while creating economic opportunities. This aligns with Thailand's Bio-Circular-Green (BCG) Economy model, which prioritizes adding value to agricultural resources through biotechnology applications.

From an industrial policy standpoint, supporting the development of biosurfactant production through targeted incentives, research funding, and regulatory frameworks could foster innovation while reducing dependency on imported chemicals. The potential to replace 20% of petroleum-based surfactants used in dishwashing detergents (approximately 4,850 tons) represents a significant contribution to industrial sustainability.

Environmentally, the projected impact includes reduced waste disposal (940,614 tons of pineapple waste annually), decreased fossil resource consumption, and minimized aquatic pollution from persistent synthetic surfactants. These benefits directly contribute to Thailand's commitments under the Paris Agreement and the Sustainable Development Goals.

From the article, **Fig 1:** Value Chain of Biosurfactant Production from Pineapple Waste and Linkage with Sustainable Development Goals (SDGs) illustrates the connection between the value chain of biosurfactant production from pineapple waste and sustainable development goals. This model shows the process from collecting pineapple waste, fermentation, extraction, to finished product manufacturing, which supports SDG 9 (Industry, Innovation, and Infrastructure) through development

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of sustainable production technologies, SDG 12 (Responsible Consumption and Production) through recycling agricultural waste materials, and SDG 13 (Climate Action) through reducing greenhouse gas emissions from both organic waste disposal and replacement of petroleum-based surfactants. This model presents a circular economy approach that transforms waste into valuable resources, adds value to agricultural waste materials, and supports sustainable development in Thailand.

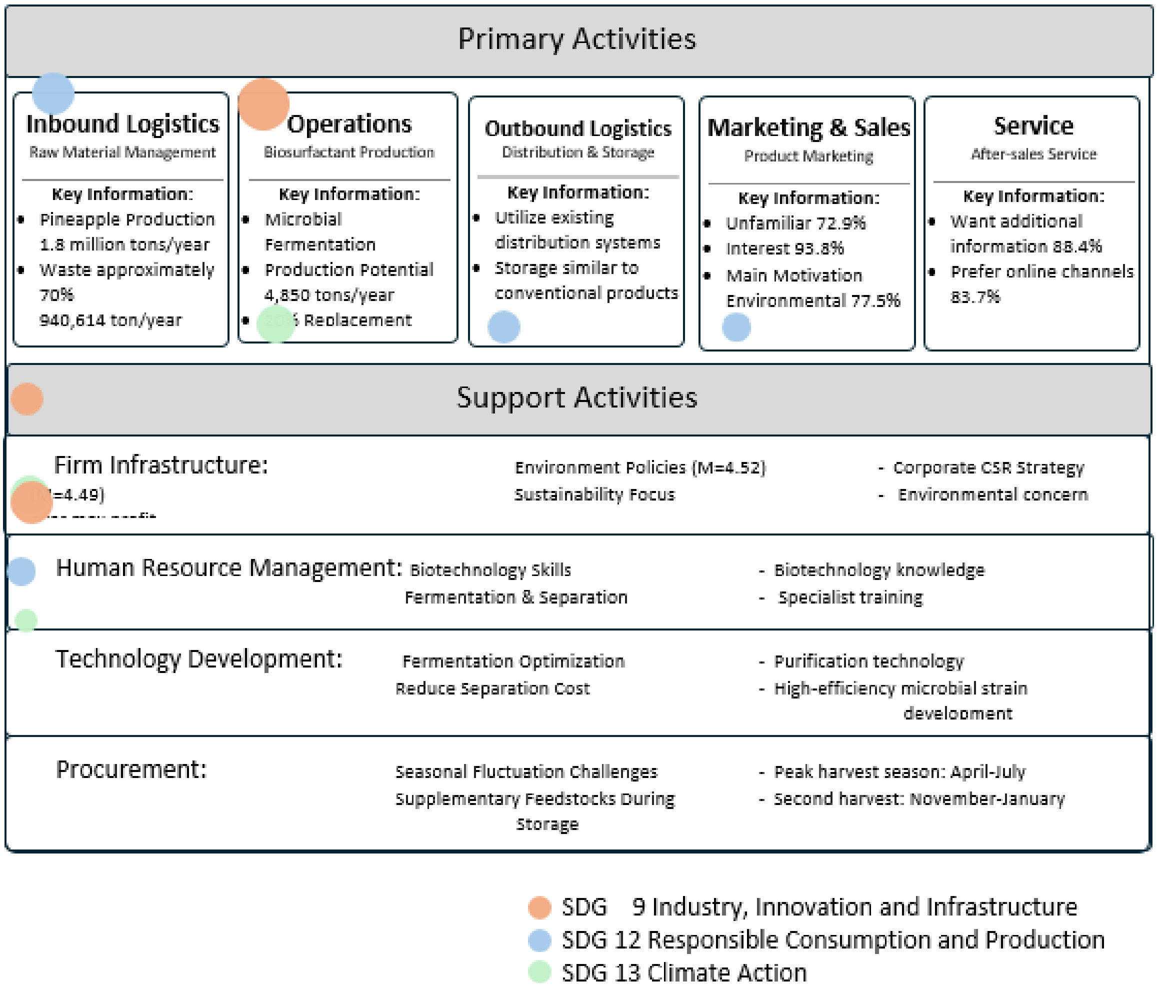

Fig 1: Value Chain of Biosurfactant Production from Pineapple Waste and Linkage with Sustainable Development Goals (SDGs)

5.5 Contributions to Sustainable Development Goals

This research directly contributes to multiple Sustainable Development Goals (SDGs) through the valorization of pineapple waste for biosurfactant production. The key contributions are summarized below:

SDG 9: Industry, Innovation, and Infrastructure

Our research supports industrial innovation (SDG 9.4) by developing production pathways that transform agricultural waste into high-value biosurfactants. This approach enables Thailand to shift from imported petroleum-based surfactants toward locally produced, renewable alternatives. The economic analysis highlights specific innovation requirements in fermentation systems and separation technologies that would enhance technological capabilities in developing countries (SDG 9.5). By

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providing a blueprint for biosurfactant production from local resources, the research supports domestic technology development in Thailand's emerging bioeconomy (SDG 9.B).

SDG 12: Responsible Consumption and Production

The circular economy approach demonstrated in this research directly addresses SDG 12.5 by reducing waste generation through recycling and reuse. Converting 940,614 tons of annual pineapple processing waste into valuable products exemplifies sustainable resource management principles. Our consumer analysis, showing 93.8% interest in biosurfactant products despite limited awareness (27.1%), provides insights for promoting sustainable consumption patterns (SDG 12.8). The value chain analysis offers practical guidance for implementing sustainable production systems tailored to Thailand's context, supporting scientific and technological capacity building in developing countries (SDG 12.A).

SDG 13: Climate Action

Biosurfactant production from pineapple waste contributes to climate change mitigation by: (1) reducing methane emissions from waste decomposition; (2) replacing petroleum-derived surfactants, potentially reducing greenhouse gas emissions by 50-80% based on comparable bio-based products; and (3) enhancing climate resilience in agricultural communities through diversified income streams from waste valorization (SDG 13.1). Though our research did not include a comprehensive carbon footprint analysis, the circular approach inherently supports climate action by minimizing resource extraction and waste generation.

Integrated Impact and Policy Coherence

The interconnections between these SDG contributions underscore the importance of policy coherence for sustainable development (SDG 17.14). Our stakeholder interviews revealed that fragmented policies currently hinder integrated value chains for agricultural waste valorization. The recommendations provided aim to address these challenges by promoting coordinated approaches that simultaneously advance multiple sustainability objectives. By demonstrating how bioeconomy development can deliver co-benefits across economic, environmental, and social dimensions, our research supports evidence-based policymaking that can accelerate progress toward the SDGs while addressing Thailand's specific context and priorities.

6. CONCLUSION AND RECOMMENDATIONS

This research presents a comprehensive analysis of the circular value chain for biosurfactant production from pineapple waste, integrating technical, economic, and consumer perspectives. Our findings contribute to both theoretical understanding and practical implementation of circular economy principles in the context of agricultural waste valorization.

Theoretically, we extend value chain analysis by incorporating circular economy principles and consumer acceptance factors, providing a more holistic framework for assessing bio-based product systems. Our integration of production feasibility and consumer perspectives addresses an important gap in existing literature, which has typically examined these aspects in isolation.

Practically, our research demonstrates that Thailand's substantial pineapple waste stream (940,614 tons annually) could potentially yield approximately 4,850 tons of biosurfactants, replacing 20% of petroleum-based surfactants used in dishwashing detergents. While laboratory-scale production remains economically challenging, industrial scaling with optimized technology could achieve financial viability with projected payback periods of 7-8 years.

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From a consumer perspective, our findings reveal substantial interest in biosurfactant products from pineapple waste (93.8% of respondents), despite limited prior awareness (27.1%). Consumer values and corporate social responsibility emerged as the most influential factors affecting purchase intentions, followed by marketing, distribution, and product attributes. These insights provide guidance for developing effective market entry strategies.

Several limitations should be acknowledged. First, our laboratory-scale production data may not fully reflect the efficiencies achievable at industrial scale. Second, our consumer survey employed accidental sampling, limiting generalizability to the broader population. Third, economic projections involve inherent uncertainties, particularly regarding future market conditions and technological developments.

Despite these limitations, our research provides a foundation for developing circular value chains for biosurfactant production from pineapple waste, offering pathways toward more sustainable surfactant production and consumption while contributing to multiple sustainable development goals.

Methodological Limitations

This study has several methodological limitations that should be considered when interpreting the findings.

First, our quantitative data collection employed accidental sampling, which limits the generalizability of consumer preferences to the broader Thai population. The sample was predominantly composed of young, educated respondents (69.8% aged 19-27 years; 97.6% with bachelor's degree or higher), with a high proportion of students (65.9%), which may not accurately represent the diversity of potential consumers for biosurfactant products. Future research should employ probability sampling techniques to ensure better population representation.

Second, our economic analysis relied on extrapolation from laboratory-scale data to industrial-scale operations. While we incorporated industry expert insights and comparative data from similar bioproduction systems, the accuracy of cost projections is inherently limited. Actual production costs may vary based on technological advancements, economies of scale, and market fluctuations. A more robust approach would involve pilot-scale validation before full industrial projections.

Third, the qualitative component of our research included interviews with nine key stakeholders across the value chain. While this provided valuable insights, it may not have captured the full spectrum of perspectives, particularly from multinational corporations that dominate the current surfactant market. Additionally, power dynamics between researchers and participants may have influenced responses, particularly when discussing environmental commitments and sustainability practices. Our methodological triangulation approach aimed to mitigate these limitations, but they should be acknowledged as potential constraints on data interpretation.

Fourth, our analysis did not comprehensively quantify environmental impacts through formal life cycle assessment (LCA) methodology. While the circular economy framework provides a conceptual structure for understanding environmental benefits, rigorous LCA would provide more precise quantification of impacts across production stages. This represents an important direction for future research.

Finally, the cross-sectional nature of our data collection provides a snapshot of current perspectives but does not capture the dynamic evolution of market conditions, consumer preferences, and technological capabilities. Longitudinal research would provide valuable insights into how these factors evolve over time and influence the development of biosurfactant value chains.

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Policy Recommendations

1. **Develop Waste Collection Infrastructure:** Establish coordinated collection systems for pineapple processing waste through public-private partnerships involving agricultural ministries, local governments, and industry associations, with financial incentives for participation and quality standards.
2. **Implement Targeted R&D Support:** Direct research funding toward cost-effective downstream processing methods through collaborative research platforms involving universities and industry partners, with specific performance targets for yield improvement and cost reduction.
3. **Create Tiered Tax Incentives:** Implement graduated tax incentives for biosurfactant production based on sustainability metrics, including corporate income tax reductions and import duty exemptions for essential equipment.
4. **Develop Green Public Procurement:** Establish government procurement preferences for cleaning products containing locally produced biosurfactants to create initial market demand.

Industry Recommendations

1. **Establish Integrated Biorefineries:** Design facilities capable of processing pineapple waste into multiple value-added products (biosurfactants, bioethanol, dietary fiber) to improve overall economics, located near major pineapple processing centers.
2. **Implement Strategic Phasing:** Adopt a phased implementation approach, beginning with pilot-scale production to validate technical and economic parameters before full industrial scaling.
3. **Develop Transparent Marketing:** Emphasize both environmental benefits and performance attributes, with transparent information about sourcing, production processes, and environmental impact metrics through online channels.
4. **Form Strategic Alliances:** Establish partnerships between agricultural processors, biotechnology developers, and consumer product manufacturers to create integrated value chains with equitable value sharing.

7. FUTURE RESEARCH

Future research should focus on optimizing fermentation conditions for pineapple waste substrates, including strain selection and nutrient supplementation to maximize yields and minimize costs. Developing cost-effective downstream processing represents another critical area, particularly investigating alternative separation technologies with lower energy requirements, such as membrane filtration and foam fractionation adapted specifically for biosurfactant recovery. Additionally, a detailed life cycle assessment comparing biosurfactants from pineapple waste with conventional surfactants should be conducted, incorporating Thailand-specific parameters for energy mix and waste management. Consumer research should be extended to include product testing with prototype biosurfactant formulations, assessing perceived effectiveness and willingness to pay across diverse demographic segments.

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