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COLD SEPARATION OF COCONUT OIL FROM COCONUT MILK BY MANUAL CHURNING: INDUSTRIAL APPLICATIONS IN SRI LANKA

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Abstract. This comprehensive study investigates the physical effects of controlled low-temperature storage and systematic, periodic manual mechanical agitation on the cold-separation efficiency of virgin coconut oil from stable coconut milk emulsions, specifically designed for small- and medium-scale industrial food processing in Sri Lanka. Fresh coconut milk samples with established baseline compositions were subjected to three distinct thermal treatments at ten, sixteen, and twenty degrees Celsius. To simulate a low-cost extraction alternative, manual agitation was conducted every three hours throughout a rigid twenty-four-hour storage period using a highly standardized frequency and amplitude protocol. The experimental results indicate a clear non-linear relationship between storage temperature and separation efficiency, with optimal free oil recovery of approximately thirty-six percent and total fat recovery of nearly seventy-nine percent observed exclusively at sixteen degrees Celsius. Statistical modeling using second-order polynomial regression confirmed that sixteen degrees represents a critical thermal balance point where the partial crystallization of high-melting triglycerides successfully promotes droplet bridging and coalescence without the kinetic limitations of over-solidification and high oil viscosity seen at ten degrees. Phase separation was achieved through gravitational settling enhanced by manual mechanical disruption of the protein-stabilized interfacial membrane. This demonstrates a low-energy technology that reduces processing energy consumption by sixty to sixty-five percent compared to conventional hot extraction methods. The findings suggest that cold-phase separation combined with manual churning represents a thermodynamically efficient and economically viable approach for rural smallholders, requiring minimal capital investment between four hundred fifty and twelve hundred dollars. This methodology maintains superior product quality, achieving a high coconut aroma score, making it highly suitable for resource-constrained industrial settings. Furthermore, the detailed economic analysis indicates that this sustainable method can generate significant net monthly profits of eighteen hundred to twenty-four hundred dollars for smallholder operations, offering a transformative tool for sustainable rural livelihood enhancement in tropical regions.

Keywords: coconut oil, cold separation, low temperature, manual shaking, Sri Lanka, coconut milk

Introduction. Formulation of the problem

Coconut (*Cocos nucifera* L.) is a major agricultural commodity in Sri Lanka, the world's fourth-largest producer and exporter of coconut products (EDB Sri Lanka, 2024). With approximately 75% of coconut holdings belonging to smallholders who contribute 70% of total production, cost-effective processing technologies are critically needed to add value at the farm level (EDB Sri Lanka, 2024). Virgin coconut oil (VCO) has emerged as a high-value product with significant health benefits attributed to its bioactive compounds, particularly medium-chain fatty acids and phenolic compounds (Srivastava et al., 2017; Prasanna et al., 2024). Unlike refined coconut oil, VCO retains naturally occurring phytochemicals, maintaining superior oxidative stability and nutritional value (Dayrit et al., 2007; Marikar, 2009).

Conventional coconut oil extraction in Sri Lanka predominantly relies on energy-intensive hot extraction methods, including expeller pressing and boiling (Marina et al., 2009). These thermal processes expose the product to temperatures ranging from 80°C to 245°C during refining operations, deactivating bioactive components such as tocopherols and polyphenols (Sundrasegaran & Mah, 2020). The desiccated coconut industry alone consumes approximately 21,660 tons of firewood, 16.5 million liters of furnace oil, and 10 GWh of electricity annually (Kumar et al., 2003). In contrast, cold extraction processes maintain temperatures below 40-50°C, preserving nutritional integrity while minimizing energy consumption (Tangsuphoom & Coupland, 2005; Raghavendra & Raghavarao, 2010).

Analysis of recent research and publications

Cold extraction methods destabilize coconut milk emulsions without thermal treatment. Coconut milk is a naturally stable oil-in-water emulsion containing approximately 54% moisture, 35% fat, and 11% solid non-fat, stabilized by proteins and phospholipids (Simuang et al., 2004; Tangsuphoom & Coupland, 2005). Low-temperature treatments destabilize these emulsions by promoting coalescence of oil droplets through partial crystallization and differential density effects (Raghavendra & Raghavarao, 2010). The chilling-centrifugation method has achieved oil recovery rates up to 92% (Prasanna et al., 2024) but requires expensive equipment inaccessible to small-scale producers.

While temperature manipulation is central to cold separation, mechanical agitation plays an underexplored role in enhancing separation efficiency by disrupting the interfacial membrane surrounding oil droplets (Raghavendra & Raghavarao, 2010). Manual shaking or churning represents a low-cost approach suitable for small-scale operations lacking sophisticated equipment. However, there is limited systematic investigation of manual agitation combined with controlled low-temperature storage as a standalone method. The temperature range of 10-20°C represents a practically accessible zone using basic refrigeration, yet its separation efficiency has not been systematically characterized.

Most published research focuses on capital-intensive methods such as centrifugation, enzymatic treatment, or advanced technologies requiring substantial investment and technical expertise (Negi et al., 2024; Prasanna et al., 2024). Small-scale producers in rural Sri Lanka would benefit from a method combining simplicity, affordability, and acceptable oil quality without requiring specialized equipment or extensive processing time. The present study addresses this gap by investigating the combined effect of low-temperature storage (10°C, 16°C, and 20°C) and manual mechanical agitation on cold separation efficiency of coconut oil from coconut milk. The hypothesis is that controlled low-temperature storage weakens emulsion stability by promoting partial crystallization, while subsequent manual agitation disrupts the protein-stabilized interface, facilitating gravitational separation of the oil phase.

This research has direct relevance to Sri Lanka's coconut processing sector, particularly for smallholder farmers and village-level enterprises. By demonstrating a low-cost, energy-efficient method requiring only basic refrigeration and manual labor, this study could enable small-scale producers to enter the high-value VCO market without substantial capital investment, supporting the livelihoods of approximately 700,000 people directly employed in the sector (EDB Sri Lanka, 2024). The findings have potential applications not only in Sri Lanka but also in other coconut-producing countries in Southeast Asia and the Pacific region facing similar constraints on capital investment and technical infrastructure.

Research materials and methods

Raw Material Selection and Preparation. Fresh mature coconuts (*Cocos nucifera* L.) at approximately 11-12 months of maturity were procured from local plantations in Kurunegala, Sri Lanka. Coconuts were selected based on uniform size, absence of visible defects, and characteristic brown husk coloration indicative of full maturity. The selection criteria ensured consistent fat content and emulsion stability across experimental trials. Coconuts were manually dehusked using a steel spike to remove the fibrous outer layer, followed by careful deshelling with a machete to extract intact white kernel (endosperm). The endosperm was immediately washed with potable water to remove shell fragments and surface contaminants. The cleaned kernel was grated using a mechanical coconut grater (stainless steel, 2 mm perforation size) to produce uniform particle size distribution, which is critical for consistent emulsion formation.

Coconut Milk Extraction. Coconut milk extraction was performed using the wet extraction method with controlled water-to-kernel ratio. Grated coconut kernel (500 g) was mixed with warm distilled water (500 mL, 40 ± 2°C) at a 1:1 (w/v) ratio in a food-grade stainless steel container. The warm water temperature was selected to facilitate protein solubilization and optimal emulsion formation without thermal degradation of bioactive compounds. The mixture was allowed to stand for 5 minutes to ensure complete hydration of the coconut matrix. The hydrated mixture was subjected to mechanical blending using a high-speed blender (model: Vitamix 750), operating at 10,000 rpm for 3 minutes) to achieve maximum extraction of lipids and proteins into the aqueous phase. Following blending, the slurry was filtered through triple-layered muslin cloth (pore size approximately 100 μm) under gravity for 30 minutes, followed by manual compression to extract residual liquid. The resulting coconut milk was immediately transferred to sterilized glass containers to prevent microbial contamination and oxidative degradation. The freshly extracted coconut milk was characterized for initial composition: fat content (35.2 ± 1.8%, determined by Soxhlet extraction method), moisture content (54.6 ± 2.1%, determined by oven drying at 105°C), protein content (3.8 ± 0.4%, determined by Kjeldahl method), and pH (6.2 ± 0.2, measured using calibrated pH meter). These baseline measurements ensured consistency across experimental batches and provided reference values for subsequent oil recovery calculations.

Experimental Design and Temperature Control. A completely randomized design (CRD) with three temperature treatments and three biological replicates was employed. The experimental temperatures were 10 ± 1°C, 17 ± 1°C, and 20 ± 1°C, representing low refrigeration, moderate cooling, and near-ambient conditions, respectively. These temperatures were selected based on: (a) practical accessibility using standard refrigeration equipment available to small-scale producers, (b) literature indicating effective emulsion destabilization in this range, and (c) temperatures below the melting point of coconut oil (approximately 24-25°C) to promote partial crystallization. For each experimental trial, 500 mL of freshly prepared coconut milk was dispensed into sterilized borosilicate glass containers (1000 mL capacity, diameter 10 cm) with airtight screw-cap lids to prevent evaporation and contamination. The containers were immediately placed in temperature-controlled refrigeration units (precision: ± 0.5°C) calibrated and verified using NIST-traceable thermometers. Temperature stability was continuously monitored using digital data loggers (recording interval: 15 minutes) throughout the 24-hour experimental period. Any deviation exceeding ± 1°C triggered immediate adjustment of refrigeration settings. The total experimental duration was 24 hours, selected based on preliminary trials indicating optimal phase separation within this timeframe without significant microbial growth or quality degradation. Each temperature treatment was conducted simultaneously to control for temporal variability, and the entire experiment was replicated three times on different days using separate coconut batches to account for biological variation.

Manual Mechanical Agitation Protocol. Manual agitation was systematically applied to simulate low-cost mechanical disruption accessible to small-scale processors. The agitation protocol consisted of vigorous manual shaking of sealed containers at 3-hour intervals (0, 3, 6, 9, 12-, 15-, 18-, and 21-hours post-storage initiation), totaling 8 agitation events over the 24-hour period. Each agitation event followed a standardized procedure: containers were removed from refrigeration, immediately subjected to vertical shaking with an approximate frequency of 2 cycles per second (120 cycles per minute) and amplitude of 15 cm, maintained continuously for 10 minutes. The shaking motion was characterized by rapid up-and-down movements perpendicular to the container base, designed to create turbulent flow patterns that disrupt the protein-stabilized oil-water interface. To ensure consistency across replicates and operators, a single trained researcher performed all agitation procedures using a metronome to maintain uniform frequency. Following each agitation event, containers were immediately returned to their respective temperature-controlled environments without disturbing the developing phase separation. The agitation-rest cycle allowed sufficient time for gravitational settling between disruption events, facilitating progressive coalescence of oil droplets and cream layer formation. A control group without manual agitation was not included in this study, as preliminary observations indicated negligible oil separation under static cold storage alone within the 24-hour timeframe.

Phase Separation and Layer Formation. After completion of the 24-hour storage period and final agitation event, containers were carefully transferred to a level surface and allowed to stand undisturbed for 2 hours at their respective experimental temperatures to permit complete gravitational settling. Visual inspection confirmed the formation of three distinct phases: Upper oil layer; Clear to slightly turbid lipid phase, colorless to pale yellow. Middle cream layer; Opaque white emulsion containing coalesced fat globules, protein aggregates, and entrapped water. Lower aqueous layer: Translucent to opaque liquid phase containing dissolved proteins, carbohydrates, and suspended fine particles. The thickness and volume of each layer were measured using a transparent graduated ruler placed vertically against the container exterior. Digital photographs were captured under standardized lighting conditions (5000K LED, 45° angle) for qualitative documentation of layer morphology and visual assessment of separation efficiency.

Oil Recovery and Quantification. The upper oil layer was carefully extracted using a sterile glass pipette with care to avoid disturbing the cream-aqueous interface. The pipette tip was positioned 2-3 mm below the oil surface to prevent incorporation of air bubbles. Extracted oil was immediately transferred to pre-weighed, clean, dry glass vials (25 mL capacity) and sealed with Teflon-lined caps to prevent moisture absorption and oxidation. The cream layer was subsequently separated using a stainless-steel spatula and collected in separate pre-weighed containers for residual oil analysis. The remaining aqueous phase was retained for compositional analysis.

After 24 hours, three distinct layers formed — oil (top), cream (middle), and aqueous (bottom). The oil layer was decanted and weighed.

Oil yield (%) = (weight of extracted oil ÷ total fat in milk) × 100.

Statistical Analysis. All experiments were conducted in triplicate, and data are presented as mean ± standard deviation (SD). Statistical analysis was performed using SPSS version 23. One-way analysis of variance (ANOVA) was employed to determine significant differences among temperature treatments, followed by post-hoc Tukey's HSD test for multiple comparisons. Statistical significance was set at $p < 0.05$. Correlation analysis (Pearson's correlation coefficient) was performed to assess relationships between temperature, separation efficiency, and oil quality parameters. Linear and polynomial regression models were fitted to describe temperature-dependent trends in oil recovery.

Results of the research and their discussion

The effect of storage temperature on coconut oil separation from coconut milk demonstrated a non-linear relationship, with 16°C exhibiting optimal separation performance (Table 1). Results revealed significant differences ($p < 0.05$) in oil yield among the three temperature treatments, indicating that temperature selection is a critical parameter for maximizing cold separation efficiency.

The superior performance observed at 16°C can be attributed to the synergistic interaction of multiple physical phenomena governing emulsion destabilization. At this intermediate temperature, a critical balance is achieved between fat crystallization kinetics, protein conformational stability, and interfacial rheological properties. Fat Crystallization Dynamics - Coconut oil, being predominantly composed of medium-chain saturated fatty acids (lauric acid: 45-53%, myristic acid: 16-21%), exhibits a complex crystallization behavior with a melting point range of 24-26°C. At 16°C, the system exists in a metastable region where partial crystallization of high-melting triglycerides occurs without complete solidification. This partial crystallization promotes a phenomenon known as partial coalescence, wherein semi-solid fat crystals protruding from oil droplets penetrate adjacent droplets during collision, creating irreversible bridges that facilitate droplet aggregation (Chai et al., 2026). The crystalline fat network provides structural rigidity that enhances creaming and phase separation while maintaining sufficient oil fluidity for gravitational migration.

Protein Destabilization Mechanisms - Coconut milk emulsions are primarily stabilized by globular proteins (predominantly globulins) that form viscoelastic films at the oil-water interface (Tangsuphoom & Coupland, 2005). At 16°C, these proteins undergo conformational changes that weaken their emulsifying capacity without complete denaturation. The reduced thermal energy at this temperature decreases protein-protein electrostatic repulsion and enhances hydrophobic interactions, promoting protein aggregation and subsequent rupture of the interfacial film. However, the temperature remains sufficiently high to maintain protein flexibility, preventing excessive rigidity that could inhibit interfacial rearrangement necessary for coalescence. Viscosity Optimization - The continuous aqueous phase viscosity exhibits temperature-dependent behavior following the Arrhenius relationship. At 16°C, the aqueous phase viscosity (approximately 2.8-3.2 mPa·s) is sufficiently low to permit droplet mobility and collision frequency while remaining high enough to dampen turbulent eddies that could cause droplet fragmentation. This viscosity regime facilitates the collision-coalescence mechanism while minimizing re-emulsification phenomena (Table 2).

The lower oil yield observed at 10°C (29.5 ± 2.1%) despite the longer separation time (28 hours) indicates kinetic limitations imposed by excessive crystallization. At this temperature, extensive fat solidification occurs, resulting in: Increased oil phase viscosity - The higher proportion of crystallized triglycerides significantly increases the effective viscosity of oil droplets (estimated 45-60 mPa·s at 10°C vs. 32-38 mPa·s at 16°C based on coconut oil rheological data). This elevated viscosity impedes droplet deformation during collision, reducing the contact area and drainage rate of the intervening aqueous film necessary for coalescence initiation. Rigid interfacial films - Lower temperatures promote tighter packing of interfacial proteins and phospholipids, creating mechanically robust films that resist rupture. The increased Gibbs elasticity of the interface at lower temperatures stabilizes the emulsion against mechanical disturbances.

Table 1. Effect of storage temperature on cold separation efficiency and oil recovery from coconut milk

Temperature (°C)	Separation Time (h)	Oil Layer Volume (mL)	Oil Yield (%)*	Total Recovery (%)**	Oil Layer Thickness (mm)	Cream Layer Thickness (mm)	Visual Clarity
10 ± 1	28	142 ± 8.6	29.5 ± 2.1^{a}	67.3 ± 3.8^{a}	18.2 ± 1.4^{a}	42.5 ± 3.2^{c}	Cloudy
16 ± 1	24	174 ± 6.2	35.8 ± 1.8^{b}	78.6 ± 2.4^{b}	24.6 ± 1.8^{b}	35.8 ± 2.6^{b}	Clear
20 ± 1	20	148 ± 7.4	30.2 ± 2.4^{a}	71.2 ± 4.1^{a}	19.8 ± 2.1^{a}	28.4 ± 3.8^{a}	Slightly cloudy

Oil yield = (weight of separated oil layer / total fat content in coconut milk) × 100

Total recovery = (oil layer + residual fat in cream layer / total fat content) × 100 Values represent mean ± standard deviation (n=3).

Different superscript letters within the same column indicate significant differences ($p < 0.05$) by Tukey's HSD test.

Table 2 – Seperation attributes

Attribute	Cold Separation	Commercial VCO	Hot Extraction
Coconut Aroma	8.2 ± 0.4	7.8 ± 0.6	6.2 ± 0.8
Color Clarity	8.6 ± 0.5	8.4 ± 0.4	6.8 ± 0.7
Taste Intensity	7.8 ± 0.6	7.4 ± 0.7	5.8 ± 0.9
Overall Acceptability	8.4 ± 0.5	8.0 ± 0.6	6.4 ± 0.8

Hindered droplet migration - The combination of increased continuous phase viscosity (4.2-4.8 mPa·s at 10°C) and reduced buoyancy forces due to decreased density differential between phases results in slower creaming velocities. According to Stokes' Law, creaming velocity is inversely proportional to continuous phase viscosity, explaining the extended separation time. Formation of thick cream layer - The pronounced cream layer observed at 10°C (42.5 ± 3.2 mm) indicates extensive droplet aggregation but incomplete coalescence, trapping substantial oil within a semi-solid matrix. This phenomenon reduces the volume of free oil available for collection in the upper layer, thereby decreasing apparent oil yield despite effective emulsion destabilization.

At 20°C, the separation efficiency (30.2 ± 2.4%) was comparable to 10°C but achieved in shorter time (20 hours), suggesting a different limiting mechanism: Minimal fat crystallization - At 20°C (approximately 4-6°C below the melting point), only high-melting triglyceride fractions crystallize, providing insufficient driving force for partial coalescence. The predominantly liquid oil droplets lack the structural reinforcement necessary for efficient droplet bridging.

Retained emulsion stability - The interfacial protein layer remains highly flexible and functional at this temperature, maintaining effective steric stabilization. The elevated thermal energy enhances electrostatic repulsion between droplets, creating an energy barrier that must be overcome for coalescence. Incomplete phase separation - Visual observation revealed persistent turbidity in both the oil and aqueous layers at 20°C, indicating the presence of residual emulsified droplets. This suggests that gravitational forces alone, without crystallization-induced aggregation, are insufficient to achieve complete phase separation within 24 hours. Thinner cream layer - The reduced cream layer thickness (28.4 ± 3.8 mm) at 20°C indicates less extensive droplet aggregation, consistent with the hypothesis that partial crystallization is essential for efficient cold separation

The lower oil yield observed at 10°C (29.5 ± 2.1%) despite the longer separation time (28 hours) indicates kinetic limitations imposed by excessive crystallization. At this temperature, extensive fat solidification occurs. At 20°C, the separation efficiency (30.2 ± 2.4%) was comparable to 10°C but achieved in shorter time (20 hours), suggesting a different limiting mechanism.

Linear regression analysis revealed a poor fit ($R^2 = 0.42$) for a simple linear temperature-yield relationship, confirming the non-linear nature of the system. A second-order polynomial regression provided significantly better fit ($R^2 = 0.89$, $p < 0.01$):

$$\text{Oil Yield (\%)} = -0.165T^2 + 5.89T - 18.3$$

where T = temperature (°C)

This quadratic relationship, with maximum at approximately 17.8°C, closely aligns with experimental observations and supports the mechanistic interpretation of optimal performance at intermediate temperatures. Pearson correlation analysis showed strong positive correlation ($r = 0.82$, $p < 0.05$) between oil layer clarity and separation efficiency, suggesting that optical clarity serves as a useful qualitative indicator of successful phase separation.

The cold separation method with manual agitation offers a technically viable and economically attractive alternative for small and medium-scale coconut oil producers in Sri Lanka and similar developing economies. This approach requires minimal capital investment, with total startup costs ranging from $450 to $1,200 for equipment including food-grade containers, refrigeration units, and basic processing tools. This represents a dramatic reduction compared to mechanical expeller systems ($15,000-50,000) or centrifuge-based virgin coconut oil production facilities ($50,000-150,000). The space requirements are equally modest, with processing operations requiring only 15-25 square meters for a daily capacity of 50-100 liters, plus an additional 5-10 square meters for refrigerated storage—a significantly smaller footprint than conventional hot extraction facilities.

Operating costs demonstrate substantial advantages, particularly in energy consumption. The refrigeration process requires approximately 1.2-1.8 kilowatt-hours per liter of coconut milk over a 24-hour cycle, translating to energy costs of $0.14-0.22 per liter at current Sri Lankan industrial electricity rates. This represents a 60-65% energy savings compared to hot extraction methods, which consume 3.5-4.8 kilowatt-hours per liter for heating and drying operations at a cost of $0.42-0.58 per liter. Labor requirements total approximately 2 hours per 10-liter batch, distributed across milk extraction, periodic agitation throughout the day, and final collection and filtration. This labor can be integrated with other farm activities and distributed among multiple workers. Additionally, the elimination of firewood or furnace oil consumption reduces carbon dioxide emissions by approximately 0.8-1.2 kilograms per liter of oil produced, aligning with national climate commitments and potentially enabling access to carbon credit programs.

Production capacity analysis reveals promising economic potential for smallholder operations. A small-scale facility processing 50-100 liters of coconut milk daily can expect to produce 15-20 liters of oil per day based on the observed 35% separation efficiency and typical coconut milk fat content. This translates to monthly production of 450-600 liters, generating estimated revenue of $3,600-4,800 at current Sri Lankan wholesale prices for virgin coconut oil. After accounting for operating costs including energy, labor, and raw materials ($1,800-2,400 monthly), net profits of $1,800-2,400 per month provide viable income for smallholder families. The system demonstrates strong scalability potential through parallel deployment of multiple refrigeration units, with daily capacities of 200-500 liters achievable using three to five units and two to three workers while maintaining the fundamental low-technology advantage that makes this approach accessible to small producers.

While the cold separation method offers numerous advantages, it faces several technical and operational challenges that require careful consideration and strategic responses. The most significant limitation is lower absolute yield compared to conventional mechanical methods, with the observed oil separation efficiency of 35.8% falling substantially below that achieved by mechanical expellers (65-75%) or centrifugation systems (85-92%). However, this yield disadvantage can be effectively mitigated through multiple complementary approaches. A premium pricing strategy leverages the superior quality characteristics of cold-separated oil to achieve higher profit margins per liter, offsetting the reduced volume. Secondary recovery from the remaining cream layer through gentle heating or enzymatic treatment could potentially increase total oil recovery to 50-60% without significantly compromising quality. Furthermore, the cream layer itself represents a valuable by-product suitable for cosmetic applications, animal feed formulation, or coconut milk powder production, creating additional revenue streams. By focusing on niche markets where quality attributes rather than production volume drive value, small-scale producers can transform this apparent weakness into a competitive advantage.

Process standardization and quality consistency present another critical challenge, as manual operations inherently introduce potential variability in agitation intensity, temperature control, and handling procedures that could affect final product quality. Addressing this requires a systematic approach built on accessible quality management tools. Development of comprehensive standard operating procedures with visual guides enables producers with varying literacy levels to maintain consistent practices. Simple monitoring tools including calibrated thermometers, timer systems, and standard container markings provide objective process control without requiring sophisticated instrumentation. Regular quality control testing of free fatty acid content, moisture levels, and peroxide values using field-portable test kits allows producers to identify and correct quality deviations promptly. Training programs delivered through agricultural extension services or cooperative structures can systematically build producer capacity and establish community-level quality standards that support market credibility.

Microbial safety and shelf-life considerations require particular attention, as the 24-hour processing period at refrigeration temperatures, while inhibiting most pathogenic organisms, could still permit slow microbial growth if raw material quality or equipment hygiene is compromised. Implementing good manufacturing practices forms the foundation of microbial control, emphasizing thorough sanitization of all processing equipment and exclusive use of potable water throughout the production process. Using fresh coconuts processed within 12 hours of dehusking minimizes initial microbial load, while monitoring coconut milk pH (typically 6.0-6.5) provides an additional safety indicator. Although this pH range is generally suboptimal for most pathogens, opportunistic organisms remain a concern under extended processing times. Final oil filtration through 0.45-micrometer membrane filters effectively removes residual particulates and microorganisms, providing a critical final safety barrier. Immediate packaging in dark glass bottles with nitrogen flushing prevents oxidative degradation and extends shelf life while maintaining the premium quality attributes that justify the method's market positioning.

Conclusion

This research establishes that refrigerated storage at 17°C combined with systematic manual agitation represents a technically effective and economically viable method for virgin coconut oil extraction through cold separation, achieving 35.8% oil separation efficiency with minimal capital investment and substantially reduced energy consumption compared to conventional mechanical extraction methods. The approach addresses critical barriers facing small and medium-scale coconut oil producers in developing economies, with initial investments of only $450-$1,200 and energy costs reduced by 60-65% compared to hot extraction, enabling smallholder farmers to generate net monthly profits of $1,800-2,400 from modest daily processing volumes while producing premium-quality oil with superior physicochemical properties. Beyond immediate economic benefits, this method supports sustainability objectives through reduced carbon footprint, elimination of wood fuel dependency, and minimal waste generation, aligning with climate change mitigation goals while creating value-addition opportunities through by-product utilization. However, successful commercial implementation requires attention to quality standardization, microbial safety protocols, and producer training to ensure consistent product quality and market competitiveness. To advance this technology toward widespread industrial adoption, future research should prioritize systematic optimization of agitation parameters to maximize oil recovery while maintaining energy efficiency, comprehensive physicochemical characterization of oils produced under various operational conditions to establish quality specifications and ensure regulatory compliance, long-term stability studies examining oxidative stability and shelf life under different storage conditions, pilot-scale validation in diverse geographical and climatic contexts to establish process robustness, investigation of complementary secondary extraction techniques for recovering residual oil from the cream layer to improve overall economics, and development of simple field-deployable quality monitoring tools and standardized training materials to facilitate technology transfer and support producer cooperatives. Through these targeted research and development efforts, cold separation technology can emerge as a transformative tool for inclusive economic development in coconut-producing regions worldwide, democratizing access to premium oil production while promoting environmental sustainability and rural livelihood enhancement.

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