



Comparative analysis of technologies for processing of coconut inflorescence sap and palm inflorescence sap

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Abstract

The global sweetener market is shifting toward natural, low glycemic alternatives, with coconut inflorescence sap (neera, *Cocos nucifera* L.) and palm inflorescence sap (*Arenga pinnata*) emerging as nutrient dense options rich in sucrose (11-16%), minerals, phenolics, and vitamins. However, traditional open pan evaporation methods (110-115°C) result in inconsistent quality, high hydroxymethylfurfural (HMF) formation (up to 462 ppm), and loss of bioactive compounds due to excessive heat and poor hygiene. This review synthesizes current research (2020-2026) on modern processing technologies from tapping through solidification for both sap types. For coconut sap, the Coco Sap Chiller Method (CSCM) maintains 2-8°C during collection, preserving 95% of phenolics and vitamin C with zero alcohol content compared to 2.32% in traditional methods. Multi effect vacuum evaporation (60-70°C) achieves gentle concentration, maintaining a low glycemic index (GI ≈ 35) and preventing HMF formation, while non-thermal hurdle technologies (High Pressure Processing at 400-600 MPa, Pulsed Electric Fields, membrane filtration) preserve fresh aromas and bioactives. Palm inflorescence sap processing employs carbonation/defecation to remove 40% ash content and Scraped Surface Heat Exchangers (SSHE) to manage high viscosity massecuite (75-85°Brix) with controlled caramelisation, producing characteristic nutty and caramel notes without bitterness. Final solidification via vacuum tray drying (<10 mbar) creates porous crystals retaining policosanols for cholesterol management, while aseptic silicone molding ensures phytosanitary compliance for export. Coconut technologies excel in cold-chain automation and bioactive preservation for premium granulated products (200-300 L/tree/year), whereas palm methods robustly handle field variable saps for artisanal blocks and crystals supporting smallholder sustainability (25 t sugar/ha). These modern interventions transform biochemically unstable saps into shelf stable, functional sweeteners, boosting farmer GDP by 17% in India and positioning tropical palm products as superior alternatives to refined cane sugar in the growing \$2 billion global market.

Keywords: Coconut inflorescence sap, Neera, Palm inflorescence sap, *Arenga pinnata*, Vacuum evaporation, Coco-Sap Chiller Method, Scraped Surface Heat Exchanger, Low glycemic index, Non-thermal processing, Bioactive preservation, Functional sweeteners.

Introduction

The global sweetener market is undergoing a paradigm shift toward natural and minimally processed alternatives. Coconut inflorescence sap, often referred to as "Neera" or "Kalparasa," and palm inflorescence sap derived from various palm species (e.g., *Arenga pinnata*, *Borassus flabellifer*) are at the forefront of this transition (Prathibha *et al.*, 2021) [25]. These saps are nutrient dense bio fluids containing a complex mixture of sugars, amino acids, vitamins, and minerals. Historically, the processing of these saps has been a cottage industry, characterized by open-pan evaporation over wood fires (Somawiharja *et al.*, 2018) [29]. While culturally significant, these traditional methods often result in inconsistent quality, high levels of hydroxymethylfurfural (HMF) due to excessive heat, and poor hygiene (Bautista & Bonto, 2025) [5]. As the demand for premium, "clean label" sweeteners grows, there is an urgent need to transition toward standardised technological interventions that preserve the bioactive profile of the sap while ensuring microbiological safety. Coconut inflorescence sap, commonly known as neera, and

palm inflorescence sap are derived from the phloem rich nectar tapped from unopened inflorescences of tropical palms such as *Cocos nucifera* and various *Arenga*, *Borassus*, and *Phoenix* species, offering low glycemic index (GI ~35) sweeteners superior to cane sugar due to their high sucrose (13-27 g/100 ml), nutrient density, and bioactive compounds like phenolics and antioxidants (Jayasinghe *et al.*, 2020) [18]. These saps, containing 9-18.6 g/100 ml total sugars (sucrose dominant at 37.9%, glucose 9.5%, fructose 4.8%), proteins, amino acids (e.g., glutamic acid up to 34.2 g/100 ml in coconut), vitamins (B-complex, C), and minerals (K: 65-1326 mg/100 ml, Mg: 0.54-31 mg/100 ml), undergo rapid fermentation unless preserved, necessitating precise tapping from 6-8 week-old spadices via slicing and beating to yield 0.96-1.71 L/day/palm, with yields varying by genotype (e.g., Nigerian Tall: 1.71 L/day, 79.45 L/inflorescence) and season (peak post-monsoon) (Sudha *et al.*, 2021) [30].

Processing technologies transform this perishable sap into stable palm inflorescence sap products like granules, blocks, or syrups through filtration, concentration, and

crystallisation, but traditional open-pan boiling (3-5 hours at 100-150°C) induces Maillard reactions yielding dark brown sugars (L^* 24-48, a^* 1.9-20.9) with reduced phenolics (2.77-194 mg/100g GAE), antioxidants, and sucrose inversion to reducing sugars (5.55-19.6 g/100g) alongside HMF formation (0.5-41.92 mg/100g) (Swasti *et al.*, 2025)^[32]. Genotypic factors profoundly influence outcomes: Nigerian Tall excels in yield (622 L/year/palm) due to more leaves (36), girth (1.26 m), and inflorescence traits positively correlated ($r=0.76$ for leaves), while West Coast Tall leads in quality (total sugars 13.4 g/100 ml, protein 609 mg/100 ml) tapping duration (31-52 days/inflorescence) and onset (15-23 days) further modulate pH (6.5-7.2), TSS (15-17°Brix). Morphological traits like inflorescence length (69-79 cm) and circumference (19-22 cm) extend flow duration, while post-tapping resting (6 months) sustains vigor, as continuous exploitation depletes reserves; biochemical profiles reflect phloem origins, with amino acids (17 types) fueling volatiles (pyrazines for nutty/roasty notes, furanones for caramel) during thermal processing (Borse *et al.*, 2007)^[7].

Advanced methods address limitations: spray drying (inlet 220°C, outlet 85°C) preserves phenolics/antioxidants with low moisture (1-3%), membrane ultrafiltration retains bioactives (antioxidant activity 4.93 mg/ml), and vacuum drying (40°C/3h) minimises inversion, contrasting traditional inefficiencies (yield loss, contamination) (Naknean *et al.*, 2025)^[22]. Palm inflorescence sap's proximate composition underscores superiority 91-95% sugars, 0.47-4.2% ash, minerals (K 451-1250 mg/100g) vitamins (B3 1.88-3.17 mg/100g) positioning it as a functional food for diabetes management (low GI), antioxidant protection (DDMP against colon cancer), and diversification amid declining copra economics, with global markets eyeing \$2B by 2025. Comparative analyses reveal coconut sap's edge in yield consistency and amino acids versus *Borassus/Phoenix's* higher minerals, but shared challenges like microbial risks demand hygienic innovations for scalability, revitalizing palm economies in India (3M tons crude sugar/year).

Coconut Inflorescence Sap (*Cocos nucifera* L.)

Cocos nucifera inflorescence sap (neera or Kalparasa) is the unfermented phloem exudate from coconut spadices (Nagendra Prasad *et al.*, 2015)^[21]. It contains sugars, minerals, vitamins, and antioxidants, making it a promising low glycemic sugar source and health beverage (Malhija *et al.*, 2025)^[19]. Detailed research reveals its improved nutritional profile over sugarcane or palm juices, with quick fermentation kinetics limiting shelf life to hours without refrigeration (Asghar *et al.*, 2020)^[4].

1. Production and Tapping

Golden brown, sterile sap (pH 6.5-7.5) is extracted from juvenile spadices (10-15 cm slices) utilizing hygienic techniques such as coco-sap chillers (4°C) to generate 2-2.5 L/day/tree for 30-50 days (Hebbar *et al.*, 2026)^[15]. Conventional earthen pots permit partial fermentation, whereas chillers retain nutrients: 21.9 mg/100g phenolics, 901 mg/100g amino acids, and 15-16% TSS (mostly sugar) (Coconut Board, 2013)^[9]. *Cocos nucifera* inflorescence sap (neera) is produced and tapped from mature palms that are 8-10 years old (50-100 trees/ha) and generate 12-13 inflorescences a year. Only 1-3 of these palms are tapped

each month to preserve the health of the plants and nut supply. In order to increase sap yield by 20-30% without damaging vascular bundles, immature spathes (20-45 cm long, firm, golden-brown) are chosen and bound tightly with coir rope or plastic for 7-14 days. This softens tissues, reroutes phloem flow, and is frequently followed by gentle stimulation using wooden mallet beating (three times daily) or mechanical vibration/rolling (Mustaufik *et al.*, 2021)^[20]. Tapping takes place before dawn: climbers use ropes to reach the spathe, then use a sharp knife to make an initial sterile V-shaped cut (5-10 cm from tip, 1-2 mm deep), which causes a 0.3-0.5 L flow within an hour. Daily renewal shaves (0.5-1 mm) reveal fresh tissue, sustaining 1-2.5 L/day per spadix over 30-50 days until nut initiation. To prevent overflow and contamination, sap is collected in clean bamboo tubes, earthen pots (1-2 L pongkor style), or plastic bags fastened beneath the cut and emptied two to four times per day. Innovations such as battery/solar coco sap chillers (4-5°C) connected by silicone tubes provide hygienic, golden sap (pH 6.5-7.5, TSS 12-16°Brix) with a shelf life of 24-48 hours as opposed to 4-6 hours ambient; automated systems (Patent WO2018096555A1, 2018) use sensors, flow stimulators, and remote cutters to reduce climbs to once a week and increase yield by 15-20%. For commercial use, pasteurization (60-70°C for 30 minutes) further stabilizes (Patent WO2004054389A1, 2004). By rotating spathes (sparing 70% for nuts), tapping during dry seasons (October to March), and avoiding dwarf types, sustainable yields reached 200-300 L/tree/year (150-200/L fresh neera in India); incorrect practices halve spathe lifespan, stressing sterilized tools and expert labor.

2. Chemical Composition

The primary components of fresh *Cocos nucifera* inflorescence sap (neera) are water (85-86%), carbohydrates (12-16% total soluble solids, mostly sucrose 6.9-13%, glucose 2.5-4%, fructose 3.5-5%), pH 5.5-7.5, and specific gravity 1.058-1.077 (Coconut Board, 2013)^[9]. Minerals such as potassium (960 mg/L), sodium (183 mg/L), magnesium (23 mg/L) calcium, phosphorus, iron, zinc, and copper in trace amounts dominate the average ash content of 0.27% (dry basis); proteins and peptides reach 0.23-0.32% with free amino acids (350-901 mg/100g, including aspartic/glutamic acids, proline, and serine). Ascorbic acid (116 µg/mL or 4.73 mg/100g), thiamine (B1, 4.3 µg/mL), riboflavin (B2), niacin (B3, 1.9 µg/mL), and traces of B6/B12 are among the vitamins; total phenolics (14.1-21.9 mg GAE/100g), flavonoids, alkaloids, glycosides, tannins, and saponins are examples of phytochemicals (Hema *et al.*, 2023)^[17]. Palmitic acid (2024 µg/L), palmitoleic acid (1042 µg/L) ethyl lactate (560 µg/L), phenethyl alcohol (phenyl ethyl alcohol), 3-hydroxy-2-pentanone, farnesol, 2-methyltetrahydrofuran, tetradecanone, 1-hexanol, and minor 2-butanol (60-68 µg/L) and acetic acid (26-30 µg/L). Fatty acid profile: palmitic (2024 µg/L fresh), palmitoleic (1042 µg/L), with esters/acids increasing after clarification/fermentation; clarified sap keeps 13 volatiles (1.31 ppm: palmitic 342 µg/L, ethyl lactate 300 µg/L, phenethyl alcohol 195 µg/L); fermented sap changes to 37.4 ppm (12 compounds): isoamyl alcohol (7467 µg/L), palmitoleic (14,603 µg/L), ethyl caprate/caprylate, dodecanoic/tetradecanoic acids) (Rao *et al.*, 2007)^[7]. Vanillic acid (2.92-3.54 µg/g sap), syringic (1.80 µg/g), trans-cinnamic (0.636-2.40 µg/g), and p-hydroxybenzoic

acid are examples of phenolics. Sugars include sucrose, glucose, and fructose make up 12.9-15.7% of the fresh *Cocos nucifera* inflorescence sap (neera). With potassium at 960 mg/L, minerals including K, Na, Mg, Ca, and P predominate in the ash content (0.27%). Among the 13+ detected amino acids, aspartic, glutamic, and proline have concentrations between 350 and 901 mg/100g. 5.33 ppm of volatiles, comprising 21 chemicals such as farnesol, palmitic acid, and ethyl lactate (Borse *et al.*, 2007) [7]. Vanillic, syringic, and cinnamic acids are examples of phenolics that contribute 14- 22 mg GAE/100g.

Palm Inflorescence Sap (*Arenga pinnata*)

Arenga pinnata palm inflorescence sap (nira or weren sap) is the sweet, nutrient dense phloem exudate tapped from the inflorescences of this versatile tropical palm native to Southeast Asia (Artati *et al.*, 2025) [2]. Rich in sucrose, minerals, phenolics, and antioxidants, it serves as a low-glycemic alternative sweetener and basis for traditional foods, beverages, and biofuels, exceeding refined sugars in bioactivity but prone to rapid microbial fermentation.

1. Production and Tapping

Mature sugar palms (15-20 m tall, 20-40 years old, 100-200 trees/ha) are harvested for their yellow-reddish, fresh sap (pH~6.4, TSS 11-15%), which yields 1-3 L/tree/day from stimulated inflorescences over a period of one to two months (Victor, 2015) [33]. In order to prevent contamination and fermentation, traditional climbers beat stalks with wooden mallets for several minutes every day for two to three weeks in order to swell tissues and reroute phloem. They then clip the enlarged peduncle into bamboo tubes or jerry cans coated with ijuk fiber twice a day (Somawiharja *et al.*, 2018) [29]. Tapping begins before sunrise and targets two to four inflorescences per palm each year (sparing others for fruits like kaong). The initial incision at the swelling portion yields 0.3 to 0.5 L/hour, which is sustained by daily shaves of 0.5 to 1 mm for a sweeter, less profuse flow. Sap is collected overnight/morning (1-2 empties/day), boiled same-day in iron woks over wood fires to curb *Saccharomyces cerevisiae* action converting sugars to acids/ethanol within hours ambiently. No widespread chillers yet (unlike coconut), however sanitary tubes increase usability to 4-6 hours; yields hit 25 t sugar/ha from chosen bleeders (half palms non-bleeders). Sustainability is labor-intensive, supports smallholders, rotates trees, encourages dry seasons, and prevents over-tapping (maximum 3 inflorescences/tree/year).

2. Chemical Composition

The composition of fresh *Arenga pinnata* sap is around 87% water, 11-15.7% total sugars (sucrose ~11.28%, glucose/fructose/reducing sugars 4-5%), TSS 12-16°Brix, pH 6.4 (decreases after tapping), ash 0.24% (dominant K, P, Mg, Na, Ca, Fe, and Cu), proteins 0.2%, and fat 0.02% (Santoso *et al.*, 2019) [27]. Asparagine and glutamine are examples of amino acids; phenolics up to 499 mg GAE/g are locally vary (e.g., Tanah Datar high) (Artati *et al.*, 2025) [2]. Furans, aldehydes (which rise with heating or fermentation), post-processed sugar (93.4% sugars, primarily sucrose 2.98% invert), phenolics (2432 µg/g GAE), and DPPH IC50 (0.6 mg/mL) are among the volatiles (Hapsari *et al.*, 2018) [14]. Nutrition is supported by minerals; FTIR verifies sucrose/O-H/C=O groups; regional quality

(West Sumatra): sugars 7-15.73%, potent antioxidants (West Pasaman). Minerals (K/P/Mg in ash 0.24%), sugars (sucrose dominant 11-15%), amino acids (asparagine/glutamine), phenolics (up to 499 mg GAE/g), and volatiles (furans/aldehydes pre-heat). Processed: reduced calories (373 kcal/100g), pH 6.3, and 93.4% TSS.

4. Processing Technologies of Coconut Inflorescence Sap

The processing of coconut inflorescence sap (CIS), traditionally known as Neera or Kalparasa, and its conversion into palm inflorescence sap represents a significant intersection of heritage and high-tech food engineering. As the global demand for low-glycemic, nutrient-dense sweeteners rises, the technology used to harvest, stabilize, and concentrate this phloem sap has evolved from rudimentary boiling to sophisticated molecular preservation. This review synthesizes current research (2020-2026) [4, 16] to detail the unit operations that define modern sap processing.

1. Stabilization and the "Cold Chain" Collection Tech

The primary technical barrier in processing coconut and palm sap is its extreme biochemical instability. Freshly harvested sap is a nearly neutral liquid (pH 6.5-7.5) with a high sucrose concentration (12-15%), making it a perfect substrate for native yeasts and lactic acid bacteria (LAB). Research by Hebbar *et al.* (2026) [15] confirms that without intervention, fresh sap undergoes a rapid pH drop to 4.5 within 12 hours due to a bacteriome-to-mycobiome transition. Traditionally, this was managed by coating collection pots with Calcium Hydroxide (Lime), which inhibits microbial growth but fundamentally alters the sap's color to an oyster-white and introduces a harsh, sulfurous odor. The modern technological solution is the Coco-Sap Chiller Method (CSCM) developed by the ICAR-Central Plantation Crops Research Institute (CPCRI). This system utilizes a double-walled vacuum-insulated container that maintains the sap at 2-8°C during the entire 12 hour collection period. This "Cold Chain" technology is a critical leap; it prevents the enzyme invertase from breaking down sucrose into glucose and fructose, preserving the sap in its "virgin" or "Kalparasa" state. Studies demonstrate that CSCM-collected sap retains over 95% of its original Vitamin C and phenolic content, while maintaining 0% alcohol content, whereas traditional methods often reach ~2.32% ethanol by the time of processing (Hebbar *et al.*, 2026) [15].

2. Thermodynamics of Concentration

Vacuum vs. Open Pan: The transformation of liquid sap into granulated sugar requires the removal of approximately 85% of its water content. The choice of evaporation technology dictates the chemical profile specifically the glycemic index and antioxidant capacity of the final sweetener. In traditional processing, sap is boiled in large open pans over biomass furnaces at temperatures between 110°C and 115°C. This triggers intense Maillard Reactions and Caramelization, producing the dark-brown color and toffee flavor characteristic of rustic palm inflorescence sap. However, kinetic studies by Bautista & Bonto (2025) [5] indicate that high-heat treatment risks the formation of mutagenic compounds like 5-Hydroxymethylfurfural (HMF), which can reach levels of 462 ppm in coconut sugar. To counter this, industrial processing now employs

Multi-Effect Vacuum Evaporation. By lowering the atmospheric pressure inside the vessel, the sap boils at much lower temperatures (60-70°C). This "Gentle Concentration" prevents the excessive thermal cracking of sugar molecules. According to research by Naknean *et al.* (2025) [22], vacuum-evaporated coconut sugar maintains a significantly lower Glycemic Index (GI \approx 35) than open-pan sugar, as the structural integrity of the complex carbohydrates is better preserved. This technology also allows for precise control of the "Strike Point" the exact moment when the syrup is concentrated enough to crystallize minimizing the risk of "over-shooting" and burning the batch.

Non-Thermal Preservation and Refining Hurdles

Recent review papers highlight a shift toward non-thermal "hurdle" technologies to satisfy the "minimally processed" market. These technologies extend the shelf life of fresh Neera without the use of chemical preservatives like lime.

1. Membrane Filtration

(Ultrafiltration/Microfiltration): This technology uses ceramic or polymeric membranes with pore sizes ranging from 0.1 to 10 μm . It physically removes microbial cells and large proteins that cause turbidity, resulting in a crystal-clear sap that is shelf-stable for months when bottled aseptically.

2. High-Pressure Processing (HPP): Also known as Pascalization, this involves subjecting the sap to pressures of 400-600 MPa. This disrupts the cell membranes of

bacteria and yeasts without affecting the covalent bonds of vitamins or flavor volatiles. HPP-treated coconut sap is indistinguishable from fresh sap in sensory trials.

3. Cold Plasma (CP) and Pulsed Electric Field (PEF):

Emerging as the 2026 [15] frontier, these technologies utilize short bursts of high voltage or ozone gas to deactivate microbes. Research indicates that PEF technology is particularly effective at maintaining the "fresh floral" aroma of the sap, which is otherwise lost during traditional pasteurization (Hebbar *et al.*, 2026) [15].

Particle Engineering: Crystallization and Granulation

The final stage of processing involves the transition from a supersaturated syrup (approx. 80°Brix) to a free-flowing granulated sugar. While traditional palm inflorescence sap is often poured into molds to form hard "slabs" (with moisture contents of 6-10%), modern granulated coconut sugar utilizes Dry Granulation and Vibratory Fluidized Bed Drying. The concentrated syrup is transferred to a cooling table where mechanical stirrers induce "secondary nucleation," creating uniform, small crystals (Hanifah, 2022) [13]. The subsequent use of fluidized bed dryers ensures that the final moisture content is reduced to below 2%, which is essential for preventing "caking" or clumping during storage. Spray drying with maltodextrin is also utilized for "instant" powders, though this often increases the glass transition temperature (Tg), necessitating strict humidity control (<85% RH) during packaging.

Table 1: Comparative table of traditional and modern technology evolved in coconut inflorescence sap

Feature	Traditional Technology	Modern Technology
Collection	Lime coated pots	Vacuum insulated chillers
Stabilisation	Chemical (High pH)	Thermal (cold chain)
Concentration	Open pan boiling (> 110)	Vacuum evaporation
Clarification	Sedimentation/Skimming	Ultrafiltration/Centrifugation
Final product	Blocks/Slabs	Granules (High phenolics)

Processing Technologies of Palm Inflorescence Sap

The processing of palm inflorescence sap is a sophisticated sequence of biochemical and thermal interventions designed to transform a highly unstable, dilute biological fluid into a shelf stable, nutrient dense sweetener. The journey begins with the immediate stabilization of the raw sap, or neera, which exits the tree with a neutral pH but rapidly succumbs to microbial fermentation and enzymatic inversion, turning sucrose into glucose and fructose. To mitigate this, modern processing technologies integrate pre-treatment phases such as micro filtration and centrifugation to reduce microbial loads and remove suspended solids before the energy-intensive evaporation stage begins. The core of the technology lies in water removal, where the industry is transitioning from traditional, high heat open pan systems often criticized for their lack of thermal control and tendency to cause excessive Maillard browning and nutrient degradation toward vacuum evaporation and thin-film technology (Bautista & Bonto, 2025) [5]. These advanced methods operate at lower temperatures under reduced pressure, effectively preserving heat-sensitive phytonutrients and antioxidants while precisely controlling the "strike point" where the concentrated syrup reaches the critical Brix level for crystallisation. The final quality of the granulated sugar is determined by the cooling and mechanical shearing processes, which dictate the crystal

morphology and hygroscopicity of the product. By synthesising mechanical engineering with food chemistry, modern palm inflorescence sap processing aims to maximise the recovery of high purity sucrose while maintaining the distinct organoleptic properties the unique caramel like aroma and mineral rich profile that distinguish palm inflorescence sap from conventional refined sweeteners in the global functional food market.

1. Selective Tapping and Pre-processing Technologies

Palm inflorescence sap technology begins with the "conditioning" of the inflorescence. Unlike coconut palms, which are often hybrid and shorter, many sugar palms are tall and wild-grown, necessitating specialised Portable Tapping Platforms. The technology of tapping involves a precise rhythmic "beating" or "massaging" of the flower stalk using wooden mallets. This mechanical stress triggers the plant's physiological response, increasing the flow of phloem sap. Research by Naknean *et al.* (2025) [22] indicates that the use of Botanical Inhibitors (bark of *Shorea robusta* or *Garcinia* hulls) in the collection stage is more than a tradition; it is a "Hurdle Technology." These botanical inserts release specific tannins that selectively inhibit *Leuconostoc mesenteroides*, the primary bacteria responsible for converting sucrose into gummy dextran. Without this technological control, the sap would become

too viscous to flow through industrial filters. Modern palm inflorescence sap plants are now replacing these barks with Food Grade Sodium Metabisulfite or Nisin based Bio preservatives to achieve a more standardized sap profile for large scale refining.

2. Advanced Clarification: Carbonation and Defecation

Palm sap is often harvested in less controlled environments than plantation coconut sap, it contains higher levels of suspended solids, waxes, and gums. The technology used to clean this sap is known as Defecation and Carbonation. In this process, milk of lime is added to the raw sap, followed by the injection of Carbon Dioxide. This creates a precipitate of calcium carbonate that "sweeps" out impurities, including color precursors and non sugar solids. This technology is critical for producing "Light Palm Inflorescence Sap" which is increasingly popular in export markets. Following carbonation, the sap is passed through Filter Presses or Rotary Vacuum Drum Filters to achieve a clear, brilliant juice. Studies show that this clarification step reduces the ash content by 40%, significantly improving the shelf stability of the final sugar (Naknean *et al.*, 2025) ^[22].

3. High Viscosity Evaporation and Scraped Surface Heat Exchangers

Palm sap typically has a higher mineral and invert sugar content than coconut sap, which makes the syrup extremely viscous as it nears the "Strike Point". In traditional palm inflorescence sap processing, this leads to localized burning at the bottom of the pan. To solve this, modern palm inflorescence sap technology utilizes Scraped Surface Heat Exchangers (SSHE) (Bautista & Bonto, 2025) ^[5]. The SSHE consists of a jacketed cylinder with internal rotating blades. As the palm syrup thickens into a heavy paste (75-85°Brix), the blades continuously scrape the heat transfer surface. This technology ensures:

4. Uniform Heat Distribution

The primary technical failure of traditional open-pan boiling is the development of a "stagnant boundary layer" where the syrup in direct contact with the vessel wall overheats while the core remains cool. The SSHE solves this by utilizing high-velocity rotating blades that continuously shear the product film away from the jacketed cylinder's walls, maintaining a high heat transfer coefficient despite the skyrocketing viscosity of the syrup. This mechanical agitation ensures that every molecule of the 75-85°Brix paste experiences a homogenous thermal environment, effectively eliminating the "hot spots" that lead to the thermal degradation of delicate sucrose molecules. By preventing these localized temperature spikes, the technology avoids the creation of acrid, "burnt" off flavors and ensures a consistent golden-brown color, which is a critical quality benchmark for premium palm inflorescence sap variants like Gula Melaka that otherwise suffer from inconsistent batch-to-batch charring.

5. Rapid Moisture Flash

As palm sap concentrates into a heavy paste, the increasing density creates a significant barrier to steam escape, often leading to a plateau in evaporation efficiency in conventional systems. The SSHE overcomes this rheological hurdle through its high-frequency scraping action, which constantly creates a large, renewed surface

area for water molecules to escape into the vapor phase. This "flash" evaporation is critical during the final stages of processing where the moisture content must be dropped rapidly to reach the crystallisation threshold without exposing the sugar to prolonged, damaging heat. This accelerated phase transition not only reduces the total residence time within the heat exchanger thereby protecting the nutritional integrity of the sugar but also allows for a continuous rather than batch based production flow, significantly increasing the volumetric throughput of the processing facility.

6. Controlled Caramelization

The characteristic sensory profile of palm inflorescence sap is a result of a delicate balance between the Maillard reaction and caramelization, both of which are highly sensitive to the "time-temperature" relationship. In an SSHE, the precise control over residence time and jacket temperature allows the processor to steer these chemical pathways with surgical accuracy. By maintaining temperatures that favor the synthesis of desirable aroma volatiles such as furfural, pyrazine, and various ketones, the technology ensures the development of the "earthy" and "smoky" notes that consumers expect. Unlike open fire methods where temperature fluctuations often lead to advanced caramelization resulting in a bitter, dark, and nutritionally depleted product the SSHE allows these reactions to proceed just enough to achieve the target organoleptic complexity while halting them before the carbonisation of sugars begins, thus preserving the natural antioxidants and mineral salts inherent in the sap.

7. Solidification Technology: Vacuum Drying vs. Molding

The final phase of palm inflorescence sap technology involves converting the "Massequite" (thick sugar paste) into its final form. While coconut sugar is almost exclusively granulated, palm inflorescence sap technology utilizes two distinct paths:

7.1. Vacuum Tray Drying: For the production of "Palm Crystals," the thickened syrup is spread onto industrial trays and subjected to drying under a deep vacuum (<10 mbar). This specific technology exploits the physical principle of boiling point reduction, allowing moisture to escape at significantly lower temperatures which prevents the degradation of heat-sensitive compounds. A unique mechanical advantage of this process is that it allows the sugar paste to "puff," expanding the internal matrix to create a highly porous, honeycombed structure. This porosity is essential for the subsequent milling phase, as it ensures the sugar can be ground into a fine, highly soluble powder that dissolves almost instantly in both hot and cold applications. Beyond texture, this low-temperature environment is a biological safeguard; research by Phaeon (2026) ^[16] demonstrates that vacuum-dried palm inflorescence sap retains a significantly higher concentration of Policosanols long-chain alcohols that may assist in managing cholesterol which are typically destroyed by the prolonged oxidative stress of open air boiling used in traditional methods.

7.2. Aseptic Molding: In contrast, the path toward traditional blocks or cylinders has been revolutionized by Aseptic Molding, a modern take on the ancient "coconut

shell mold" technique. In this process, the concentrated massecuite is precisely cooled to a "tacking temperature" of approximately 90°C, at which point its rheological properties are optimal for shaping without risking premature crystallization within the piping. The syrup is then injected into food-grade silicone molds under strictly controlled aseptic conditions. This technological intervention is vital for food safety and global export; by eliminating manual handling and environmental exposure during the cooling phase, the system prevents the inoculation of the sugar with xerophilic molds fungi that thrive in high-sugar, low-moisture environments which are the primary cause of spoilage in artisanal palm inflorescence sap blocks. This method preserves the iconic structural integrity and "bite" of the sugar while ensuring it meets international phytosanitary standards.

Comparison between Coconut Inflorescence Sap and Palm Inflorescence Sap

Coconut inflorescence sap (Neera, from *Cocos nucifera*) and palm inflorescence sap (from *Arenga pinnata*) processing technologies both address the core challenges of rapid microbial fermentation, high water content (85-87%), and sucrose-dominant sugars (11-16% TSS), but reveal stark differences in tapping precision, stabilization efficacy, thermal management, and final product versatility, ultimately positioning coconut methods as more nutrient-preserving for premium low-GI granulates while palm excels in robust, scalable handling of field-variable saps for artisanal blocks and crystals.

From tapping through solidification, coconut leverages plantation-scale automation like Coco-Sap Chillers (CSCM at 2-8°C vacuum-insulated via silicone tubes) on shorter hybrid palms (8-10 years, 2-2.5 L/day/spadix over 30-50 days from bound immature spathes with V cuts and mallet stimulation), yielding golden pH 6.5-7.5 sap retaining 95% phenolics (14-22 mg GAE/100g), vitamins (ascorbic 116 µg/mL), and volatiles (palmitic acid 2024 µg/L) with 15-20% higher output (200-300 L/tree/year) via sensors/pasteurization (60-70°C/30 min), far surpassing palm's labor-intensive climber-dependent mallet-beating on tall wild trees (20-40 years, 1-3 L/day/inflorescence for 1-2 months into ijuk lined bamboo tubes).

Palm's pre-dawn clipping and botanical hurdles (*Shorea/Garcinia* tannins or nisin inhibiting *Leuconostoc* dextran) extend usability to just 4-6 hours without chillers, grappling with higher contamination and regional swings (e.g., West Sumatra 7-15.73% sugars, phenolics to 499 mg GAE/g), yet supports smallholder sustainability (25 t sugar/ha from rotated bleeders, max 3 inflorescences/tree/year) where coconut mandates spathe sparing (1-3/month, 70% for nuts) to avoid vascular damage.

In stabilization and clarification, coconut's cold-chain dominance prevents invertase-driven sucrose loss

(preserving 6.9-13% sucrose vs. glucose/fructose spikes) and LAB/yeast pH drops (to 4.5 in 12h), integrating non thermal hurdles like HPP (400-600 MPa cell membrane rupture), PEF/cold plasma for floral aromas, and UF/microfiltration (0.1-10 µm ceramic/polymeric pores yielding crystal clear sap) over lime-coated pots that impart sulfurous off notes retaining full amino acids (350-901 mg/100g aspartic/glutamic dominant) and zero ethanol unlike ambient fermentation (2.32%).

Palm counters dirtier saps with carbonation/defecation (lime + CO₂ precipitating 40% ash including waxes/gums via filter presses/rotary drums) and metabisulfite for "light" export sugars, but sacrifices some antioxidants (DPPH IC₅₀ 0.6 mg/mL processed) to viscosity from minerals (K/P/Mg in 0.24% ash) and inverts (4-5% reducing sugars), making its pre-evaporation cleaner yet less "virgin" than coconut's minimally invasive chillers. Both shun traditional earthen pots for hygiene, but coconut's tech aligns with ICAR-CPCRI protocols for 10,000 L/day plants (150-200/L returns, 17% farmer GDP boost), while palm's field realities favor quick boil-outs in iron woks to curb *Saccharomyces cerevisiae* ethanol/acid shifts.

Concentration phases highlight thermal sophistication: coconut's multi-effect vacuum evaporation (60-70°C under reduced pressure) achieves "gentle" strikes at 80°Brix with precise strike-point control, slashing Maillard/HMF risks (462 ppm in open-pan at 110-115°C) for GI ≈ 35 granules richer in complex carbs, versus palm's Scraped Surface Heat Exchangers (SSHE) mastering ultra-viscous massecuites (75-85°Brix from higher minerals/inverts) via rotating blades that shear boundary layers for uniform heat, flash moisture escape, and steered caramelization(furfural/pyrazines/ketones yielding smoky "Gula Melaka" notes without bitterness or carbonization). Traditional open pan boiling plagues both with dark-brown jaggery (Maillard volatiles, nutrient loss), but coconut prioritizes phenolic/Vitamin C integrity (e.g., 95% retention), while palm's SSHE enables continuous flow and higher throughput despite equipment costs, better suiting its rheological hurdles over coconut's lower-viscosity sap.

Final solidification underscores product divergence: coconut cools supersaturated syrup on tables with mechanical stirrers for secondary nucleation, then fluidized-bed dries to <2% moisture free flowing granules (or maltodextrin spray-dried powders under 85% RH), ideal for health beverages/sweeteners with uniform crystals and high solubility (Pandiselvam *et al.*, 2023) [24]. Palm bifurcates into vacuum tray drying (<10 mbar puffing porous honeycombed crystals retaining policosanols for cholesterol benefits) or aseptic silicone molding (90°C tacking temp injection for blocks/cylinders dodging xerophilic molds), yielding 6-10% moisture slabs (93.4% sugars, 373 kcal/100g) with "bite" and export phytosanitary compliance preserving

Table 2: Comparison between palm sugar and coconut sugar

Technology component	Palm sugar (Arenga/Palmyra)	Coconut Sugar (Cocos nucifera)
Primary Inhibitor	Tannin-rich barks / Metabisulfite	Cold-chain / Vacuum chilling
Clarification	Carbonation & Filter Pressing	Ultrafiltration & Centrifugation
Evaporation Tech	Scraped Surface (SSHE)	Thin-Film / Multi-effect Vacuum
Dominant Flavor Path	Controlled Caramelization	Minimal Maillard (Floral preservation)
Final Form	Blocks, Slabs, or Granules	Primarily Granulated/Crystalline

artisanal earthiness but risking caking absent strict humidity. Coconut edges in scalability/automation (dry season peaks October-March), palm in versatility for toffees/vinegars (2B market, 3.4% CAGR).

In verdict, coconut Neera technologies (Hebbar *et al.*, 2021-2026) ^[15, 25] superiorly safeguard bioactives/low GI for industrialized granulates via cold chain/vacuum/PEF, thriving in controlled plantations but demanding expertise to avert over-tapping stress; palm (Arenga) methods (Bautista & Bonto, 2025 ^[5]; Phaeon, 2026) robustly tame wild variability through SSHE/carbonation/molding for flavorful, mineral-dense forms supporting smallholders, though lagging chillers heightens losses. Hybridisation palm chillers plus coconut SSHE promises optimized low-GI functionals outperforming cane, with coconut leading premium exports and palm sustaining cultural markets.

Conclusion

The processing of coconut and palm sap represents a complex evolution from traditional cottage-industry practices to a sophisticated domain of modern food engineering, designed to meet the burgeoning global demand for natural, low glycemic, and nutrient-dense sweeteners. At the heart of this transition is the challenge of managing the extreme biochemical instability of these saps, which are phloem exudates rich in sucrose (11-16% total soluble solids), amino acids, vitamins, and minerals, but prone to rapid fermentation by native yeasts and lactic acid bacteria within hours of collection. Traditional methods, while culturally significant, relied on open-pan evaporation over wood fires at temperatures exceeding 110°C, which frequently resulted in inconsistent quality, the loss of bioactive phenolics, and the formation of potentially harmful 5-Hydroxymethylfurfural (HMF). In contrast, modern technological interventions like the Coco Sap Chiller Method (CSCM) have revolutionised the "cold chain" collection process by utilizing vacuum-insulated containers that maintain the sap at 2-8°C, effectively inhibiting the enzyme invertase and preserving the sap in its "virgin" or "Kalparasa" state (Hebbar *et al.*, 2026) ^[15]. This technological leap ensures that the sap retains over 95% of its original Vitamin C and phenolic content while maintaining zero alcohol, a stark improvement over traditional methods where ethanol levels can reach 2.32% by the time of processing.

For coconut inflorescence sap (*Cocos nucifera*), the use of shorter hybrid palms and automated systems allows for consistent yields of 200-300 liters per tree annually, utilizing precise V cuts and mallet stimulation to maximise flow without damaging the plant's vascular bundles. The concentration phase further differentiates modern practice through Multi Effect Vacuum Evaporation, where lowering atmospheric pressure allows the sap to boil at just 60-70°C. This "gentle concentration" prevents the thermal cracking of sugar molecules, maintaining a Glycemic Index of approximately 35 and preserving the structural integrity of complex carbohydrates (Naknean *et al.*, 2025) ^[22].

Palm inflorescence sap processing (*Arenga pinnata*) faces different rheological hurdles, as it is often harvested from taller, wild grown trees and contains higher levels of minerals, waxes, and gums than coconut sap. To manage these impurities, the technology employs carbonation and defecation, where milk of lime and CO₂ are used to precipitate out 40% of the ash content, resulting in a clearer, more shelf stable juice preferred for export. As the palm

syrup nears the "strike point," its high viscosity typically leads to localized burning in traditional vessels; however, modern Scraped Surface Heat Exchangers (SSHE) solve this by using internal rotating blades to continuously shear the product film away from the heated walls (Bautista & Bonto, 2025) ^[5]. This mechanical agitation ensures a homogenous thermal environment for the 75-85°Brix paste, allowing processors to precisely steer the "time-temperature" relationship to favor desirable aroma volatiles like pyrazines and furanones which provide the characteristic nutty and caramel notes without the bitterness of over caramelisation. Beyond thermal treatments, the 2026 ^[15] frontier of sap technology includes non-thermal "hurdle" methods such as High Pressure Processing (HPP) at 400-600 MPa and Pulsed Electric Fields (PEF), which deactivate microbes while leaving delicate flavor volatiles and covalent bonds of vitamins completely intact. These methods are particularly effective at maintaining the "fresh floral" aroma of Neera that is often lost during standard pasteurization. The final stages of solidification have also undergone significant engineering refinements to enhance product versatility and shelf life. While coconut sugar is primarily processed into free flowing granules via secondary nucleation on cooling tables followed by fluidized bed drying to under 2% moisture, palm inflorescence sap technology often utilizes vacuum tray drying to create "palm crystals". This deep vacuum (<10 mbar) environment exploits the principle of boiling point reduction, causing the sugar paste to "puff" into a porous, honeycombed structure that is highly soluble and preserves heat-sensitive compounds like policosanols, which are linked to cholesterol management (Phaeon, 2026). For the production of traditional blocks or slabs, aseptic silicone molding at a "tacking temperature" of 90°C has replaced manual handling, successfully preventing the inoculation of xerophilic molds and ensuring that the final product meets international phytosanitary standards for the global market.

By synthesising mechanical engineering with food chemistry, these modern technologies have not only improved the recovery of high-purity sucrose but have also revitalized local economies such as in India, where refined sap processing can boost farmer GDP by 17%. Ultimately, the technological superiority of coconut's cold-chain and vacuum systems provides an edge in the premium granulated market, while palm's robust SSHE and carbonation methods allow for the scalable handling of variable wild saps, together positioning these tropical sweeteners as powerful functional alternatives to conventional cane sugar in a \$2 billion global market.

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