

# The Fermentation-Distillation Optimization of Palm Juice for High-Content Bioethanol: Literature Review

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## Abstract

*This review examines recent progress toward high-purity bioethanol from *Arenga pinnata* to support national energy independence and the planned E10 gasoline blend. *Arenga pinnata* is a strategic local feedstock with high soluble sugars ( $\approx 7\text{--}15\%$  sucrose), mildly acidic sap (pH 5.5–6), broad availability across Indonesia, and minimal competition with staple foods. In contrast, traditional spontaneous fermentation and single-stage distillation typically yield 30–70% (v/v) ethanol with inconsistent quality. Focusing on studies published from 2020 to 2025, we synthesize advances in: (1) controlled fermentation of palm sap through microbiological and process parameters (yeast dose, temperature, pH, and time); (2) multistage or column distillation to raise ethanol to 70–90% (v/v), commonly  $\sim 89\%$  (v/v); and (3) dehydration via pervaporation membranes to surpass the water–ethanol azeotrope and produce  $>99\%$  anhydrous ethanol. Emerging Internet-of-Things (IoT) monitoring maintains fermentation at 30–35 °C and pH 4.5–5.5 in real time, cutting energy use by  $\sim 20\%$  and increasing sugar-to-ethanol conversion by  $\sim 35\%$ . Overall, high-grade bioethanol production from palm sap requires integrated fermentation control, reflux/multistage distillation, and advanced dehydration, underpinned by digital monitoring transferable through farmer-oriented training models.*

**Keywords:** Palm sap, High grade bioethanol, Multistage distillation, Pervaporation, IoT process.

## I. INTRODUCTION

The acceleration of the energy transition positions bioethanol as a key oxygenate in cleaner gasoline to reduce dependence on fossil fuels and transportation emissions, including within Indonesia's policy agenda [1-2]. Consequently, ethanol used for blending must meet fuel-grade specifications, i.e., be dehydrated beyond the ethanol–water azeotrope so that residual water is minimal; achieving this typically requires a polishing step after conventional distillation [3].

*Arenga pinnata* (sugar palm) is a promising domestic feedstock because it is widely available across Indonesia's tropics, does not directly compete with staple food crops, and contains high soluble sugars that ferment readily without complex hydrolysis pretreatments [4-6]. Practically, year-round supply in rural centers enables aren sap to serve as a local carbon source supporting E7–E10 blending

targets from domestic feedstocks [1-2], while its chemistry (slightly acidic pH, sucrose-dominant with glucose and fructose fractions) facilitates direct conversion to ethanol [4, 5].

In traditional practice, spontaneous fermentation followed by stepwise distillation can yield medium- to high-strength distillate; field observations often report an initial cut near  $\sim 70\%$  v/v, though batch quality varies widely due to unstandardized process parameters (inoculum, pH, temperature, residence time) [5,7]. Controlled fermentation with *Saccharomyces cerevisiae* at appropriate temperature and pH improves ethanol formation and prepares a more consistent feed for subsequent distillation [5-7]. Nevertheless, even multistage distillation—while capable of reaching  $\sim 70\text{--}90\%$  v/v—still requires further dehydration to meet anhydrous fuel-grade specifications [3].

Thermodynamic limits imposed by the azeotrope

and the high energy intensity of distillation motivate integration of membrane dehydration (e.g., pervaporation), which has been shown at pilot scale to reduce water content to near-specification with improved energy efficiency [3]. In parallel, Internet of Things (IoT)-based process monitoring and control—using sensors for temperature, pH, flow rate, and other key variables—enables real-time adjustment that stabilizes product quality, decreases batch-to-batch variability, and lowers process energy demand [3, 8].

To ensure innovations translate beyond the laboratory, context-appropriate technology transfer—such as deploying low-cost, solar-assisted distillers as vocational training media—can accelerate diffusion of best practices among sap producers; prototype studies indicate technical readiness for producing medium-strength ethanol that can be polished via membrane dehydration [9]. By aligning community feedstock availability with controlled fermentation, more energy-efficient multistage distillation, membrane purification, and IoT-enabled control, the aren-based bioethanol chain offers a realistic pathway to high-quality product supporting the national fuel blend targets [1, 3-4, 8-9].

## II. MATERIALS AND METHODS

This article is a narrative-structured literature review. The source search was conducted in the 2020-2025 publication range with a focus on: bioethanol from palm sap (*Arenga pinnata*), *Saccharomyces cerevisiae* fermentation on palm sap/sugar, multistage distillation or multistage column to increase ethanol content, ethanol purification/dehydration techniques up to >99%, sensor/IoT-based process control, and the context of national bioethanol supply policies. Sources are taken from indexed national journals (example: Biodiversity) and open access international journals/proceedings (example: IOP Conference Series: Earth and Environmental Science; Membranes; Heliyon), as well as credible energy policy articles (Reuters). Inclusion criteria: (i) peer-reviewed articles or fully accessible scientific proceedings, (ii) present quantitative data related to one of the stages of palm juice bioethanol production (juice composition, fermentation conditions, distillation performance, advanced purification efficiency, or process control system), and/or (iii) contain data on national bioethanol supply needs for fuel blending programs.

## III. RESULTS AND DISCUSSIONS

### A. Characteristics of Palm Sap as Bioethanol Feedstock

Sugar-palm sap (*Arenga pinnata*) is widely tapped across Indonesia and has long supported rural value

chains (sugar, beverages, vinegar, alcohol), indicating strong social acceptance and dependable access to fermentable substrate [10]. Region-wide surveys further confirm high soluble sugars (dominantly sucrose with glucose/fructose fractions), weakly acidic initial pH, and bioactive constituents, with quality varying by tapping location—information that can be mapped from the point of collection to guide raw-material standardization [11]. Compared with starch or lignocellulosic feedstocks, palm sap can be directly fermented without complex hydrolysis, although prompt sanitation and controlled inoculation are essential to avoid rapid acidification and quality loss [10].

### B. Fermentation of Palm Sap to Ethanol (Role of *S. cerevisiae*; Time, Temperature, pH)

Uncontrolled, spontaneous fermentation (~3 days) yields low and inconsistent ethanol due to mixed microflora and acidogenic contamination [10, 11]. By contrast, standardized inoculation with *Saccharomyces cerevisiae* under hygienic, anaerobic conditions accelerates sugar conversion during the first 24–48 h, typically reaching ~5–6.5 % (v/v) and producing a more uniform feed for distillation [4, 6]. Process productivity is maximized near 30–35 °C with initial pH ~4.5–5.5; beyond these bounds, yeast activity declines and contaminants proliferate, so fermentation time should be bounded (~48 h) to prevent yield loss [4, 6].

### C. Multistage Distillation and Column Operation

Traditional batch distillation practiced in producing regions concentrates palm-sap fermentate into sequential fractions (~70%, then ~45% and ~31% v/v), but quality is operator-dependent and energy-intensive [10]. Purpose-built multistage columns (with controlled reflux and managed temperature gradients) replicate vapor–liquid contact across effective stages, delivering more stable 70–90% (v/v) distillate per cycle and reducing specific energy consumption compared with “staged pot-still” approaches [5, 10]. This transition shifts community practice from artisanal fraction-cutting to repeatable process engineering, increasing the volume and consistency of high-strength product at farmer-group scale [12].

### D. Advanced Dehydration (Pervaporation) to Achieve Anhydrous Ethanol

Because distillation is capped by the ethanol–water azeotrope (~95–96 wt% ethanol), a post-column dehydration step is required for fuel-grade specifications. Hydrophilic pervaporation modules

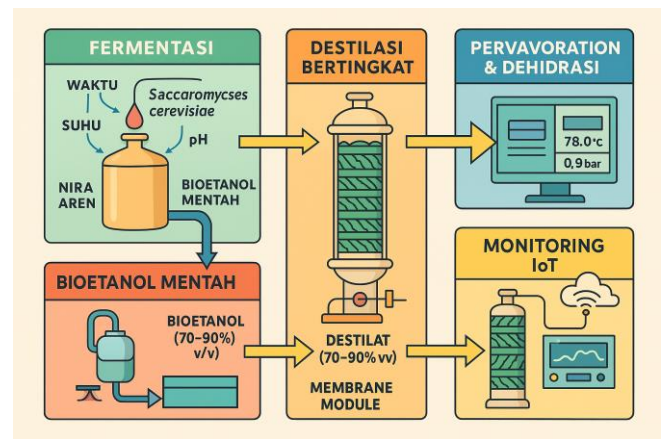
(e.g., PVA-based or mixed-matrix membranes) selectively remove water from 70–90% feeds to >99% ethanol with favorable separation factors and improved energy efficiency versus further thermal distillation [12–15]. Pilot data (ECO-001) show higher feed temperature/flow increases flux and shortens time-to-spec, enabling decentralized “polishing” of column outputs to anhydrous quality [12].

#### E. IoT-Enabled Monitoring and Soft Sensing

The integration of Internet of Things (IoT)-based process control in the production of bioethanol from palm juice is aimed at addressing two main issues at the small-medium production scale, namely the fluctuating ethanol quality from batch to batch and the high energy intensity during fermentation and especially distillation. Conventional systems often rely on operators to manually set the fermentation temperature, monitor the pH, or control the heating rate of the distillation column, leading to variations in sugar-to-ethanol conversion and excessive use of heating fuel [16]. Integrating inexpensive sensors (temperature, pH, turbidity, flow/pressure) with microcontrollers and dashboards enables real-time supervision of fermentation and distillation, stabilizing product quality and lowering process energy demand [7,17,18]. Data-driven soft sensors can estimate ethanol, cell biomass, and column performance from easy-to-measure signals, reducing reliance on costly lab analytics and supporting consistent operation at community scale [19]. Reports indicate ~20% energy savings and ~35% gains in sugar-to-ethanol conversion versus manual operation when deviations are corrected proactively [7,17,18].

#### F. Technology Transfer and Training Context

Low-cost, solar-assisted distillers have been piloted as vocational training media, producing ~75–90% (v/v) ethanol at ~0.4–0.5 L per 5 L batch with ~600 Wh of electrical input while improving student biofuel literacy—an approach that can accelerate diffusion of best practices to producer groups. [9, 21]. Aligning community feedstock, controlled fermentation, multistage column distillation, membrane dehydration, and IoT control offers a realistic pathway to anhydrous product that supports Indonesia’s ethanol-blending policy trajectory [1].



**Figure 1.** The process flow of producing high-content bioethanol from palm sap in an integrated manner, starting from controlled fermentation using *Saccharomyces cerevisiae* (time, temperature, and pH settings), followed by multistage distillation to increase ethanol content to 70–90% v/v, then the advanced purification stage through pervaporation/membrane dehydration to reduce water content to anhydrous ethanol (>99%), and an IoT-based monitoring system that monitors process parameters in real time to maintain product quality and energy efficiency).

## IV. CONCLUSIONS

Based on a literature review, the production of high levels of bioethanol from palm sap can be achieved sustainably through the integration of three key stages of the process, namely controlled fermentation based on *Saccharomyces cerevisiae* (with time, temperature, and pH settings to maximize the conversion of nira sugar into ethanol), multistage/column distillation to increase ethanol levels to 70–90% v/v in a stable and energy-efficient manner, and advanced purification based on membrane technology (pervaporation/dehydration) to cross the water-ethanol azeotrope limit and achieve >99% purity to meet anhydrous ethanol standards as a fuel component. This approach is becoming increasingly relevant in the context of the national bioethanol gasoline blend implementation target (E7-E10), which demands the supply of high purity bioethanol from local biomass sources without relying on imports. In addition to the core process aspects, the implementation of IoT-based process control—including real-time monitoring of temperature, pH, flow rate, and distillation column performance—offers a pathway for quality standardization and energy savings (to lower process energy consumption and improve sugar-to-ethanol conversion efficiency), so that bioethanol production no longer relies on traditional operator skills alone but moves towards a system that is scalable, replicable, and compatible with modern industry standards. Thus, palm sap is not only a local commodity with economic value, but can be positioned as a strategic raw material

for the provision of high-grade bioethanol based on village resources, whose technology can be transferred to farmer groups through standardized process training towards national energy independence.

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