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Review article

Tapping into Palm Sap: Insights into extraction practices, quality profiles, fermentation chemistry, and preservation techniques

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ABSTRACT

The quality profile, extraction yield, and fermentation chemistry of palm sap depend on various factors such as extraction technique, weather conditions, and preservation methods. This review aims to provide a detailed overview of palm sap extraction techniques and the methods for its preservation. The compositional analysis of palm sap, including physical and chemical parameters such as sugar content, acidity, and mineral composition, is discussed thoroughly. The role of microorganisms in fermentation and the effects of various influencing factors are also critically examined. Additionally, this review evaluates different preservation methods, including thermal processes, refrigeration, and electrical techniques, highlighting their effectiveness in extending the shelf life of palm sap. The review further explores the emerging impact of nanotechnology on palm sap preservation, offering insights into the latest industry challenges, developments, and future prospects. By presenting these findings, this review aims to enhance the scientific understanding of palm sap and stimulate additional research and innovation in the field, paving the way for improved production practices and product quality.

1. Introduction

Palm sap is a sweet liquid extracted from various palm species, such as nipa, sago, and date palm trees. Over the centuries, palm sap has been used as a sweetener and fermented into alcoholic beverages, particularly in Southeast Asia and the Middle East. The global production of palm sap has seen steady growth in recent years, with Asia and Africa emerging as the primary producers [1]. Due to its unique flavor profile and potential health benefits, palm sap is increasingly regarded as a sustainable alternative to traditional sweeteners [2]. It has been produced for centuries and remains a prevalent practice today. Specifically, in the Arab regions, date palm sap is a staple food and a major source of income for rural communities. Palm sap is typically collected in the morning and evening, then either stored or processed into sugar syrup, which is used as a sweetener in culinary preparations [3].

The increased awareness of the therapeutic benefits of palm sap, along with a growing market for natural and sustainable sugar substitutes, has fueled its production in recent years [4]. One of the main advantages of palm sap is its distinct flavor profile, similar to

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honey and maple syrup. Additionally, its low glycemic index and high caloric content make it an ideal option for managing type 2 diabetes and other conditions requiring a low-sugar diet [3]. Generally, fresh palm sap is alkaline, with a pH ranging from 6.5 to 8, which tends to decrease during the harvesting period [5]. The quality of palm sap is influenced by various factors, including harvesting techniques, processing conditions, palm variety, and sanitation practices [6]. Moreover, the chemical composition, nutritional content, surface properties, and foam stability of palm sap can vary based on the breed and sex of the palm trees. For instance, a notable difference was observed in the myo-inositol content between female and male date saps during collection [7]. Male date sap showed higher myoinositol levels due to tapping-induced stress, whereas female sap exhibited consistently low adsorption, hydrophobicity, and viscosity. Furthermore, the quality of palm sap depends on the collection time and the type of storage vessel. Neera collected in the morning using an aluminium container displayed a clearer colour, a sweeter taste, and a fragrant smell, along with fewer bacterial colonies, with a mean pH of 6.95 and a total soluble solids (TSS) value of 13.7 Brix [5].

Palm sap syrups, recognized for their natural antimicrobial and antioxidant properties, could be utilized commercially [8]. Beyond their inherent properties, this syrup also possesses homoeopathic properties [9]. In one previous study, the effect of palm sap on gastrointestinal transit (GIT) activity was examined in healthy adult rats, and it was shown that rats treated with palm sap exhibited stronger GIT activity [10]. Interestingly, date palm extracts are used in traditional Tunisian medicine for constipation treatment [10]. The healing properties of ’lagmi’ date palm sap were studied *in vivo* healing properties on mechanically wounded Wistar male rats, compared with the group of rats treated with CICAFLORA® and a control (untreated) group. The rats treated with ’lag’ sap experienced faster and more comprehensive healing, purportedly due to the anti-inflammatory compounds and antioxidant capacity of date sap [11]. Palm saps have also been used as a raw material for bioethanol production, a potential biofuel [12]. For instance, the sap from the Palmyra palm has been used to produce ethanol and biomass through fermentation with *Saccharomyces cerevisiae*. In batch cultures without aeration, the strains yielded 70g of ethanol and 6g of biomass per liter of sap containing 150g of sucrose. Conversely, aerobic growth resulted in biomass production of 0.5 g/g sucrose, with crude and true protein contents of 57 % and 52 %, respectively [13]. Another study, aimed at enhancing the productivity of honeybees (*Apis cerana*) by feeding them coconut sap, sugar palm sap, and pollen [14]. It was found that honeybees significantly increased their brood areas, honey production, and pollen collection. The honey yield generated by coconut and sugar palm saps in an area of 100 ha was found to be 1543 tons/year and 1150 tons/year, respectively [15].

Despite its numerous benefits, palm sap production faces several challenges. The fluctuation in the quality and consistency of palm sap is a major concern, as the quality can vary based on the species, climate, and harvesting and processing methods. This variability makes it difficult for producers to standardize their products and meet consumer expectations. Another significant challenge is the limited shelf-life of palm sap, which, due to auto-fermentation, can lead to deterioration in composition, rendering it unsuitable for consumption. Fresh, unfermented sap generally contains 3–10 % glucose, 10–20 mg/mL vitamin C, 4–8 mg/mL protein, and 0 % alcohol [16]. Detailed analysis of fresh and aged palm sap samples has reported changes in sap quality during storage, including alterations in alcohol content and microbial populations with simultaneous lactic and acetic acid formation [17]. Consequently, it is difficult to transport and distribute palm sap on a large scale while ensuring its quality and freshness at the point of use. Despite these challenges, the demand for palm sap is expected to rise globally in the coming years, driven by its nutraceutical and therapeutic values.

Thus, a critical review of palm sap is essential to explore the latest trends in its extraction techniques, quality profiles, fermentation chemistry, and preservation methods. This review aims to unlock the full potential of palm sap as a nutrient-rich and health-promoting resource, paving the way for innovative applications and sustainable use in various industries. Our systematic review provides a comprehensive examination of both conventional and advanced sap extraction techniques, addressing the challenges of production, including variability in quality and consistency, shelf life, and physicochemical analysis. Additionally, this review introduces the

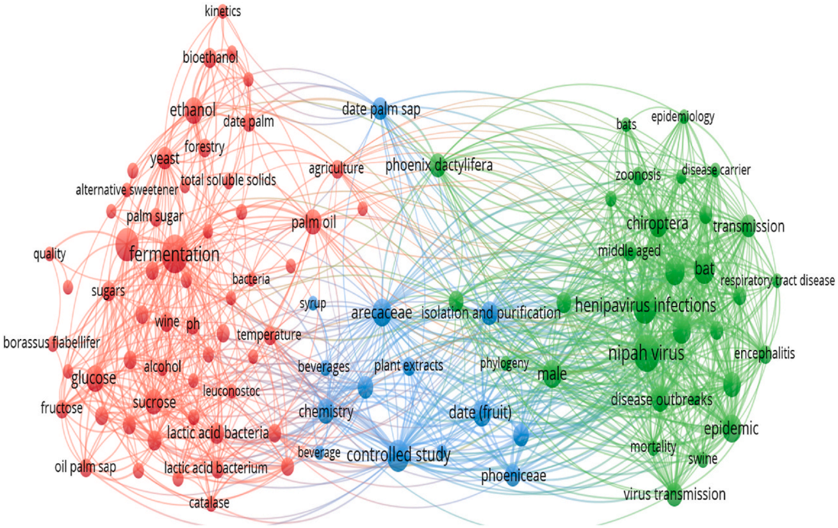

Fig. 1. Keyword mapping for palm sap.

innovative application of nanotechnology and advanced processing techniques in enhancing the shelf life of extracted sap by preventing fermentation. By integrating insights from various disciplines and highlighting cutting-edge technologies, this review not only synthesizes current knowledge but also sets the stage for future research and development in palm sap utilization.

2. Palm sap: a quick overview and bibliometric analysis

Palm sap is tapped from various palm species globally due to its rich nutritional profile and unique flavors. The data collection process was conducted by an extensive search through academic databases, such as Scopus, using the following keywords (("palm sap" OR "date Sap")) as demonstrated in the keywords mapping (Fig. 1).

Subsequently, the collected literature was thoroughly scrutinized by implementing the following four successive steps of a funnel technique, i.e. keywords-based selection, title-based selection, abstract-based selection and full-article-based selection. Based on the Scopus search engine, the number of articles published from 1960 to 2023 on sap and the institutions/organizations and countries/territories performing and supporting the sap-based research work is presented in Fig. 2a-c, respectively. It can be observed that from 2010 onwards, research on sap dramatically increased, while Indonesia, the United States and Bangladesh are among the three main countries leading sap-based research. Moreover, Fig. 2d presents the sap-based publications under specific subject areas such as agricultural and biological science, immunology and microbiology, biochemistry, genetics and molecular biology, environmental science, medicine, earth and planetary sciences, chemistry and chemical engineering etc. The coming sections discuss in detail the physicochemical characteristics of palm sap and its preservation technique.

2.1. *Key determinants of palm sap yield*

The extraction yield of date palm sap holds significant economic value for countries that cultivate date palms and is influenced by variety of factors. Environmental variables, such as temperature, rainfall, and humidity play pivotal roles in determining sap yield. A temperature range of 24–32 °C is considered ideal for extraction, with peak yields typically occurring in regions characterized by moderate rainfall and humidity levels [18,19]. Conversely, high temperatures, low rainfall, and low humidity can adversely impact sap yield. In addition, genetic factors such as tree variety and selection significantly affect yields. Certain varieties, like Deglet Nour, are known for their high sap output. Selecting the appropriate tree variety or genetically enhanced trees is crucial for achieving high yields. Management practices such as tapping frequency, tapping time, and tapping location, also influence date palm sap yield. Generally, tapping should not occur more than twice a day. Noticeably, tapping time and sample age also affect the sugar content of the sap. Sap collected in the morning has a higher sugar content than that collected in the afternoon, and fermented (aged) sap has lower total sugars [20]. Identifying the optimal tapping season is essential to maximize yield; sap harvested in spring usually has lower sugar

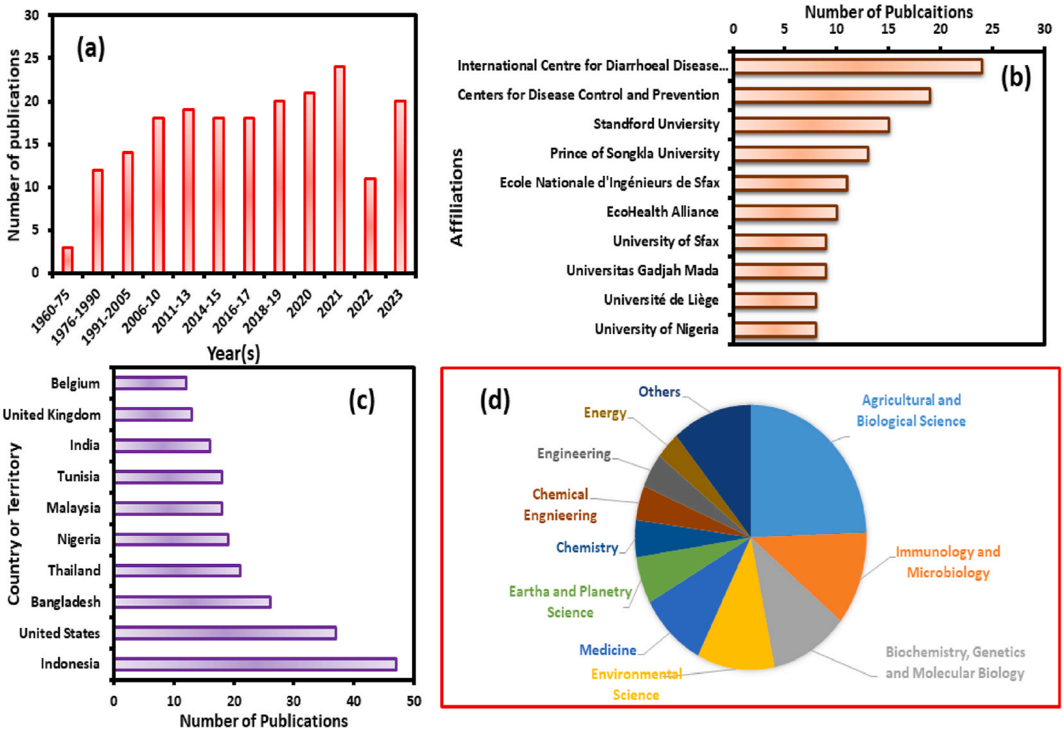

Fig. 2. Bibliometric analysis for palm sap based on the number of publications (a) from 1960 to 2023, based on (b) affiliations, (c) country/territory and (d) subject area.

levels and higher acidity than that collected in winter [21]. In addition, sap quality and productivity are affected by the age of the palm trees. The initial tapping age level (7–10 years) typically produces between 323 and 612 L/inflorescence, with a significant increase in the middle tapping age (10–20 years), which yields 570–2650 L/inflorescence. However, sap productivity declines in the final tapping phase (over 20 years), recording yields of 76–445 L per inflorescence [22]. Furthermore, tapping the same location repeatedly can damage the cambium layer and reduce sap yield. Hence, it is recommended to rotate the tapping locations to prevent tree damage. Yield declines during the fruiting stage and trees may cease sap production entirely during winter. Additionally, the microorganism population also has a detrimental effect on sap yield. An increase in bacteria and yeast populations throughout the tapping period has been reported. A reduction in palm sap yield has been observed when yeast or bacterial counts exceeded 10^8 per gram of tissue, underscoring the impact of microbial activity on sap production [23].

3. Physicochemical characteristics and qualitative analyses

3.1. Physical analysis

Key physical attributes such as color, viscosity, density, refractive index, odor, and flavor are crucial for assessing the quality of palm sap and its suitability for diverse applications. Physical characterization techniques include using pH meters to measure acidity, spectrophotometers for light absorption evaluation, and colorimetry for color analysis. Furthermore, flavor testing and odor analysis of palm sap help in evaluating the taste, aroma, and mouthfeel, which is essential for determining its quality and suitability for use in food and beverages. The sap generally has a sweet, nutty odor; deviations from this odor can indicate contamination or exposure to air or heat. Color analysis is one of the primary physical tests for determining the contamination or spoilage in the sap. For example, colorimetric analysis of 10 palm sap samples collected in southern Thailand showed that L*, a*, and b* values ranged between 61.49 and 87.53, 1.46–3.52, and 12.41–19.31, respectively [24]. Moreover, palm sap has been described in terms of viscosity and texture. Higher sap viscosity may indicate ageing or thermal damage, while lower viscosity indicates contamination or improper processing. An in-depth study of the physicochemical characteristics of processed and stored *Raphia hookeri* palm sap demonstrated that sap thermally processed at 75 °C for 45 min and preserved in green bottles retained the nutritional content and physicochemical characteristics for 24 months, as shown in Table 1 [25]. However, a similar analysis for the unpreserved sap and a detailed gas chromatography-mass spectroscopy (GC-MS) analysis for volatile organic constituents have not been reported.

3.2. Chemical composition of palm sap

3.2.1. Carbohydrates and total sugars

Fresh palm sap, harvested directly from the palm tree's trunk, is a sweet and nutrient-rich liquid. It contains a considerable concentration of carbohydrates and sugars, including sucrose, glucose, fructose, xylose, rhamnose, and galactose. The sugar profile of palm sap varies depending on factors such as geographical origin, seasonality, extraction methods, and the age of the sample [26]. A detailed comparative analysis of specific subdivisions of oil palm trunks reveals that sap extracted from different parts of the oil palm exhibit variations in sugar concentrations [27]. The natural fermentation process transforms fresh date palm sap into palm wine, characterized by a decrease in sugar levels and a concurrent increase in alcohol content. Typically, fermented sap contains 30–50 % sugar and approximately 2–8% alcohol by volume. Noticeably, fresh and fermented sap's physicochemical composition and nutritional contents differ significantly due to the natural fermentation process. Further research is needed to thoroughly investigate the mechanism involved in altering the nutritional value of these products.

3.2.2. Volatile and organic constituents

Uzochukwu et al. [28] reported a detailed procedure for analyzing the volatile constituents of fresh palm sap, palm wine, and palm wine spirits using gas chromatography. A total of 82 components were identified, including 47 esters, 9 alcohols, 5 acids, 6 carbonyls, 2 acetals, 4 terpenes, and 9 hydrocarbons. Specifically, the difference in aroma between palm sap and palm wine is attributed to the

Table 1

Shelf life studies of raw and preserved *R Hookeri* palm sap based on its physiochemical characteristics (with permission from Ref. [25]).

Day/Month	Color	Acidity (%) Acetic acid	pH	Relative density	Moisture (%)	Total solid (%)	Sucrose (%)	Protein (mg/100 ml)	Taste	Alcohol
Day 1 (raw sap)	Whitish	0.21	7	1.03	97.65	2.35	9	0.08	Sweet	0.5
1st Month	Whitish	0.22	6.99	1.04	97.60	2.40	8.5	0.07	Sweet	0.49
3rd Month	Whitish	0.20	7	1.03	97.65	2.35	8.7	0.08	Sweet	0.47
6th Month	Whitish	0.20	6.97	1.05	97.71	2.29	8.5	0.06	Sweet	0.49
9th Month	Whitish	0.22	7	1.05	97.65	2.35	8.8	0.07	Sweet	0.48
12th Month	Whitish	0.20	6.89	1.04	97.69	2.31	8.6	0.08	Sweet	0.46
15th Month	Whitish	0.21	6.9	1.06	97.65	2.35	8.7	0.08	Sweet	0.49
18th Month	Whitish	0.20	7	1.05	97.45	2.55	8.9	0.07	Sweet	0.48
21st Month	Whitish	0.22	6.99	1.03	97.60	2.40	8.6	0.08	Sweet	0.5
24th Month	Whitish	0.21	6.95	1.06	97.63	2.37	8.8	0.08	Sweet	0.49

presence of specific esters and alcohols present in the wine compared with the sap. The temperature and duration of heating significantly influence the composition and transformation of these volatile constituents in palm sap. Pyrazine and furanone were the main components detected by GC-MS analysis of heated-sap samples. Notably, furan derivatives formed at higher temperatures, specifically above 105 °C after 180 min [29].

Additionally, the quality of palm sap, in terms of flavor, taste, and acidity, is largely determined by its organic acid content. During fermentation, microorganisms like yeast and bacteria convert sap sugars into organic acids and ethanol. This process notably affects acids such as lactic, citric, and tartaric acids, enhancing the sourness and tanginess of palm wine. A 32 h storage study revealed changes in the concentrations of primary (lactic, acetic, ascorbic acids) and secondary (oxalic, citric, tartaric, malic, fumaric acids) organic acids in various palm sap/wine samples (Fig. 3) [17]. The highest lactic acid content was observed in a sap sample collected during the fourth week, while tartaric acid decreased during storage. The other acids initially increased from 8 to 24 h before declining in all samples within 32 h of storage period.

* 1st ds: first day sap; 1st ws: first week sap; 2nd ws: second week sap; 3rd ws: third week sap; 4th ws: fourth week sap.
* *Note: The data for Fig. 3 were extracted from the published literature [17] using the WebPlotDigitizer. While the standard error (SE) bars represent 5 % of the mean values for consistency and clarity in visual presentation.

3.2.3. *Proteins and free amino acids*

Protein and free amino acid content in fresh and fermented sap were analyzed by the Kjeldahl method [30]. The Deglet Nour palm sap contained 2.29 g protein per 100 g of ash (dry matter basis) [30]. However, the sap is highly sensitivity to temperature and time changes, which can lead to proteins and amino acids degradation [31]. Two-dimensional electrophoresis (2DE) revealed that a large proportion of the identified proteins belong to *Saccharomyces cerevisiae* yeast, which is involved in glycolysis [32]. Compared to fresh sap, fermented product contains an average of 0.5–1.5 % protein and a higher concentration of free amino acids. During the later stages of palm sap tapping (15–25 days), levels of gevotroline and essential amino acids decrease. This demonstrates that the sap obtained in the early stages of tapping is more nutritional than that collected later [33]. Ibegbulem et al. [34] studied the bioactive anti-polymerization effect of palm sap on the osmotic fragility of sickle cell anaemia (SCA) in red blood cells (RBCs). The results revealed that palm sap contained four antisickling amino acids, namely phenylalanine (4.20 ± 0.07 g/100 g protein), leucine (2.05 ± 0.07 g/100 g protein), arginine (3.22 ± 0.08 g/100 g protein), and valine (4.38 ± 0.09 g/100 g protein). It was claimed that *R. hookeri* sap has antipolymerization potential to reduce the osmotic lysis of SCA RBCs due to various bioactive agents. In summary, the protein and amino acid content in palm sap are influenced by temperature and time. Natural fermentation increases these constituents, but elevated temperatures can degrade them, reducing the nutritional value of the sap. Further research is needed to identify the optimal conditions for preserving protein and amino acid content in fresh date palm sap.

3.2.4. *Total phenols and flavonoids*

The total phenolics and flavonoids in palm sap significantly contribute to its nutritional properties. These constituents can be quantified calorimetrically at 750 nm using the Folin-Ciocalteau reagent method [30]. Flavonoids, a subgroup of phenolic compounds,

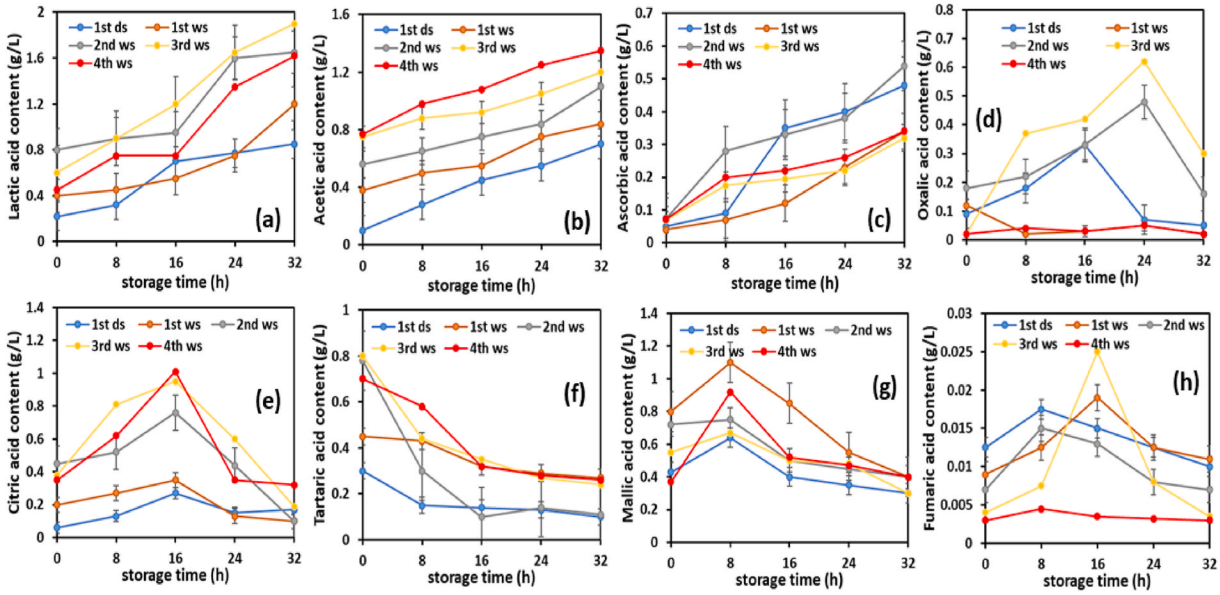

Fig. 3. Changes in the content of organic acids during the 32 h storage of different palm wine samples. (a) Lactic acid, (b) acetic acid, (c) ascorbic acid, (d) oxalic acid, (e) citric acid, (f) tartaric acid, (g) maleic acid, and (h) fumaric acid (replotted with permission from Ref. [17]).

possess high antioxidant and anti-inflammatory properties. The health benefits associated with flavonoids include enhanced cardiovascular health, reduced cancer risk, and improved cognitive function. A study on Deglet Nour palm sap showed that the sap contained 7.64 mg gallic acid equivalent/100 mL of the sample. Accordingly, the sap exhibited antioxidant activity with 147.61–224.55 mg of ferulic acid equivalents/kg fresh weight and 47.64 % inhibition of DPPH radicals [30]. Recently, date palm sap was investigated for its potential protective effect against bleomycin (BLM)-induced lung fibrosis in rats [35]. Following BLM treatment, increases in lipid peroxidation (MDA) and superoxide dismutase (SOD) levels were observed, alongside a decrease in catalase (CAT) activity. BLM also induced inflammation and the accumulation of collagen bundles in the lungs. Interestingly, treatment with date sap improved the morphological lesions, reducing hydroxyproline levels and normalizing MDA, SOD, and CAT levels in rats. The rich phenolic and vitamin content in date sap provides protection against BLM-induced murine lung fibrosis and could be effective in treating lung cancer [35]. Further study is essential to identify the optimal conditions for preserving total flavonoids and phenols in fresh date palm sap.

3.2.5. Vitamins

Palm sap is also rich in a variety of vitamins and minerals, including vitamins C (ascorbic acid), B1 (thiamin), B2 (riboflavin), B3 (niacin), B5 (pantothenic acid), and B6 (pyridoxine) [36]. Fresh palm sap contains approximately 9.74 % (w/v) of vitamin C, which decreased to 7.56 % (w/v) in samples aged for four days [37]. Noticeably, palm sap has the highest concentration of niacin which is 31.7 mg/kg, followed by ascorbic acid (5.00 mg/kg), cyanobalamin (5.00 mg/kg), pyridoxine (0.40 mg/kg), thiamine (0.20 mg/kg), riboflavin (0.10 mg/kg), and folic acid (0.10 mg/kg) [9]. The concentration of these vitamins can vary depending on factors such as species, collection time, and storage. Therefore, it is essential to consider temperature and storage duration to preserve the vitamin content in palm sap.

3.3. Mineralogical studies

In terms of mineral content, palm sap contains a range of essential minerals vital for maintaining good health. It is particularly high in potassium, which helps in regulating heart function and muscle contractions. A 100 mL portion of fresh date sap comprises approximately 220 mg and 26 mg of potassium and calcium, accounting for about 5 % and 2 % of the suggested daily intake, respectively. In addition to potassium and calcium, fresh date sap is a significant source of magnesium, phosphorus, and iron and includes trace minerals, including manganese, copper, and zinc. The mineral composition per 100 g of dry matter in sap includes potassium (522.92 ± 9.67), magnesium (330 ± 6.57), phosphorous (41.49 ± 3.11), calcium (14.67 ± 0.3), sodium (12.00 ± 0.6), iron (1.19 ± 0.26), copper (0.12 ± 0.03), and zinc (0.23 ± 0.09) [30,38]. Another study identified four macro-minerals in palm tree samples, such as K (451 mg/100 g), Na (59.7 mg/100 g), Mg (17.4 mg/100 g), and Ca (2.43 mg/100 g), and five trace elements, namely Fe, Cu, Zn, Ni, and Mn, each with respective mean concentrations of 1.16, 0.18, 0.22, 0.06, and 0.05 mg/kg, respectively, were also identified [9]. Low temperatures during processing are recommended to preserve these minerals, as they help mitigate mineral loss over time.

4. Palm sap extraction techniques

There are several techniques for palm sap extraction, namely the conventional approach, tapping technique, and cutting method. Any collection process must prioritize sustainability by preserving trees and promoting unhindered growth. Over-tapping or tapping at inappropriate sites can seriously harm a palm tree, causing damage and decreasing productivity. Therefore, following proper tapping techniques and switching locations regularly is essential, allowing the tree sufficient time to recover and regrow. The following section briefly describes different sap extraction processes along with their advantages and shortcomings.

4.1. Conventional approach

Traditionally, palm sap is extracted by cutting down the entire palm tree. It has been used for centuries and still practiced in some remote rural areas. In this method, containers such as mud pots, bamboo tubes, and plastic bottles are either hung from tree's trunk or placed near its base. Due to gravity, the sap flows into the containers and is periodically collected. Traditional methods are simple, inexpensive, and do not require specialized equipment, allowing for the collection of large quantities of sap, which can be stored and used later. However, the main disadvantages of this method are its inefficiency and the possibility of sap contamination, and the destruction of the palm tree, which eliminates future harvests and income opportunities. According to a recent study, uncovered pots caused honeybee mortality, suggesting that containers should be covered to prevent sap contamination and deter insects [39]. Moreover, this practice contributes to deforestation and the loss of biodiversity, rendering it unsustainable.

4.2. Mechanical pressing

This technique is based on enhancing the surface area by shredding the palm tree trunk, thereby boosting sap extraction efficiency. Pretreatment approaches, such as adjusting shredding size and duration, can significantly boost the extraction yields. It has been reported that using a smaller shredding size and extended processing time results in higher sap output. Although mechanical pressing can enhance efficiency, it is important to note that this method also destroys the palm tree, making it less advisable [40]. Fig. 4 illustrates the mechanical pretreatment of palm oil trunks to obtain oil palm trunk sap.

4.3. Tapping technique

Palm tree sap can be harvested by tapping the tree's trunk and collecting the sap as it drips out of the trunk. This involves inserting a specific instrument, known as a "tap", into the trunk, allowing the sap to flow into a container or vessel attached to it. The containers are frequently replaced to collect the sap, as shown in Fig. 5. The tapping method is more sustainable than the conventional techniques because it does not involve cutting down the tree, thus allowing for continuous sap production over the years. This approach provides residents with long-term revenue and helps preserve the trees. However, the need for specialized equipment and skilled labor makes this method relatively expensive. In addition, its time-consuming nature and limited daily sap production capacity render it relatively inefficient.

4.4. Cutting method

This method involves cutting a portion of the palm tree at the top, allowing sap to flow freely into containers placed below the tree. This method is more efficient than the conventional approach as it yields a larger amount of sap without destroying the entire palm tree. A variety of cuts, namely forehead-shaped cut, tongue-shaped cut, forehead-shaped cut with sap collection pot, and tongue-shaped cut with sap collection pot, are used to collect sap from palm trees [41]. Typically, sap collection spans 2–3 days after each scraping, followed by a 3–5-day resting period before the next round of scraping. The cutting technique is relatively sustainable as the cut portion of the tree will eventually grow back, enabling continued sap production. To prevent Niphas viras spillovers, the cut area, sap stream, tap, and collection container are often covered with materials such as bamboo, dhoincha, jute sticks, or polyethylene skirts serves [42]. However, compared to tapping, the cutting technique is more environmentally taxing as it involves more intensive tree cutting and higher energy consumption during sap harvest.

5. Fermentation of the palm sap

A natural fermentation occurs when yeast and other microorganisms come into contact with the sugar in palm sap, producing alcohol and carbon dioxide. This process usually begins within hours of tapping the sap and lasts for a few days to a week, influenced by factors such as temperature, pH, and sugar content. Fermentation can also be initiated using kefir grains or inocula of *Saccharomyces cerevisiae* as starters to produce kefir-like beverages and bioethanol, respectively [43]. It was observed that the yeasts and bacteria inherently present in the palm sap expedite the natural fermentation process. Interestingly, palm sap fermentation is also a potential source of lactic acid bacteria (LAB), a commonly used probiotic in foods, exhibiting antimicrobial, immune-stimulating, and anticancer properties. The alcohol content in the fermented sap proliferates over time, leading to the production of alcohol such as palm wine or toddy. Preferentially, palm sap contained 32.3 % bioethanol, which increased to 75.6 % after 24 h. During this time, there is an increase in lactate, acetate, propionate, and succinate content, whereas the citrate content decreases in comparison with fresh sap, as shown in Fig. 6a–d. It is also reported that the glucose and fructose concentrations within palm sap rise from 10 to 16 g/L and 7–13 g/L, respectively, during a 16 h due to the action of yeasts in kefir grains on sucrose (Fig. 6e–g) [43]. In addition, significant changes in the microbial populations were observed as fermentation progressed. Typically, the pH of the sap decreases due to lactic acid production, which suppresses yeast growth and allows LAB to dominate. The consistent presence of certain species in palm sap might result from their dominance or susceptibility to persist despite being washed out from palm tap holes. In other studies, it was reported that the main microbiota recovered in the fermented sap samples were yeasts, LAB, acetic acid bacteria, aerobic mesophilic bacteria and total coliforms [44].

Enzymes also play a crucial role in breaking complex sugars into simpler compounds that can be fermented. Invertase, the most important enzyme during palm sap fermentation, converts sucrose into glucose and fructose. In addition to invertase, other enzymes,

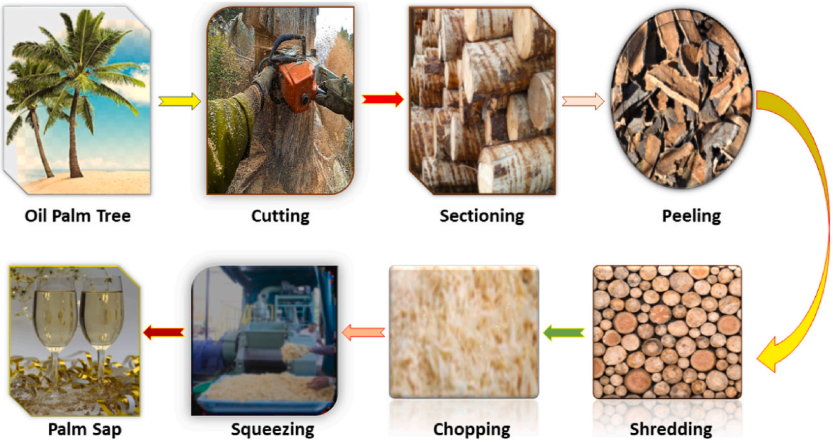

Fig. 4. Details of the mechanical pretreatment of palm oil trunks to obtain oil palm trunk sap.

Fig. 5. The indigenous processes of palm sap tapping practiced in Côte d'Ivoire for palm wine production from ron palm (*Borassus aethiopum*) (A) and oil palm (*Elaeis guineensis*) (B). Perforation of the apical meristem of the tree trunk is in practice for sap tapping from the ron palm, whereas the oil palm tree is uprooted before tapping (with the permission from Ref. [33]).

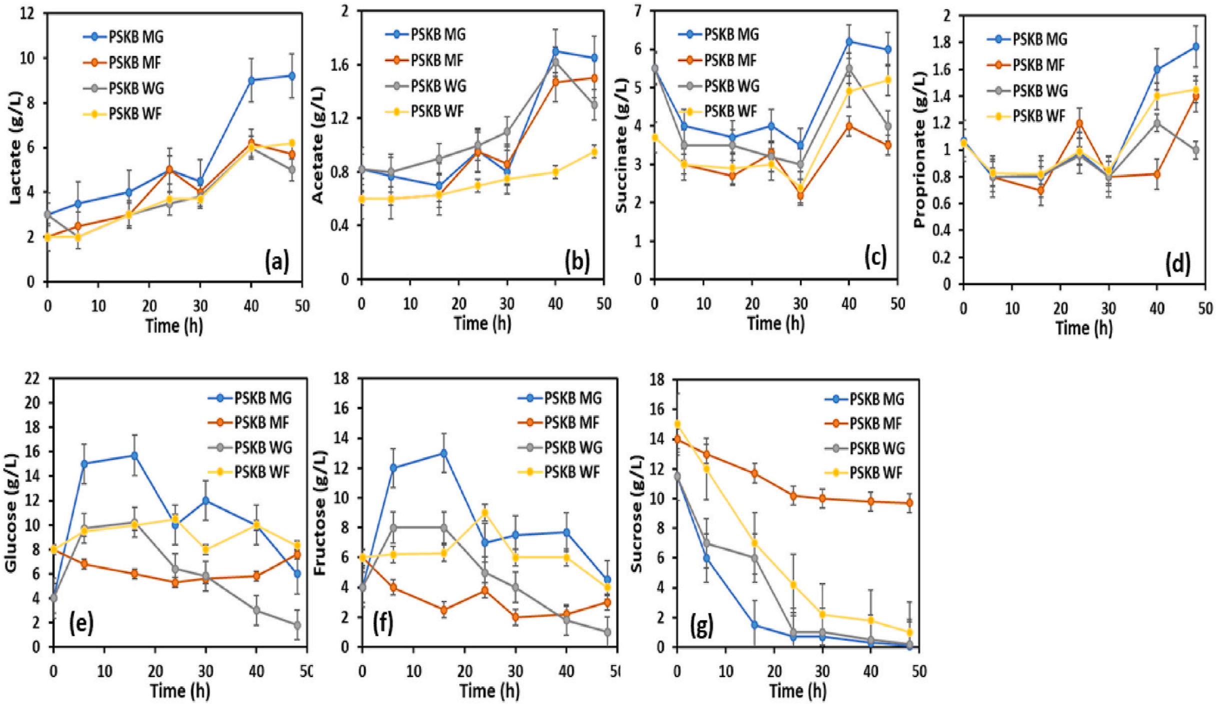

Fig. 6. Kinetics of (a–d) organic acids (a) lactate, (b) acetate, (c) succinate, (d) propionate, and (e–g) individual sugar content (e) glucose, (f) fructose, and (g) sucrose during palm sap fermentation with kefir grains and ferments (replotted with permission from Ref. [43]).
PSKB MG: palm sap-based kefir beverage fermented using milk grains; PSKB MF: palm sap-based kefir beverage fermented using milk ferment; PSKB WG: palm sap-based kefir beverage fermented using water grains; PSKB WF: palm sap-based kefir beverage fermented using water ferment.
**Note: The data for Fig. 6 were extracted from the published literature [43] using the WebPlotDigitizer. While the standard error (SE) bars represent 5 % of the mean values for consistency and clarity in visual presentation.

such as amylase and proteases, aid in degrading carbohydrates and proteins. These enzymes are typically produced by yeast and LCB during fermentation. Additionally, unhygienic practices during the production and storage of fermented palm sap can lead to contamination of the beverage with bacteria and other harmful microorganisms, posing a risk to human health. It is important to follow best practices in palm sap fermentation to minimize these adverse effects, including proper hygiene, the use of clean containers, and proper disposal of waste.

Table 2

Changes in the physicochemical characteristics, microbial loads, and individual sugar content of pasteurized palm sap during storage (with permission from Ref. [47]).

Parameters	Nisin concentration (IU/mL)	Storage times (week)					
		0	2	4	6	8	10
Changes in the Physicochemical Properties							
pH	0	6.6	5.8	4.5	3.8	3.6	3.5
	10	6.2	6.0	5.7	5.2	4.5	4.0
	20	6.0	6.0	5.9	5.8	5.4	4.8
	30	5.8	5.8	5.8	5.7	5.7	5.6
	40	5.6	5.6	5.6	5.6	5.5	5.5
Total acidity (%)	0	0.038	0.045	0.060	0.090	0.180	0.290
	10	0.040	0.044	0.048	0.055	0.100	0.150
	20	0.042	0.042	0.048	0.048	0.050	0.104
	30	0.044	0.044	0.044	0.047	0.050	0.055
	40	0.046	0.046	0.046	0.050	0.050	0.055
Residual PPO activity (%)	0	55.23	49.57	36.42	9.12	5.78	3.21
	10	52.25	46.21	40.14	30.63	22.34	10.65
	20	48.63	43.14	35.75	60.62	24.11	13.36
	30	46.21	40.63	35.21	60.62	27.52	24.21
	40	42.75	36.25	35.51	28.22	25.14	23.45
Invertase activity (unit/min/g)	0	24.14	22.63	19.98	21.36	24.96	28.14
	10	24.53	22.96	17.93	16.32	18.96	22.68
	20	23.06	21.36	19.52	18.69	17.98	20.36
	30	24.68	22.12	18.52	17.22	16.93	15.56
	40	24.42	22.28	18.84	16.23	16.21	15.24
Changes in Microbial Loads							
TVC (log cfu/mL)	0	1.65	2.28	3.04	4.35	5.71	6.85
	10	nd	1.75	2.19	2.65	3.33	4.72
	20	nd	nd	1.81	2.18	2.67	3.81
	30	nd	nd	nd	nd	2.18	2.67
	40	nd	nd	nd	nd	2.09	2.68
M&Y (log cfu/mL)	0	nd	1.75	2.54	3.49	5.39	8.17
	10	nd	nd	1.61	1.93	2.49	4.73
	20	nd	nd	nd	1.65	1.96	3.63
	30	nd	nd	nd	nd	1.63	1.98
	40	nd	nd	nd	nd	1.72	1.95
LAB (log cfu/mL)	0	1.54	1.79	2.59	3.33	4.55	5.71
	10	nd	nd	2.21	2.63	3.11	4.54
	20	nd	nd	nd	2.27	2.65	3.68
	30	nd	nd	nd	nd	2.17	2.66
	40	nd	nd	nd	nd	2.13	2.62
Changes in the Sugar Content							
Sucrose content (%)	0	13.50	12.46	10.05	6.23	3.12	1.04
	10	13.14	12.80	10.52	7.40	4.23	2.63
	20	12.84	12.02	10.53	8.79	6.53	3.79
	30	11.50	10.20	9.50	8.52	7.34	6.89
	40	11.04	10.43	9.64	8.21	7.38	6.55
Glucose content (%)	0	1.93	2.15	2.89	3.25	4.84	5.87
	10	1.89	1.95	2.46	2.95	3.83	4.61
	20	1.97	1.99	2.23	2.39	3.64	5.64
	30	1.94	1.98	2.31	2.46	3.55	4.25
	40	1.86	1.98	2.35	2.48	2.50	4.40
Fructose content (%)	0	1.75	2.03	2.63	3.14	4.75	5.72
	10	1.76	1.89	2.35	3.05	3.62	4.51
	20	1.70	1.92	2.21	2.43	3.62	5.51
	30	1.79	1.98	2.26	2.41	3.24	4.20
	40	1.72	1.89	2.25	2.43	2.51	4.32

TVC: Total viable count, LAB: Lactic acid bacteria, M&Y: Mold and yeast, nd: not detected.

6. Palm sap preservation techniques

6.1. Thermal and chemical treatment

Palm sap is pasteurized at high temperatures to deactivate harmful microorganisms and extend its shelf life. Several methods are available for pastuerization, including hot water bath, ultra-high temperature treatment, boiling, and steam methods. The hot water bath technique involves heating sap to temperatures of 60–65 °C for 30–60 min in a large container, effectively inactivating the harmful microorganisms. In the ultra-high temperature treatment, the sap undergoes rapid heating at 135–140 °C for 2–5 s, followed by swift cooling to avert excessive cooking. The boiling technique entails eradicating harmful microorganisms by subjecting the sap to 100 °C for 10 min. This simple method can be conducted at home, though it may impart a cooked flavor to the sap. The steaming method involves heating the sap for 30–60 min at 80–85 °C, followed by rapid cooling to prevent overcooking. It is similar to hot water bath pasteurization, however, provides more uniform heating than the hot water bath and reduces the risk of overcooking.

Baliga and Ivy [45] reported that palm sap tapped from coconut and date palm trees can be effectively pasteurized and bottled at 170–175 °F using sodium benzoate. They found that aerating the sap or adding a small amount of citric or malic acid with sodium benzoate enhanced its resistance to fermentation. In another study, sodium metabisulphite, diethylpyrocarbonate (DEPC), and sorbic acid were tested as preserving agents to inhibit several yeasts and bacteria. Among them, sorbic acid was the most suitable preservative agent because DEPC has a pungent smell, whereas sodium metabisulphite is not recommended for human consumption above 0.35 mg/kg [46]. Naknean [47] reported the addition of different nisin concentrations to pasteurized palm sap to improve its quality and safety. Table 2 llustrates that nisin addition preserved the sucrose, polyphenol content, DPPH radical scavenging activity, and reduced browning during storage. It is typically measured in International Units (IU) per milliliter (mL). The results revealed that the addition of nisin minimized the loss of sucrose, polyphenol content, the DPPH radical scavenging activity, and browning intensity increment during storage. Combining pasteurization with nisin (30 IU/mL) and low-temperature storage extended the shelf life of palm sap to 10 weeks, compared to the control sample, which fermented within two weeks. Thus, a combined chemical and thermal treatment approach is recommended to preserve palm sap. In addition, chitosan inclusion (at a concentration of 0.50 g/L) in pasteurized sap can prolong its shelf life for at least six weeks while reducing the microbial load below standard levels. However, a higher chitosan concentration (1 g/L) led to increased sedimentation and bitterness, making the sap less palatable [48]. Additionally, sap preserved with gum-lack tree bark has higher total soluble solids and reducing sugars than boiled sap [49]. A natural preservative derived from jackfruit wood was also tested for oil palm sap preservation [50]. In another interesting study, natural preservatives extracted from chengal wood chips, mangosteen rind, and guava leaves containing phytoconstituents that exhibited antimicrobial activity were employed [51]. An antimicrobial study demonstrated that a water-based mangosteen rind extract effectively inhibited *E. coli* growth. Regardless of the method used, monitoring and controlling sap temperature during pasteurization is imperative. It is important to note that pasteurization does not ensure complete sterilization, and improper handling and storage can still lead to sap contamination.

6.2. Electro-thermal process

Ohmic heating, or electric field-based extraction and preservation, is an emerging approach in the food industry [52]. Electro-thermal pasteurization, which involves electrically heating the sap to 70 °C for a specified period to kill bacteria and other microorganisms, has been studied for maple syrup production [53]. This method provides the advantage of precise control, ensuring uniform and reproducible outcomes. Electrothermal pasteurization could be a reliable technique for pasteurizing sap in a controlled and consistent manner. However, it is crucial to address potential limitations, such as variation in flavor and color, for the commercial implementation.

6.3. Freezing

Freezing is another method used for palm sap preservation, where the sap is subjected to temperatures below its freezing point for a designated duration, effectively eradicating bacteria and other microorganisms [54]. It is then thawed and heated back to its original temperature at the point of use for further processing. The freezing method offers the advantage of being a relatively simple and low-tech process that does not require specialized equipment or excessive energy consumption [55]. The low temperature of the process prevents the caramelization of sugar compounds, thereby preserving the product's flavor and color. However, freezing has several limitations, including its time-consuming, particularly if the sap is maintained at freezing temperatures for an extended period. In addition, the formation of ice crystals during freezing can detrimentally impact the sap quality.

6.4. UV treatment

UV radiation is a highly efficient approach for rapidly eliminating bacteria and microorganisms, making it one of the most effective methods for sap pasteurization [56]. This process does not impart any influence on the flavor, color, or texture of the sap, establishing it as a suitable approach for maintaining the final product quality. Thus, UV light pasteurization method can be highly effective in providing rapid and efficient sap preservation without compromising the quality. However, the process does have some limitations, including the potential for uneven UV exposure and the demand for specialized equipment, UV light sources, and high energy costs [57]. Further research is needed to thoroughly investigate the mechanism involved in UV-based sap preservation and overcome the challenges of implementing this technique on a large scale.

6.5. *Ultrasonication*

Recently, ultrasonic technology has been extensively studied for its use in food processing [58]. Numerous studies have demonstrated that ultrasonic treatment effectively reduces the number of bacterial colonies in palm sap, including *Escherichia coli*, *Staphylococcus aureus*, and *Bacillus cereus* [59,60]. This bacterial reduction is attributed to ultrasonic waves' mechanical agitation and thermal energy. Notably, this treatment preserves the palm sap's flavor and aroma, which are important product quality. Despite these promising results, further studies are necessary to evaluate the long-term safety and quality of ultrasonically pasteurized palm sap, as well as its environmental impacts.

6.6. *Ozone treatment*

The application of ozone treatment is a promising avenue in the preservation of palm sap, offering a novel approach to enhance its shelf life and safety. Ozone, a highly reactive gas, has proven effective in eradicating various microorganisms such as bacteria, viruses, and yeasts [61]. Its adoption in palm sap treatment is growing due to its ability to improve both the safety and quality of the product. Notably, ozone treatment is highly effective against common pathogenic bacteria prevalent in raw palm sap, including *Staphylococcus aureus* and *Escherichia coli*. One of the key benefits of this method is that it can be conducted at lower temperatures, mitigating the risk of thermal degradation and helps maintain the sap's desirable aroma and flavor [62]. Compared to the traditional thermal pasteurization, ozone treatment is fast and efficient, with treatment times ranging from a few minutes to an hour. However, due to its high reactivity, ozone can damage sap components, including lipids and proteins, potentially compromising the sap quality. Additionally, this treatment requires specialized equipment and technical expertise.

6.7. *Membrane filtration*

Membrane filtration, a physical separation technique utilizing a semipermeable membrane, effectively separates particles based on size and charge. Several studies have focused on this method's impact on palm sap preservation. For instance, a study by Makhlouf-Gafsi et al. [63], employed ultrafiltration to investigate its effects on the physicochemical, rheological, microstructure, and thermal properties of syrups from male and female date palm sap. The ultrafiltration process significantly altered the syrup's composition, notably reducing the sucrose content and increasing the reduced sugars. This change led to less crystallization in syrup made from filtered sap than that made directly from raw palm sap. Microscopic observations with polar light at various temperatures (10, 20, 30, 40, and 50 °C) confirmed a reduction in crystal size, particularly at higher temperatures [63]. Membrane filtration, thus shows promise for preserving palm sap by modifying its composition and reducing undesirable crystallization phenomena. However, further comprehensive studies are needed to elucidate the long-term effects of membrane filtration on the sensory attributes, nutritional content, and overall quality of the preserved palm sap.

6.8. *Pulsed electric field*

Pulsed electric field (PEF) is a non-thermal processing technique that uses high-intensity electric fields to eradicate bacteria from food and beverage items, including palm sap [64,65]. The technology generates electrical fields that penetrate the bacterial cell membranes, effectively rendering them dormant and idle. PEF offers a practical and efficient alternative to conventional thermal pasteurization, demonstrating its ability to deactivate bacteria and other microorganisms in palm sap, including strains such as *E. coli* and *S. aureus*. This method is particularly effective against heat-resistant microorganisms, which often pose a challenge in traditional pasteurization processes. PEF's low-temperature operation helps to minimize the risk of sap degradation and preserves essential quality attributes, like taste and aroma. Moreover, PEF is a faster and more efficient process than traditional thermal pasteurization, which can require several hours. While PEF is a promising option for pasteurizing palm sap, a more comprehensive and extended assessment is necessary to determine the long-term safety and quality of PEF-treated palm sap.

6.9. *Cold plasma processing*

Cold plasma treatment is an innovative non-thermal technique that inactivates microorganisms and extend the shelf life of food products, by generating plasma gas; a highly reactive mixture of ions, electrons, and free radicals that can destroy microorganisms and break down organic compounds. In a study by Ding et al. [66], cold plasma treatment was used to inactivate spoilage-causing microorganisms in apple juice. The results showed that the treatment significantly reduced the total bacterial count, yeasts, and molds, thereby increasing the juice's shelf life. Similarly, Surowsky et al. [67] investigated the effect of cold plasma treatment on enzymatic and non-enzymatic browning reactions in date palm sap. The results showed that the treatment significantly reduced the activity of polyphenol oxidase, an enzyme responsible for browning reactions, thereby preventing color changes and extending the shelf life of the date palm sap. Furthermore, Hoque et al. [68] examined the synergistic effect of cold plasma treatment and packaging on date palm sap preservation. Applying cold plasma followed by packaging in high-density polyethylene containers substantially lowered bacterial levels and further extended the sap's shelf life. Given its efficacy and chemical-free approach, cold plasma treatment offers a promising method for preserving palm sap.

6.10. Supercritical CO_2 processing

The supercritical CO_2 process is a non-thermal technique used to extract and preserve bioactive compounds from various sources, including plants, fruits, and vegetables. Briefly, at a temperature above 31 °C and a pressure over 73.8 bar, CO_2 becomes supercritical and manifests its unique solvent properties. Research has shown that supercritical CO_2 processing not only preserves bioactive compounds but also reduces microbial load and extends the shelf life [69]. This method offers a non-thermal, chemical-free, and environmentally friendly approach to maintaining the nutritional and sensory quality of palm sap. Rawson et al. [70] thoroughly reviewed supercritical CO_2's applications in extracting, processing and preserving palm sap. The results indicated that the treatment substantially enhanced the antioxidant activity of date palm sap, consequently increasing its shelf life. Furthermore, CO_2 treatment greatly decreased the microbial load and increased the shelf life of date palm sap. Given these benefits, supercritical CO_2 treatment is emerging as promising, substantial preservation method for palm sap, leveraging its dual solvent and antiseptic properties. However, a detailed analysis is required to optimize the operating conditions and examine the large-scale implementation of this technology in the food sector.

7. Role of nanotechnology and anti-fermenting agents in the palm sap industry

Nanotechnology has revolutionized various aspects of the food industry, including palm sap extraction and processing, by enhancing product safety, quality, and shelf life. This innovative technology involves the application of nanoparticles such as silver, copper, zinc, and calcium, as well as biocompatible materials like cellulose and chitosan, which are renowned for their antimicrobial properties. For example, nanosilver and other metal-based nanoparticles have been investigated for their potential to improve the quality and safety of palm sap [71]. Additionally, the industry employs anti-fermenting and clarifying agents such as sodium benzoate, bentonite, polyvinylpolypyrrolidone, gelatin, chitosan, and potassium sorbate to inhibit the growth of yeasts and bacteria that cause spoilage and fermentation [72]. Research by Naknean et al. demonstrated that bentonite effectively reduces enzyme activities responsible for spoilage, while polyvinylpolypyrrolidone and gelatin excel in removing polyphenols, significantly extending the shelf life of pasteurized palm sap to 25 days [72,73]. In terms of pasteurization, nanoparticles such as silver, zinc oxide, chitosan, calcium oxide, and titanium dioxide have been synthesized using methods like co-precipitation, sol-gel, and green synthesis. These nanoparticles exhibit strong antibacterial, antifungal, and antiviral properties, making them highly effective against pathogens such as *E. coli* and *S. aureus*. For example, the addition of silver nanoparticles to Murcott mandarin fruit during cold storage significantly reduced bacterial counts, thereby enhancing the juice's shelf life and quality [74]. Similarly, zinc oxide nanoparticles effectively reduced bacterial populations in palm sap [75].

Titanium dioxide (TiO_2) is a photocatalyst with robust antibacterial capabilities and is commonly used for the degradation of organic pollutants and disinfection of water and air [76]. TiO_2 nanoparticles have been reported to exhibit antibacterial properties against different pathogenic microorganisms in fruit juice and clarification of pomegranate juice [77]. However, photocatalytic activities can be limited under certain conditions because they depend on light. Chitosan is a biopolymer derived from a naturally occurring polymer (chitin) present in the exoskeleton of invertebrates such as shrimp and crabs [78]. Chitosan nanoparticles (CSNPs) exhibit potent antimicrobial properties against a wide range of microbes, including bacteria, fungi, and yeasts. CSNPs can be synthesized using various techniques, such as electrospraying, emulsion cross-linking, and ionic gelation. Incorporating CSNPs into palm sap has been shown to effectively suppress bacterial strains, thereby significantly extending the shelf life of the beverage [48]. Nanocellulose is another renewable nanomaterial derived from plant materials and has been extensively used in various applications, such as food packaging, biomedical applications, and environmental remediation. Nanocellulose can be prepared by various methods, namely acid hydrolysis, enzymatic hydrolysis, and mechanical treatment [79]. It exhibits antibacterial effects against numerous microorganisms, enhancing the shelf life and quality of fruit juice and palm sap.

Recently, nanostructures have been extensively studied for food applications because of their special mechanical, electrical, and thermal characteristics [80]. Various techniques, including chemical vapor deposition, arc discharge, and laser ablation, can be used to produce these nanostructures. These nanomaterials exhibit strong antibacterial action against different microbial communities in fruit juice and palm sap, prolonging the shelf life of the drinks [80]. Although nanotechnology and anti-fermentation agents offer substantial benefits in enhancing the safety and quality of palm sap, there are concerns about the environmental and health impacts of nanomaterials like silver nanoparticles. In summary, the application of nanotechnology and anti-fermenting agents holds substantial potential to revolutionize the palm sap sector by enhancing preservation and extending shelf life. Nonetheless, further research is crucial to ascertain the most effective and reliable methodologies, as well as to thoroughly evaluate any potential risks and safety concerns associated with their use in palm sap preservation.

8. Challenges and outlooks for the palm sap industry

Several challenges affect the efficiency, profitability, and sustainability of palm sap extraction and processing. One significant challenge is the seasonal variability, as production rates are influenced by factors such as temperature, rainfall, and tree age, making it difficult for producers to predict available quantities for processing. Another way to maintain the quality of palm sap during extraction, transportation, and processing poses challenges. Inadequate handling and storage can lead to spoilage, contamination, and reduced product quality, resulting in lower consumer demand and profitability. Another concern is the lack of standardization and quality control in the palm sap industry. Sap is often collected by small-scale farmers using traditional methods, culminating in quality and quantity variations. Sometimes, the sap is processed and packaged under unhygienic conditions, causing contamination and spoilage.

These issues eroded consumer confidence, reducing demand and market viability. Environmental concerns, including deforestation, soil erosion, and biodiversity loss resulting from over-tapping and habitat destruction, pose significant threats to the industry's sustainability. Furthermore, small-scale farmers often encounter technological and resource limitations that impede the adoption of sustainable practices.

The palm sap extraction and processing industry also face challenges such as labor costs, low efficiency, and limited shelf life. Despite these challenges, the palm sap industry has growth potential due to the increasing demand for natural and sustainable sweeteners. Advanced preservation methods have emerged, showcasing their proficiency in safeguarding the sap by eradicating foodborne pathogens while ensuring the retention of its quality attributes. The industry could adopt these advanced processing and preservation techniques to extend sap shelf life and reduced microbial growth. Noticeably, nanoparticles have shown promise in reducing foodborne pathogens, although further research is needed to determine the optimal conditions for the use of nanoparticles in palm sap preservation.

Moreover, using best practices for harvesting, processing, and packaging palm sap can address quality control issues. It is also possible for the industry to establish quality control programs and certifications, which can improve consumer confidence in the products. Technological advancements, such as automation and robotics can reduce labor costs, improve efficiency, and enhance product quality. Palm sap collection can be simplified with automated systems, and palm sap quality can be monitored regularly with sensors. In this regard, integrating AI and machine learning offers the potential to automate palm sap collection, enhancing efficiency, lowering expenses, and enabling accurate demand prediction. This, in turn, facilitates improved production planning and resource management. Additionally, AI can be used to monitor trees and their health, providing early warnings for any potential issues. The development of such technological advancements can result in increased production and higher quality products, resulting in increased industrial revenues. Furthermore, diversifying products and applications are being developed by palm sap producers, such as beverage and food ingredients, personal care products, and biofuels from crude sap. In addition to mitigating the effects of seasonal variability, this diversification can ensure the industry's long-term viability. Remarkably, the toxicity of crude sap obtained from the *Nypa fruticans* Wurmb plant was also studied in Sprague–Dawley rats. The results revealed that sap had low toxicity, with no lethal effects reported in rats, even at the highest tested dose. Interestingly, blood glucose levels decreased significantly in the treated groups at higher sap concentrations (>300 mg/kg) [81]. Hence, fresh sap is not toxic; however, further investigation is required before palm sap can be used as a medicinal or nutritional supplement for humans. In addition, palm sap could serve as an essential ingredient in resolving challenges in the food industry. For instance, chocolate has a solid texture at low temperatures but melts easily at higher temperatures, making it difficult to produce high-quality chocolate in tropical countries. This issue could be addressed by using fat and palm sap sugar in different proportions to improve the thermal stability of milk chocolate. It has been reported that fat content, palm sap sugar proportion, and their interaction significantly influence the hardness of milk chocolate [82]. Furthermore, fermented sap is a raw material for the production of bioethanol, lactic acid, and other value-added products such as methylfurone, which could be used as a biofuel. Advanced research is needed to explore the effective conversion and sustainable use of sap for renewable energy applications. Noticeably, probiotic and antimicrobial properties can be found in fermented palm sap, which is a source of lactic acid bacteria. However, further research is needed to isolate the specific lactic acid bacteria species and employ them for treating water or synthesizing drugs to treat viral infections such as COVID.

9. Conclusion

Palm sap is a sweet, uniquely flavored, and nutritious sweetner, making it a great choice for those valued natural and sustainable products. It offers numerous health benefits and is low in calories. However, the sap industry faces challenges in collecting, processing, and distributing palm sap. These challenges include inconsistency in quality, low extraction yields, and the need for improved preservation methods to increase the shelf life of the final product. To address these issues, innovative solutions are required. More efficient extraction techniques and novel preservation methods could significantly enhance the quality and sustainability of palm sap. By working together, producers and consumers can ensure that palm sap becomes popular and sustainable choice for sweetening beverages in the future.

Data availability statement

Data availability is not applicable to this article as no new data were created or analyzed in this study.

CRediT authorship contribution statement

Abdul Hai: Writing – review & editing, Writing – original draft, Conceptualization. **K. Rambabu:** Writing – original draft. **Ayesha S. Al Dhaheri:** Writing – review & editing, Supervision, Resources. **Shyam S. Kurup:** Writing – review & editing, Validation. **Fawzi Banat:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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