



Physicochemical properties of coconut inflorescence sap (neera) under double wall open heating system

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Abstract

Utilization of plant sap-derived sugars and syrups, such as palm sugar, birch syrup, maple syrup, and agave syrup, provides versatile alternatives to conventional sweeteners like cane sugar and high-fructose corn syrup, thereby enriching culinary options and catering to diverse consumer preferences. One noteworthy product derived from coconut palm sap is neera, a traditional beverage celebrated for its natural sugars, vitamins, minerals, and bioactive compounds. Its nutritional value and cultural significance make it a cherished component of local diets. It is nutritionally important due to its natural sugars (sucrose, glucose, and fructose), rich in vitamins and minerals (potassium, magnesium, zinc, and iron). The focus of this study is to comprehend the biochemical changes that occur during the conversion of neera into sugar using an open double-jacket cooker. The process entails meticulous monitoring of various parameters, including total soluble solids (TSS), pH levels, total sugar content, reducing sugar content, total phenol content (TPC), antioxidant activity (measured by DPPH and FRAP assays), and ascorbic acid concentration. Throughout the 3 h heating process, samples are collected at 30 min intervals to track the changes in biochemical composition. Continuous stirring and precise temperature control ensure uniform heat transfer and accurate results. The findings reveal significant alterations in biochemical composition, with notable increases observed in TPC and antioxidant activity, possibly attributed to the Maillard reaction. The conversion from neera to coconut sugar yields a range of compositions suitable for various culinary applications, presenting opportunities for entrepreneurship and the development of value-added products. This not only enhances market competitiveness but also fosters economic growth in the food sector.

Keywords Caramelization · Sucrose · Nutritional profile · Inflorescence sap · Maillard reaction · Indirect heating · Palm sugar

Introduction

Coconut sugar, also referred to as coconut palm sugar or neera sugar, is a natural sweetening agent extracted from the sap of the coconut palm tree (*Cocos nucifera* L.) [1].

With an increasing inclination towards natural and minimally processed sweeteners, coconut sugar emerges as a sustainable and healthier option. As coconut sap undergoes minimal processing, it retains more nutrients than refined sugar. Coconut palms thrive in diverse ecosystems without deforestation, promoting biodiversity. Additionally, local production of coconut sugar supports rural economies in tropical regions, providing sustainable livelihoods for small-scale farmers. The manufacturing process entails tapping the inflorescence of the coconut tree to collect the sap, which is then subjected to heating in an open vessel with continuous stirring to remove moisture, resulting in concentrated syrup. Subsequently, the syrup is further dehydrated to yield granulated sugar [1, 2]. Coconut sugar has emerged as a preferred alternative to refined sugar and artificial sweeteners, owing to its natural origins [3]. The global coconut

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sugar market is anticipated to grow from USD 3,635.3 million in 2023 to USD 4,936.2 million by 2033. This market is expected to expand at a compound annual growth rate (CAGR) of 3.6% during the forecast period from 2023 to 2033 [4]. What sets it apart from conventional sugar is its distinct flavor profile, often described as having caramel-like notes with subtle hints of coconut. Variations in taste may be influenced by factors such as the specific variety of coconut palm, the geographical region of production, and the methods employed during processing [5]. Its nutritional merits and versatile culinary applications position coconut sugar as an environmentally conscious choice for individuals seeking conscientious dietary alternatives [2]. Coconut sugar typically demonstrates a lower glycemic index (52.47) in comparison to refined sugar, resulting in a more gradual and consistent increase in blood sugar levels [6]. This attribute holds potential advantages for individuals managing diabetes or seeking to regulate their blood glucose levels [7, 8]. Furthermore, coconut sugar boasts a lower calorie content than other sugars, with approximately 288 cal per 1/2 cup, in contrast to 387 cal for an equivalent quantity of refined sugar [9].

Studies conducted by Hebbar et al. [10] and Saraiva et al. [8] have identified thirteen phenolic acids and seven flavonoids in coconut sap, sap concentrate, and sap sugar. Prominent phenolic acids include vanillic acid, syringic acid, transcinnamic acid, and *p*-hydroxybenzoic acid, while major flavonoids encompass catechin, hesperidin, and myricetin. Additionally, coconut sap is replete with vitamins such as vitamin C, niacin, and tocopherol.

Research findings suggest that coconut sap exhibits elevated levels of DPPH, FRAP, and ABTS in comparison to sugar palm and sugarcane juices. Moreover, coconut sap is notably enriched with vitamin C (116.19 µg/mL) and ash, accompanied by significant mineral content including potassium (960.87 mg/L) and sodium (183.21 mg/L) [11]. Additionally, coconut sap sugar contains a notable quantity of inulin (4.7 g/100 g), pivotal for the production of short-chain fatty acids like acetate, butyrate, and propionate [12]. Coconut sugar is a staple in traditional Indonesian cuisine, playing a crucial role in numerous dishes and beverages. It is especially important for imparting the unique taste and flavor to Indonesian sweet soy sauce (kecap manis) and for the preparation of Indonesian intermediate moisture meat (dendeng) [13].

Traditionally, coconut sugar was crafted using an earthen hearth, involving a boiling process in a large open vessel over an open flame. However, this method, while culturally significant, presents challenges such as time consumption, manual monitoring and stirring, contamination risks, and imprecise temperature control, potentially resulting in quality inconsistencies or caramelization and burning issues. The current study endeavours to evaluate

the effectiveness of open heating employing a double-jacketed cooker and scrutinize the biochemical alterations during the conversion of neera to sugar.

Materials and methods

Collection of samples

Neera, also known as coconut sap, was gathered utilizing a coconut sap chiller (developed by ICAR-CPCRI: Patent Number: 373309) from coconut trees located at ICAR-CPCRI, Kasaragod. Following extraction, the collected neera was promptly stored at $-18\text{ }^{\circ}\text{C}$ freezer to prevent fermentation and maintain its quality.

Coconut sugar preparation

The frozen neera underwent a thawing process before being heated to $90\text{ }^{\circ}\text{C}$ in a double-jacket cooker. This batch-type cooker, designed and developed by ICAR-CPCRI, utilizes thermal fluid to indirectly supply heat to the sample, and ensures uniform heating. Continuous stirring during the heating process is achieved through a mechanical setup employing a reduction gearbox and an electric motor [14]. The batch-type cooker utilized for sugar making is equipped with specific dimensions and components to facilitate the process effectively. The container has an inner diameter of 950 mm and an outer diameter of 1090 mm, with a height of 245 mm. It is constructed from food-grade stainless steel material, ensuring compliance with safety standards. The container boasts a thickness of 20 gauge to enhance durability and heat distribution. Within the container, four stirrer arms operate at a speed of 25 rpm, driven by a 1 hp motor running at 1440 rpm. Additionally, the cooker is supported by four legs for stability during operation. An expansion tank, measuring 175 mm in diameter and 450 mm in height, is also incorporated into the design to accommodate any thermal expansion during the heating process. Together, these components contribute to the efficient and reliable operation of the batch-type cooker for sugar production.

Over a duration of 3 h, a total volume of 35 L of neera underwent heating, with the thermal fluid temperature maintained at $105\text{ }^{\circ}\text{C}$, while the temperature profile inside the cooker (coconut sap) was monitored throughout the process. Samples were extracted every thirty minutes for analysis of their biochemical components. Subsequently, the neera was concentrated to produce sugar granules, which were ground, dried in a drier at $65\text{ }^{\circ}\text{C}$ and sieved.

Biochemical analysis

Moisture content

The moisture content (w.b. %) of the samples was assessed utilizing the oven drying technique. Approximately 5 g of each sample was pre-measured and placed in Petri plates before being subjected to a temperature of 105 °C in a hot air oven until a constant weight was achieved. Subsequently, the moisture percentage was calculated following the standard AOAC 925.09, 2015 method [15].

TSS and pH

The TSS content, measured in °Brix, was determined using a pocket refractometer (ATAGO, Tokyo, Japan, 0–93%, PAL-BX/RI) as per the method described by Mamede et al. [16]. The pH level was measured using a pH meter (EUTECH Instruments, Singapore, model-700) in accordance with the methodology outlined by Liew et al. [17].

Determination of total sugar and reducing sugar

The total sugar content was evaluated using the phenol sulfuric acid method. The outcomes were presented as grams of glucose equivalent per 100 g of sample (g/100 g). The reducing sugar was determined utilizing the Nelson-Somogyi method. The absorbance was measured at 620 nm and reported as grams of glucose equivalent per 100 g of sample (g/100 g), following the procedure outlined by Somogyi [18] and Sadasivam et al., [19].

Determination of TPC

The TPC was determined using the Folin-Ciocalteu method, following the procedure outlined by Lamuela-Raventós [20]. Initially, the absorbance of all samples was measured at 745 nm using a UV spectrophotometer (Shimadzu, UV-160A, Japan). Each sample was adjusted to a volume of 1 mL using distilled water, followed by the addition of 0.2 µL of Folin-Ciocalteu reagent to each tube. Subsequently, 2 mL of a 7% Na₂CO₃ solution was added to each tube. The tubes were then placed in the dark and incubated for 45 min, after which the absorbance was measured again at 745 nm. The results for liquid samples were expressed as milligrams of gallic acid equivalent per 100 mL (mg GAE/100 mL) of the original sample, while honey and sugar were expressed as milligrams of gallic acid per 100 g of dry weight (mg GAE/100 g of dw).

Determination of FRAP

The Ferric reducing antioxidant power (FRAP) assay was performed according to the method outlined by Benzie and Strain [21]. Initially, 1 mL of the sample was placed into a test tube, followed by the addition of 2 mL of FRAP reagent to all tubes. The volume was then adjusted to 10 mL with distilled water. Subsequently, the tubes were incubated for 20 min at room temperature, and the absorbance was measured at 593 nm. Results for liquid samples were expressed as milligrams of trolox equivalent per 100 mL of the original sample, while honey and sugar were denoted in milligrams of trolox equivalent per 100 g of dry weight (mg TE/100 g dw).

Determination of DPPH

The 2,2-diphenyl-1-picrylhydrazyl (DPPH) assay was conducted utilizing the spectrophotometric method. A fresh stock solution of 10⁻³ M DPPH radicals in methanol was prepared and 3 mL of the stock solution was diluted to 50 mL with methanol in a volumetric flask and kept in dark. Samples were transferred to test tubes, and their volume was adjusted to 2 mL using methanol. To create a blank, 2 mL of methanol was added. Subsequently, 750 µL of methanolic DPPH solution was added to both the sample and the blank. The mixture was then allowed to incubate for 15 min in the dark. Absorbance readings were recorded at 510 nm using a UV–visible spectrophotometer (Shimadzu, UV-160A, Japan). A standard graph was plotted based on the absorbance values obtained, following the protocol described by Brand-Williams et al. [22].

Determination of ascorbic acid

Ascorbic acid was quantified via titration. A dye solution was made by dissolving 42 mg of sodium bicarbonate and 52 mg of 2,6-dichlorophenol indophenol in distilled water to 200 mL. Then, 1 g of the sample was diluted to 10 mL using 4% oxalic acid. In a flask, 5 mL of the prepared solution was mixed with 10 mL of oxalic acid and titrated against the dye solution until a stable pale pink color appeared for at least 15 s, indicating the endpoint. The amount of dye used in titration determined the concentration of ascorbic acid in the sample Thimmaiah et al., [23].

Statistical analysis

The experimental results underwent analysis using the ICAR statistical analysis tool, Web Agri Stat 2.0 package. Each experiment was conducted with replicates, and the findings were presented as mean values accompanied by their

respective standard deviations. A confidence level of 95% was established, with a significance threshold set at $p < 0.05$.

Result and discussion

Neera to coconut sugar by open pan system

Neera, a highly nutritious beverage, is prone to fermentation if stored at room temperature [24]. To extend its shelf life, it necessitates processing and preservation in alternative forms. Heat treatment emerges as an efficient method for converting raw neera, which is highly perishable, into improved products. Thus, the neera was subjected to continuous heating at 80–90 °C for 3 h in a double-jacketed cooker, with continuous mixing to ensure uniform heat distribution. The temperature profile was depicted in Table 1. Initially, the process to reach 50°Brix was gradual, yet once attained, a rapid increase in temperature was noted. Consequently, the heat supply was discontinued at the 150th min, despite the container retaining significant heat (Table 1).

Throughout this process, samples were collected (Fig. 1, 2, 3) and analyzed for various parameters including TSS, pH, moisture, total sugar, reducing sugar, TPC, FRAP, DPPH, and ascorbic acid. The heating process led to a change in the color of neera from golden-brown to a darker brown, resulting in a semi-solid sugar syrup (Fig. 2), which was further heated to obtain sugar granules (Fig. 3).

In a study by Jamfa [25], the physical and chemical characteristics of palm sugar syrup processed using both an open pan and a vacuum evaporator were examined, including color (measured by L and a values), pH, total acidity, TSS, and protein content. It was found that the syrup produced

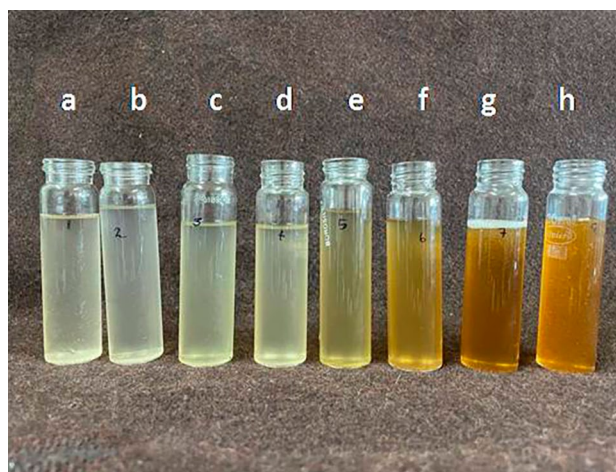


Fig. 1 Samples collected during sugar processing, **a** initial neera sample, **b** 30th min, **c** 60th min, **d** 90th min, **e** 120th min, **f** 150th min, **g** 165th min, **h** 172th min

through an open pan exhibited a darker color compared to that produced via a vacuum evaporator, attributed to the accelerated occurrence of the Maillard reaction and caramelization due to prolonged exposure to high processing temperatures and duration.

Furthermore, the temperature and duration of heating significantly influence the speed of chemical reactions, particularly the Maillard reaction, as observed in studies by Brands & van Boekel [26] and Martins et al. [27].

TSS and moisture during heating

Throughout the process, TSS measurements were taken at 30 min intervals. Continuous heating facilitated the concentration of neera, leading to a steady escalation in the TSS

Table 1 Temperature profile inside-bottom and walls of the container. The heating unit was switched off after 165th min since there was a sudden increase in the TSS value

Time (min)	Temperature (°C)	
	Inside the open pan heating system	Walls surface of open pan heating system (average temperature of 4 readings)
30	78	132
60	85	148
90	84	158
120	85	156
150*	88	160
165	93	146
172 min	92	136
180 min	90	103
Sugar	90	95

*The heating unit was switched off at 165th min



Fig. 2 Sample collected at 180th min



Fig. 3 Coconut sugar

values. Initially, the neera’s TSS registered at 15° Brix, gradually increased to 36° Brix within 2 h, followed by a notable surge. At the 2 h and 45 min mark, the neera transitioned into the honey stage, reaching 72.3° Brix, prompting the cessation of the burner. By the end of the 3 h period, the TSS had peaked at 85.1° Brix. Subsequently, the neera was manually ground into granules and subjected to oven drying at 65 °C.

The rapid increase in TSS observed in the neera is attributed to the evaporation of water at elevated temperatures, resulting in a reduction in volume. This phenomenon mirrors similar findings observed in the processes of jaggery production from sugarcane, palmyra-palm, and date-palm juices [28–30].

The moisture content in fresh neera notably decreased from 83.75 to 1.61% upon reaching the sugar stage, indicating that approximately 82.14% of the water evaporated during open heating. This loss of moisture during the process is detailed in Table 2.

As a consequence of the heating process, the moisture content in neera underwent evaporation, resulting in an increase in the solid content of the final product. The reduction in moisture content in sugar granules is recognized as a critical factor for extending the shelf life of the product, allowing for prolonged storage [31]. This diminished moisture content holds promise for various applications within the food industry, facilitating the development of innovative products.

Transformation of pH of neera during heating

The pH of the neera was initially recorded to be slightly alkaline, ranging between 7 to 8, accompanied by a golden-brown color. Throughout the heating process, the pH level exhibited an initial increase followed by a subsequent

Table 2 Biochemical constituents of processed neera samples collected during the open pan heating

Constituents	Sample									
	Fresh neera	30 min	60 min	90 min	120 min	150 min	165 min	172 min	180 min	Coconut sugar
Moisture (%)	83.75 ± 0.22 ^a	82.80 ± 0.42	78.64 ± 0.30 ^b	73.20 ± 0.09	64.54 ± 0.29 ^d	47.07 ± 0.16 ^e	27.48 ± 0.19 ^f	20.71 ± 0.05 ^g	10.25 ± 1.47 ^h	1.60 ± 0.22 ⁱ
TSS(°BRIX)	15 ± 0.00 ^j	16.1 ± 0.07 ^b	25.1 ± 0.00 ^g	29.1 ± 0.07 ^f	36 ± 0.00 ^e	52.9 ± 0.07 ^d	72.3 ± 0.00 ^c	79.3 ± 0.00 ^b	85.1 ± 0.07 ^a	–
pH	7.01 ± 0.01 ^e	7.33 ± 0.02 ^c	7.59 ± 0.01 ^a	7.45 ± 0.04 ^b	7.12 ± 0.01 ^d	6.67 ± 0.01 ^f	6.42 ± 0.00 ^g	5.97 ± 0.02 ^h	–	–
Total sugar (g/100 g)	7.36 ± 0.64 ^a	7.83 ± 0.06 ^b	8.65 ± 0.35 ^c	9.23 ± 0.95 ^d	23.7 ± 0.83 ^e	39.72 ± 0.68 ^f	58.57 ± 1.52 ^g	56.05 ± 1.61 ^g	62.77 ± 0.12 ^g	83.63 ± 1.19 ^g
Reducing sugar (g/100 g)	0.85 ± 0.03 ^a	0.65 ± 0.00 ^b	0.99 ± 0.01 ^c	0.75 ± 0.01 ^d	2.03 ± 0.02 ^e	3.59 ± 0.03 ^f	5.98 ± 0.09 ^g	5.06 ± 0.15 ^{gh}	5.43 ± 0.03 ^{hi}	5.75 ± 0.06 ⁱ
Total phenol content *(mg GAE/100 g)	16.45 ± 0.33 ^a	17.69 ± 0.27 ^b	19.84 ± 0.47 ^b	22.82 ± 0.13 ^b	40.12 ± 11.95 ^c	47.55 ± 3.54 ^c	87.40 ± 2.78 ^d	87.64 ± 3.57 ^d	91.83 ± 0.82 ^d	127.86 ± 2.10 ^d
FRAP* (mg TE/100 g)	14.79 ± 0.46 ^a	14.25 ± 0.16 ^b	14.54 ± 0.32 ^b	15.68 ± 0.11 ^c	20.96 ± 1.21 ^d	32.48 ± 0.82 ^e	46.84 ± 1.48 ^f	54.60 ± 1.45 ^f	56.22 ± 1.15 ^f	70.26 ± 0.90 ^f
DPPH * (mg TE/100 g)	5.47 ± 0.06 ^a	4.34 ± 0.06 ^b	4.45 ± 0.22 ^c	4.45 ± 0.17 ^d	7.06 ± 1.11 ^e	13.94 ± 0.70 ^f	21.32 ± 1.17 ^{fg}	16.80 ± 0.60 ^g	18.90 ± 1.79 ^g	41.44 ± 0.57 ^g
Ascorbic acid (mg/100 g)	8.82 ± 0.00 ^a	9.06 ± 0.41 ^c	9.06 ± 0.41 ^c	9.26 ± 0.00 ^d	11.67 ± 0.00 ^e	18.49 ± 0.46 ^f	25.25 ± 0.46 ^g	33.93 ± 0.00 ^g	52.99 ± 0.00 ^g	55.14 ± 1.73 ^g

The different letters in the columns indicates a significant effect at level of 0.05

Values are given as mean ± standard deviation of duplicates

GAE gallic acid equivalent, FRAP ferric reducing antioxidant power, TE trolox equivalent, DPPH 2,2-diphenyl-1-picrylhydrazyl

*TPC, FRAP, and DPPH, of samples - fresh neera, 30 min, 60 min, 90 min, are recorded for mg/100 ml, while for the samples withdrawn at 120 min, 150 min, 165 min, 172 min, 180 min and sugar are recorded for mg/100 g

decrease. The rise in pH could be attributed to chemical reactions occurring under heat, potentially resulting in the release of OH⁻ ions from the constituents of neera. Subsequently, as temperature rises within a solution, molecular vibrations increase, leading to ionization and the generation of hydrogen ions (H⁺), with a higher concentration of hydrogen ions corresponding to increased acidity [32].

The browning observed during neera heating, known as the Maillard reaction, is a non-enzymatic process wherein the carbonyl group of a reducing sugar reacts with the primary amino group found in amino acids, peptides, and proteins [33]. The progression of the Maillard reaction is significantly influenced by pH, intensifying as the pH level increases [34]. The subsequent decrease in pH could be attributed to the concentration of organic acids occurring during the heating process [35].

Studies by Woo et al. [36] demonstrated that the pH of 20% glucose and maltose solutions decreased with increasing heating temperatures (ranging from 110 to 150 °C) and durations (from 1 to 5 h). Higher temperatures resulted in lower pH values when the heating time was constant, while longer heating times led to lower pH values at constant heating temperatures. This decline in pH under high temperature and pressure conditions is associated with an increase in the production of organic acids. Additionally, investigations regarding the chemical qualities of palm sugar syrup revealed that the pH value of palm sugar syrup (5.30) was higher than that of palm sap (4.69), attributed to the loss of volatile acids during the heating process conducted in an open pan [35]. The reactivity between sugar and amino acids is significantly influenced by the pH level.

Changes in total sugar and reducing sugar content

The total and reducing sugar content was expressed as grams of glucose equivalent per 100 g of sample. In fresh neera, the total sugar ranged from 7.36 ± 0.64 to 83.63 ± 1.19 g/100 g in coconut sugar. Similarly, the reducing sugar content in fresh neera to coconut sugar ranged from 0.85 ± 0.03 g/100 g to 5.75 ± 0.06 g/100 g, respectively. The increase in total sugar content was attributed to the removal of moisture from the syrup, leading to sugar concentration. The evaporation process also influenced the reduction of sugar content, likely dependent on the occurrence of an inversion reaction [35]. The reduction in sugar content exhibited a pattern aligning with the pH values, indicating the influence of acidity on sugar inversion.

According to Naknean & Meenune [37], a reduction in sucrose content was observed after the concentration process, accompanied by an increase in reducing sugar content due to sucrose inversion. Sucrose hydrolysis depends on factors such as pH, invertase activity, and temperature, with sucrose inversion being induced by both pH decrease and

temperature elevation [38]. Despite the typical decrease in reducing sugars during the Maillard reaction, an increase was observed in this study, possibly due to the sucrose inversion rate surpassing the Maillard reaction rate during sugar syrup production. The content of reducing sugars significantly influences the characteristics of palm sugar syrup over time, serving as a substrate for the Maillard reaction during storage [35].

During the thermo-evaporation process used in making jaggery from cane juice, fructose plays a more significant role than glucose and sucrose in promoting non-enzymatic browning through caramelization [39]. The increase in the proportion of reducing sugar to total sugar in palm sugar syrup may be explained by the conversion of sucrose into glucose and fructose under conditions of high-temperature boiling and acidity. This process, known as inversion [40]

Sucrose inversion involves the hydrolysis of the glycosidic linkage in a disaccharide, releasing its monosaccharide components, α -D-glucose and β -D-fructose. The progress of this reaction depends on factors such as pH, temperature, and hydrolyzing agents, including enzymes. Sucrose hydrolyzes readily under acidic conditions, with the ability of acids to catalyze sucrose inversion varying based on their degree of ionization or dissociation constants. Moreover, higher temperatures facilitate sucrose inversion [41].

Changes in TPC

This rise in TPC during the heating process can be attributed to the breakdown of larger phenolic compounds into smaller, more soluble forms. Heat can disrupt complex structures, facilitating the release and conversion of phenolic compounds, ultimately leading to an overall augmentation in the TPC [42]. Detailed results are outlined in Table 2.

In comparison to alternative processing techniques such as rotary evaporation and microwave evaporation, open heat evaporation has demonstrated notably higher TPC values [11]. The temperature and duration of processing play pivotal roles in influencing the TPC of coconut sugar syrup samples. Asikin et al. [43] reported an increase in the TPC of sugarcane brown sugar following processing at elevated temperatures. Similarly, Karseno et al. [33] noted a rise in the TPC of coconut sugar with increasing processing temperatures, suggesting that this elevation could be attributed to the formation of Maillard reaction products (MRPs) and caramelization products (CPs).

The Maillard reaction, particularly the formation of melanoidins, has been significantly associated with the overall phenolic content [44]. The duration of heating intensifies the Maillard reaction, leading to the generation of MRPs. Consequently, it is plausible that phenolic groups derived from MRPs contribute to the observed increase in TPC during the heating of coconut sap, as corroborated by studies conducted

by El-Ghorab et al. [45] and Karseno et al. [33]. Hence, it can be deduced that the augmentation in TPC and subsequent enhancement of antioxidant activity can be attributed to the involvement of MRPs.

Changes in FRAP

An antioxidant in food is defined as any compound capable of slowing down, inhibiting, or preventing the onset of rancidity or other flavor degradation caused by oxidation [46]. Table 2 presents data on the antioxidant capacities of neera, syrup, and coconut sugar, assessed using the FRAP method. It was observed that heating in the open cooker resulted in increased FRAP values. Liquid samples were quantified as milligrams of Trolox equivalent per 100 mL of sample, while semi-solid and solid samples were expressed as milligrams of Trolox equivalent per 100 g of sample. Different processing techniques and temperatures exerted a significant impact on antioxidant activity, as reflected by FRAP values.

Various studies have indicated that Maillard reaction products (MRPs) and caramelization products (CPs) possess antioxidant properties [47]. Therefore, the augmented FRAP values observed in the open-heat processing method are likely attributable to the formation of MRPs and CPs.

An examination of the impact of open pan (at 110 °C) and vacuum evaporation (at 60 °C) of palm sugar syrup on FRAP values revealed an increase in values, approximately 48 $\mu\text{mol TE g}^{-1}$ and 34 $\mu\text{mol TE g}^{-1}$ respectively [11]. This underscores the significant influence of different processing methods and temperatures on the antioxidant activity of samples, as measured by FRAP values.

Changes in DPPH

The DPPH assay demonstrated an increase in antioxidant activity with the application of heat and prolonged processing time, likely attributed to the formation of Maillard reaction products (MRPs) [48]. Turkmen et al. [48] investigated the DPPH scavenging activity of MRPs in honey at 70 °C and observed an enhanced DPPH radical scavenging capacity with prolonged heating durations. Similarly, the pH of coconut sap and the heating temperature during coconut sugar production significantly influenced its antioxidant characteristics, with TPC and DPPH scavenging activity showing a positive correlation with elevated temperatures.

Comparing open pan sugar palm syrup and vacuum-evaporated syrup, Naknean & Meenune [37] found significantly higher DPPH antioxidant activity in the former, indicating the impact of processing methods on antioxidant properties. Previous studies on coconut sugar also reported increased antioxidant activity with higher processing temperatures [33].

MRPs derived from various model systems have been shown to exhibit antioxidant properties, including FRAP, reducing power, and DPPH radical scavenging [49–51]. Furthermore, CPs and MRPs are known to possess DPPH radical scavenging activity, effectively reducing the DPPH radical to yellow-colored diphenylpicrylhydrazine [52, 53].

Intermediate degradation products and brown polymers formed during the Maillard reaction also demonstrate antioxidant activity [54]. Additionally, MRPs exhibit hydrogen-donating ability, indicating their potential to react with free radicals and scavenge them [55, 56]. The antioxidant activity of phenolic compounds is attributed to their ability to scavenge free radicals and donate hydrogen [57].

Changes in ascorbic acid

The ascorbic acid content exhibited a notable increase from 8.82 to 55.14 mg per 100 g, respectively, from fresh neera to coconut sugar. This rise can be attributed to the concentration effect caused by water evaporation during the processing stages, leading to a higher relative concentration of ascorbic acid in the final product Goula et al., [58].

Studies conducted by Brands & van Boekel [26] and Lertittikul et al. [52] support the notion of an increase in total acidity during the Maillard reaction, primarily due to the concentration of organic acids. As the Maillard reaction progresses, the concentration of organic acids increases, contributing to the observed rise in total acidity.

Conclusion

This study highlights the impact of open heating on neera, indicating a reduction in moisture content leading to its concentration and subsequent formation of sugar granules, as evidenced by the increased TSS values. The concentration process resulted in gradual increases in total sugar, reducing sugar, TPC, antioxidants, and ascorbic acid levels. Initially, the pH increased before declining, reflecting dynamic chemical changes during heating. The heating process also triggered an increase in reducing sugar content, attributed to sucrose inversion. Concurrently, the development of browning, indicative of Maillard reaction products (MRPs), correlated with enhanced antioxidant activity. This suggests that MRPs and caramelization products (CPs) in heated neera possess antioxidant properties through electron donation and radical scavenging mechanisms. Given neera's high perishability, processing is essential to extend its shelf life and create value-added products. The modern food industry is increasingly focused on enhancing food characteristics using natural ingredients. Incorporating low-glycemic index coconut sugar into diets may offer health benefits, aligning with current dietary trends favoring healthier alternative.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

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