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Effect of Microclimate Temperature and Relative Humidity on the Postharvest Quality of Coconut Sap and Sugar

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ABSTRACT

Coconut sap, increasingly recognized as a functional sweetener, is highly perishable and influenced by environmental conditions during postharvest handling, yet the specific impacts of microclimatic variables such as temperature and relative humidity (RH) on sap and sugar quality remain inadequately studied. This research investigates the effects of RH and temperature on key physicochemical parameters of coconut sap—pH, Brix, and density—and evaluates their influence on coconut sugar quality, focusing on moisture, ash content, and color. Sap was collected biweekly in Central Java over a five-week period and analyzed in conjunction with environmental data recorded using an IoT-based weather station. Increased RH was significantly associated with decreased sap pH (r = –0.482, p = 0.007) and showed a weak negative correlation with Brix. Density remained stable across varying RH levels. Although temperature showed visual trends in sap quality parameters, statistical analysis did not reveal significant correlations, likely due to the narrow temperature range during the observation period. Throughout sugar processing, TSS increased consistently across boiling, saturation, and oversaturation stages. Final sugar blocks maintained stable moisture (6–8%) and ash content (1.8–2.2%), with color variations reflecting Maillard and caramelization reactions. Maintaining RH below 85% is recommended to preserve sap quality and product consistency.

1. INTRODUCTION

Coconut (*Cocos nucifera* L.) is a species of palm tree that belongs to the Arecaceae family (Divya *et al*., 2023). It is a versatile crop that yields various products, including fronds, wood, fruit, and sap (Nair, 2020; Parisi *et al*., 2024; Srivaro *et al*., 2020). Coconut sap, a sweet, clear, and nutrient-rich liquid obtained from the palm's inflorescence, has emerged as a notable natural sweetener and delicacy, especially in Asia (Carlini *et al*., 2023; Chinnamma *et al*., 2019; Rajan *et al*., 2024). Coconut sap and its derivatives, including coconut sugar, are gaining popularity among health-conscious consumers as alternatives to traditional cane sugar, attributed to their low glycemic index (Raghu & Joseph, 2020). Maintaining the quality of coconut sap from tapping to processing presents significant challenges due to its high perishability and sensitivity to environmental microclimate conditions, particularly temperature and relative humidity (Mustaufik *et al*., 2022).

Key parameters of coconut sap, such as pH, Brix (sugar concentration), and density, are essential indicators of its quality and suitability for processing (Rini *et al*., 2022; Saidan *et al*., 2020). Fresh coconut sap typically exhibits pH below 6, total soluble solids (TSS) between 13 and 14 ºBrix (Hebbar *et al*., 2020). The pH of fresh sap determines its susceptibility to microbial activity and fermentation, which can lead to sugar degradation and lower-quality end products if not controlled promptly (Asghar *et al*., 2020). Brix reflects the total soluble solids, particularly sucrose content, which directly correlates with the sweetness and efficiency of sugar production (Haryanti *et al*., 2018). Density is a critical measure of sap concentration, influencing the cooking process's energy requirements and the final sugar yield (Hanifah *et al*., 2022; Rane *et al*., 2016).

In parallel, the quality of the coconut sugar produced is evaluated based on moisture content, ash content, and color, which are widely recognized as critical determinants of marketability and storage stability. Low moisture content in the final sugar ensures longer shelf life and resistance to microbial spoilage (Ergun *et al*., 2010; Rawat, 2015). Ash content serves as a measure of mineral content and purity, with excessive ash indicating impurities that can affect sugar quality standards (Engida *et al*., 2013). On the other hand, color is a key visual quality attribute of sugar that reflects the caramelization process and influences consumer preferences (Sung *et al*., 2020).

Despite previous research highlighting the importance of these parameters, studies rarely examine the combined effects of environmental factors, namely temperature and relative humidity on coconut sap characteristics and the subsequent sugar quality during postharvest handling and processing. Previous study by Motha *et al*. (2018) provides an insightful background into the seasonal variation of quantitative parameters in coconuts, highlighting how factors such as the weight and water content of coconuts vary across different seasons. This work illustrates the influence of broader environmental conditions on coconut quality but does not delve into specific microclimatic factors. Moreover, temperature and humidity are known to affect enzymatic activity, microbial growth, and moisture dynamics in food systems, suggesting their critical role in determining the quality of coconut sugar (Saraiva *et al*., 2023).

Indonesia's tropical climate and geographic diversity create an optimal environment for examining the environmental dynamics associated with coconut sap production (Alouw & Wulandari, 2020; Setiado *et al*., 2021). Previous studies have explored factors such as tapping time, storage methods, and sap handling on quality parameters (Haryanti *et al*., 2018; Mustaufik *et al*., 2022), limited research has investigated how specific environmental factors, particularly temperature and relative humidity, affect the postharvest characteristics of coconut sap and the quality of the resulting sugar. This is a critical gap, considering the established influence of these microclimatic variables on enzymatic activity, microbial growth, and moisture behavior in food systems sugar (Saraiva *et al*., 2023).

Despite growing interest in coconut sugar production, only a few studies have examined the relationship between environmental conditions and sap or sugar quality in real-world, field-based settings. Moreover, the absence of real-time environmental monitoring in most of these studies limits our understanding of short-term fluctuations that may significantly influence product consistency. As a result, current knowledge remains insufficient to guide best practices for maintaining quality across varying microclimatic conditions. This study attempts to address this gap; however, it is also constrained by its relatively short observation period and the natural variability in sap composition, which may affect the detectability of environmental impacts.

Addressing this gap is crucial for optimizing production processes to satisfy the growing consumer demand for high-quality, health-conscious sweeteners while preserving their desirable properties (Chuntarat *et al*., 2015; Kumar *et al*., 2021). It is hypothesized that fluctuations in temperature and relative humidity significantly influence the quality of coconut sap and the characteristics of the resulting sugar, with higher temperature and humidity levels expected to accelerate sap degradation and negatively impact final product attributes. This study aims to examine the effect of microclimate factors of relative humidity and temperature on essential quality parameters of coconut sap, specifically pH, Brix, and density, throughout collection and processing. Additionally, it evaluates their effect on the quality of the coconut sugar product, focusing on moisture content, ash content, and color. This research identifies the environmental conditions that produce high-quality sap and sugar, offering insights for producers to improve control over environmental and processing variables, thereby enhancing the consistency and marketability of coconut sugar.

2. MATERIALS AND METHODS

2.1. Materials

Coconut sap was collected from local field in Wonogiri village, Kajoran District, Magelang, Central Java, nearby laboratorium where AWS located. The sap was collected from 13 coconut trees and thoroughly mixed, with the data representing the average values from the combined sample. To account for potential variation among trees, Levene's test for homogeneity of variance was performed, showing no significant differences among the trees (p>0.05). Thus, the sap samples were considered homogeneous, ensuring that the sample size was sufficient for reliable conclusions.

Sap collection was conducted twice a week for five weeks during the dry season. The collected sap was immediately analyzed and subsequently processed into molded sugar at ambient temperature. Throughout the production processes, all samples were handled at room temperature. After production, the molded sugar was stored in a refrigerator at 4°C until further quality analysis to maintain sample stability prior to testing. All the chemical used for analysis was analytical grade.

2.2. Methods

2.2.1. Environment Condition Assessment

Real-time environmental data were acquired via an Internet of Things (IoT)-based Automatic Weather Station (AWS) ((MaxiMet GMX600 Compact Weather Station, Gill Instuments, UK) and securely transmitted to a cloud platform (https://iotplatform.thingsnesia.com/), accessible with secure researcher credentials. Temperature and humidity data were recorded every 10 minutes, and the recorded values were averaged to obtain daily mean temperature and humidity for further analysis. Data retrieval was facilitated by two methods: direct download in Excel (.xlsx) format for detailed analysis, and dynamic graphical displays within the platform for immediate visualization of trends.

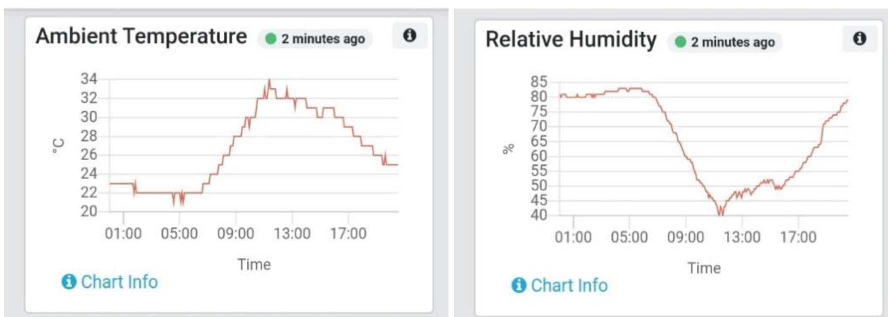


Figure 1. Environmental data recorded by the AWS are visualized in real-time on the cloud platform

2.2.2. Total Soluble Solids (TSS)

Total soluble solids (TSS) were determined using a digital refractometer (Atago, Japan). It was calibrated with distilled water prior to each measurement. A drop of liquid sample was placed on the prism of the refractometer, and the reading was recorded. The results were expressed in °Brix, which is approximately equivalent to the percentage of sucrose by weight. All measurements were conducted in triplicate, and the mean values were reported.

2.2.3. pH

The pH of the sap samples was measured using a digital pH meter (Ohaus St300) at room temperature. The pH meter was calibrated using standard buffer solutions (pH 4.01, 7.00, and 10.01) before each set of measurements. The electrode was washed with distilled water between each sample measurement. All measurements were performed in triplicate, and the mean values were reported.

2.2.4. Density

The density of samples was determined by measuring the mass of a clean, dry glass cylinder. Then, the cylinder filled with the sample, and the weight was recorded. All measurements were performed in triplicate, and the mean values were reported. The density was calculated using the following formula:

$$Density\ (\frac{g}{cm^3}) = (weight\ of\ sample)/(volume\ of\ sample) \tag{1}$$

2.2.5. Coconut sugar production

Following sap harvest, many essential processing stages were used to convert raw sap into sugar blocks. Initially, the freshly collected sap, was filtered through clean clothes to eliminate any debris, insects, or other contaminants that accumulated during the tapping procedure. The filtered sap was then transferred to a big wok and heated over a wood-fired burner. To avoid burning and for even heat distribution, the sap was continuously heated and boiled while being stirred. This evaporation process eventually thickens the sap and concentrates its sugars. As the sap boils, it thickens into a viscous syrup. The syrup's consistency and color were thoroughly examined by looking at its viscosity when dripped from a spatula or the creation of tiny crystals on its surface. The heat was then decreased, and continuous stirring encourages the production of sugar crystals inside the thickened syrup.

When the required consistency had been achieved, the viscous, crystallized sugar was poured into molds. The filled molds are then allowed to cool and solidify, usually for several hours. During this cooling phase, the sugar totally crystallized and hardened into solid blocks. The sugar blocks were then carefully removed from the molds and prepared for packaging.

2.2.6. Moisture Content

Moisture content of the coconut sugar samples was determined using the toluene distillation method, following the procedure described in AOAC 1970. ± 30 g sample was placed in a distillation flask with toluene. The mixture was heated, and the water distilled off was collected in a Sterling-Bidwell tube. The volume of water collected was used to calculate the moisture content. All measurements were performed in duplicate, and the mean values were reported.

$$Moisture\ content\ (\%wb) = \frac{volume\ water\ after\ distillation \times density\ water}{weight\ of\ sample} \times\ 100\% \tag{2}$$

$$Moisture\ content\ (\%db) = \frac{moisture\ content\ (\%wb)}{1 - moisture\ content\ (\%wb)} \times\ 100\% \tag{3}$$

2.2.7. Ash Content

Ash content of the coconut sugar samples was determined by incineration in a muffle furnace. ± 2 g weight of the sample was placed in a pre-weighed crucible and ashed at 600 °C for 6 hours. Then the samples kept in furnace for overnight before weighed. The ash content was calculated as the percentage of the initial sample weight remaining after incineration. All measurements were performed in triplicate, and the mean values were reported.

$$Ash\ content\ (\%) = \frac{weight\ after\ ashing - weight\ empty\ crucible}{weight\ of\ sample} \times\ 100\% \tag{4}$$

2.2.8. Color

Color analysis of the coconut sugar samples was performed using a Konica Minolta Chroma Meter, Japan] colorimeter. The instrument was calibrated using a standard white tile. The color was measured according to the CIE L*a*b* color system, where L* represents lightness (0 = black, 100 = white), a* represents redness/greenness (+a = red, -a = green), and b* represents yellowness/blueness (+b = yellow, -b = blue). From the L*a*b* values, chroma (C*) and hue angle (h°) were calculated using the following equations:

$$C^* = \sqrt{a^{*2} + b^{*2}} \tag{5}$$

$$h^{\circ} = \arctan(\frac{b^*}{a^*}) x \frac{180}{\pi} \tag{6}$$

3. RESULTS AND DISCUSSION

3.1. Coconut Sap Quality Assessment

Figure 2 shows the effect of ambient relative humidity (RH) on the qualitative attributes of coconut sap, specifically total soluble solids (TSS), pH, and density, throughout five weeks. Relative humidity (RH) plays a crucial role in regulating plant water relations, primarily by influencing transpiration, the process of water evaporation from leaves that drives water and nutrient transport from roots to shoots (Chia & Lim, 2022). Figure 2(a) shows how TSS (°Brix) varies in proportion to RH (%). A notable trend was observed, demonstrating that increases in RH were associated with small reductions in TSS levels. This is supported by Pearson correlation analysis, which showed a negative but non-significant correlation between RH and Brix (r = –0.328, p = 0.077), indicating a weak inverse relationship. The TSS levels consistently fluctuated between 15 and 17.5 °Brix. On day 16, there was a considerable increase in RH, which coincided with a fall in TSS. It indicates a possible impact of elevated humidity on coconut sap content. RH directly affects the rate of transpiration through the vapor pressure deficit (VPD), the difference in water vapor pressure between the leaf and the surrounding air. High RH reduces the VPD, slowing transpiration, thus potentially lowering Total Soluble Solids (TSS) (Li *et al*., 2024).

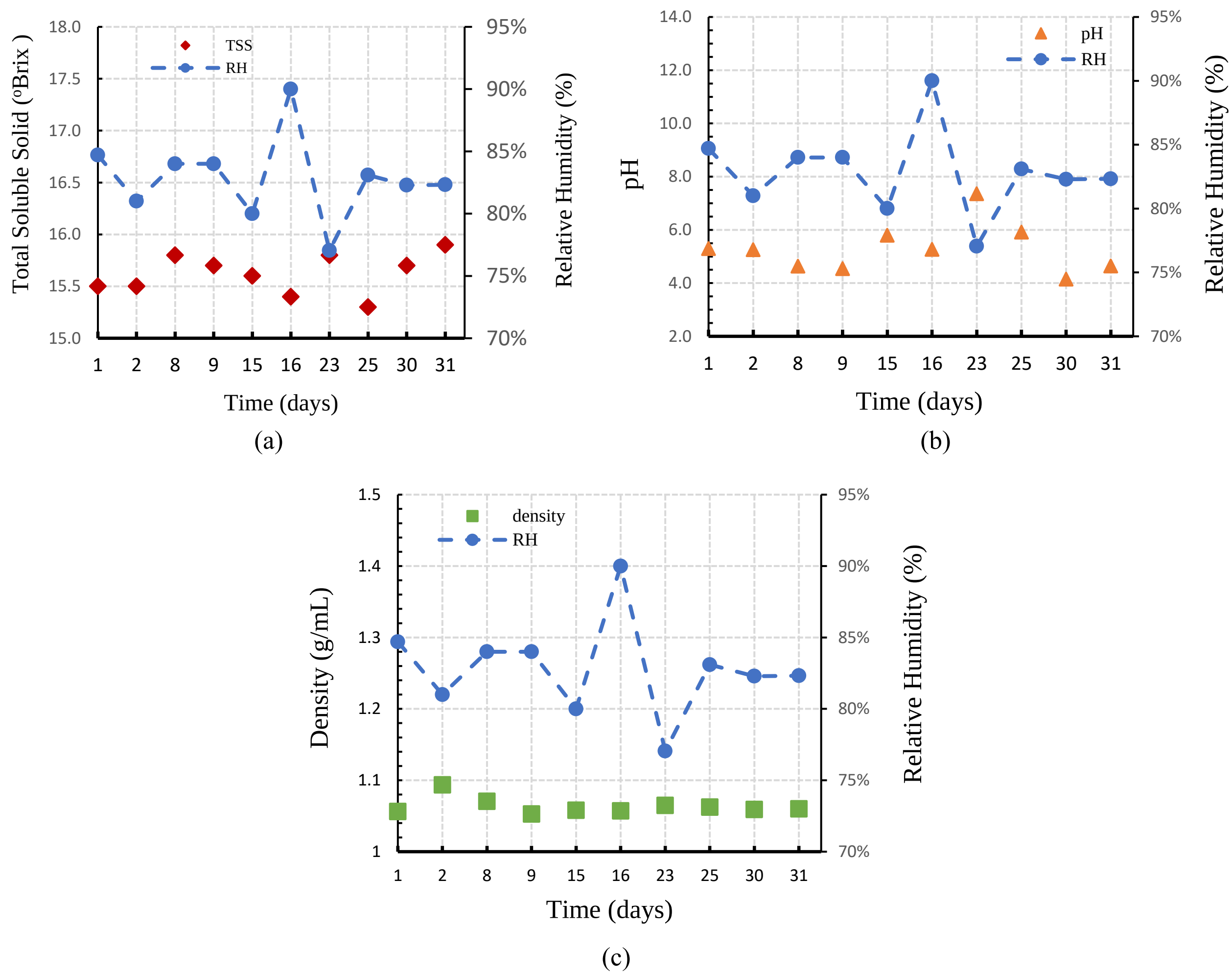


Figure 2. Effect of environment relative humidity on coconut sap quality: (a) Total soluble solids, (b) pH, and (c) density

Figure 2(b) illustrates the correlation between pH and relative humidity (RH). Similar to the TSS trend, variations in RH seem to correlate with alterations in pH. The Pearson correlation analysis confirmed a significant negative correlation between RH and pH (r = –0.482, p = 0.007), suggesting that higher humidity levels may promote conditions conducive to increased sap acidity. The pH levels demonstrate relative fluctuation, generally ranging from 4 to 8, with minor fluctuations observed in reaction to variations in relative humidity. Low pH values often characterize the initial stages of palm sap fermentation, particularly during collection (Lasekan *et al*., 2007). This decrease in pH is typically attributed to the production of organic acids by microorganisms. As these acids accumulate in the solution, they release hydrogen ions, thereby lowering the pH (Naknean *et al*., 2010). A previous study found that the bacterial group associated with coconut sap fermentation. Another study found that fresh coconut sap exhibited the highest abundance of *Leuconostoc*, followed by *Acetobacter, Gluconobacter, and Fructobacillus* (Gopal *et al*., 2021). In contrast, another study analyzing 'tuba,' a fermented coconut palm wine consumed in Mexico, identified *Fructobacillus* as the dominant genus in all samples, followed by *Leuconostoc, Gluconacetobacter, Sphingomonas*, and *Vibrio* (Astudillo-Melgar *et al*., 2019). Figure 2(c) shows the correlation between density and relative humidity. Pearson correlation analysis revealed a weak and non-significant negative correlation between RH and density ($r = –0.244$, $p = 0.194$), suggesting a minimal influence of humidity on sap density. Density data displays a limited range, varying between about 1 and 1.3 g/ cm^3. Minor variations in density tend to correlate with changes in relative humidity. Ysidor *et al*. (2015) studied density of coconut sap also remain stable during storage.

Based on Figure 2, the results indicate a possible impact of ambient relative humidity on the quality characteristics of coconut sap. Although relative humidity fluctuations seem to correlate with modest variations in density, the most distinctive effect was shown on total suspended solids and pH, where increased relative humidity is generally associated with marginally reduced TSS values and pH. Given that most RH values during the observation periodremained below 85%, this threshold may be a reasonable upper limit to preserve sap quality, particularly in maintaining higher TSS and pH values.

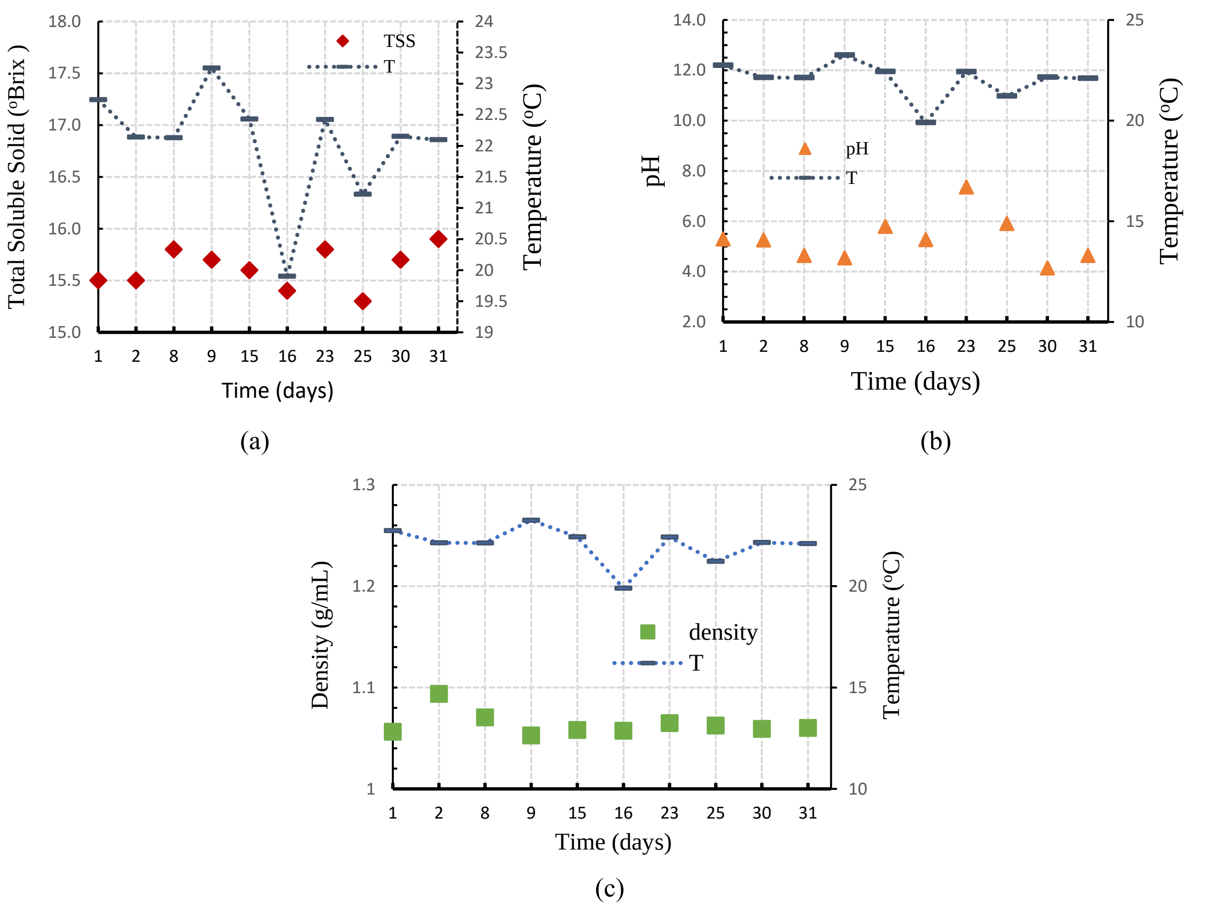
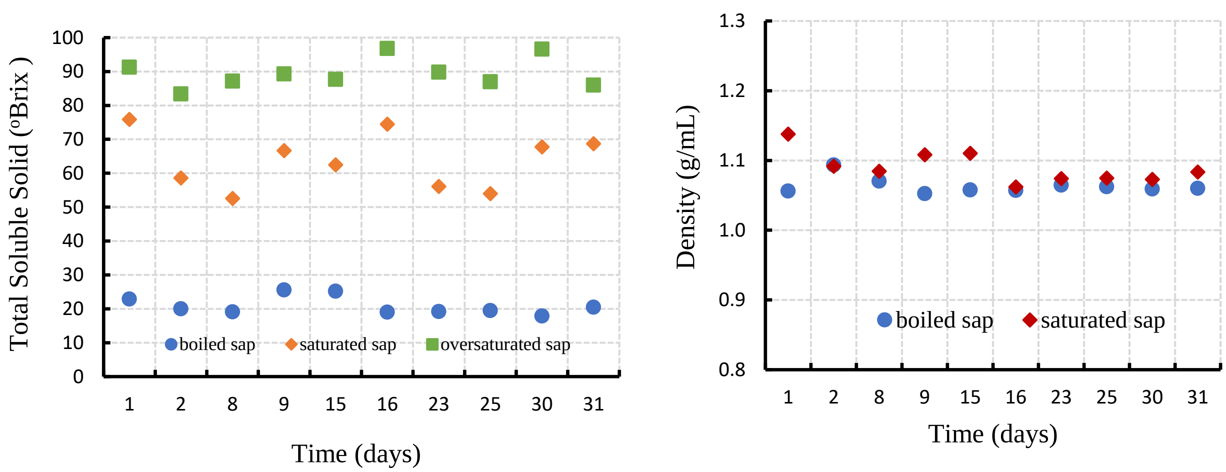


Figure 3. Effect of environment temperature on coconut sap quality (a) Total soluble solids, (b) pH, and (c) density

Figure 3 illustrates the effect of ambient temperature (T) on the essential quality parameter of coconut sap, specifically total soluble solids (TSS), pH, and density, observed over a 31-days. Figure 3(a) presents the correlation between TSS (°Brix) and T (°C). Temperature peaks typically align with TSS value, indicating that elevated temperatures may lead to an increase in sugar content in the sap. The temperature decreased on day 16 corresponds with a notable decrease in TSS. This observation indicates that the increased temperatures may affect sugar concentration, possibly through plant metabolism to produce sugar (Haryanti *et al.*, 2018). Agro-meteorological factors, including precipitation, air temperature, and drought periods, exert significant influence on agricultural productivity (Apiratikorn *et al.*, 2012). Specifically, temperature, sunlight exposure, and humidity play crucial roles in plant metabolism and sugar production across various species, including coconut palms (Priya *et al.*, 2023). The TSS levels varied between about 15 and 17.5 °Brix during the observation period.

Figure 3(b) depicts the correlation between pH and temperature. The pH readings fluctuated within the range of 4 to 8. The change in pH may correlate with microbial activity due to higher temperature. Another study found that *Saccharomyces cerevisiae*, the key microorganism involved in fermenting coconut sap, showed a higher level of fermentative activity as temperatures rise (Pathirana *et al.*, 2023). In Figure 3(c), density (g/cm^3) is influenced by temperature. The results reveal that the density remained stable during the study, fluctuating between 1 and 1.1 g/ cm^3 with little variation. The density of a solution is predominantly influenced by the concentration of dissolved solids; therefore, the relatively stable total suspended solids (TSS) values, aside from the peaks, may account for the observed consistent density.

Despite the visual trends described above, no statistically significant correlation was found between ambient temperature and any of the sap quality parameters (TSS, pH, or density). This suggests that the degree of temperature fluctuation during the study period may have been too limited to elicit measurable changes in sap composition. These findings contrast with prior studies reporting stronger temperature effects on plant physiological processes and microbial dynamics (Haryanti *et al*., 2018; Priya *et al*., 2023; Pathirana *et al*., 2023). It is therefore plausible that under more extreme or variable temperature conditions, or with longer monitoring, a clearer statistical relationship might emerge.



(a) (b)

Figure 4. (a) Total soluble solids change, and (b) Density changes of coconut sap during coconut sugar block production

3.2. Coconut sugar production

Figure 4a illustrates the variation of TSS (°Brix) across the three sap phases during coconut sugar production. The boiling sap demonstrates a consistent TSS, fluctuating between 18 and 25 °Brix. This signifies that the preliminary boiling step attains a uniform sugar concentration. The saturated sap, in which the sap getting thickens and started change phase, exhibits a more variable TSS profile, ranging between about 52 and 76 °Brix. This wider range presumably reflects the ongoing evaporation of water during the heating process, leading to a progressive increase in sugar concentration as the sap transitions towards supersaturation. The continuous evaporation of water during boiling is a fundamental principle in sugar production, leading to increased sugar concentration (Morales *et al*., 2024). The oversaturated sap, the stage immediately preceding crystallization, exhibits the highest TSS values, consistently exceeding 80 °Brix. This high sugar concentration is essential for initiating and sustaining the crystallization process, as supersaturation is the driving force for crystal nucleation and growth (Slavyanskiy *et al*., 2021). The high TSS values in the oversaturated sap create the necessary conditions for sugar molecules to come together and form stable crystal structures, ultimately resulting in the formation of solid sugar blocks

Error! Reference source not found. illustrates the variations in density (g/cm^3) across the two sap stages. The boiling sap exhibited a consistently low and steady density, generally between 1.0 and 1.1 g/cm^3. The saturated sap demonstrates more variable density, typically ranging from 1.05 to 1.09 g/cm^3, indicative of the rising sugar concentration. The density disparity between boiling sap and saturated is less evident than the TSS difference; still, it conforms to the trend that an increase in sugar content results in elevated density. The similar finding was also reported by (Rini *et al*., 2022). Study by Wisnu *et al*. (2021) showed the linear model for density supports this finding, as an increase in sugar content results in elevated density. The model predicts a steady increase in density over time during evaporation (Wisnu *et al*., 2021).

3.3. Coconut sugar quality

Figure presents the moisture content (%) of the final coconut sugar blocks generated daily. The moisture content exhibits relative consistency across the 31-day duration, varying between 6% and 8%. The minimal change in moisture content indicates effective regulation of the processing parameters. On day 8 and day 9 was observed as the highest moisture content that related to low pH of sap on those days. The acidic sap (low pH) causes sucrose to hydrolyze into glucose and fructose, both reducing sugars. The hygroscopic nature of fructose then leads to increased water absorption and thus higher moisture content in the sap (Zulfia *et al*., 2022).

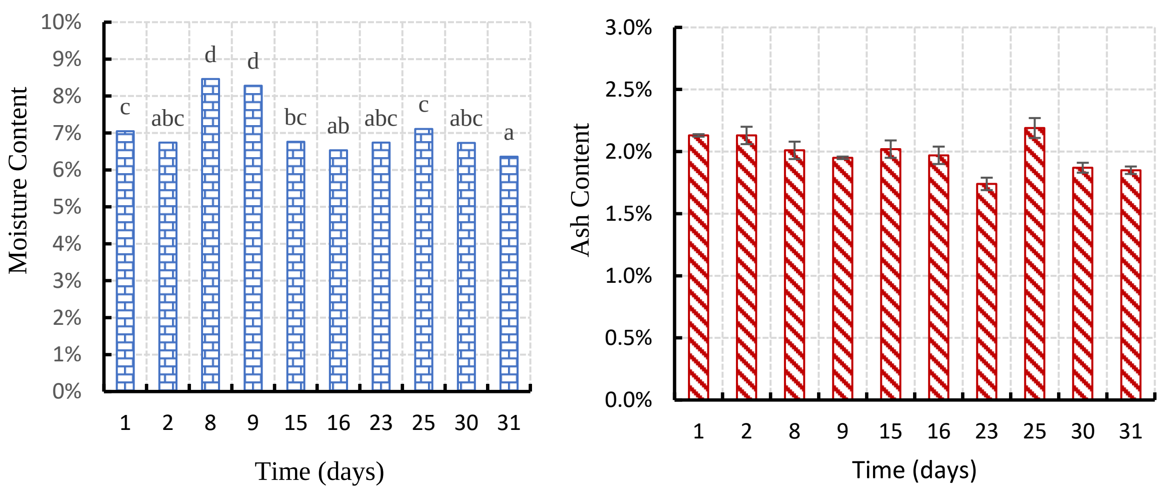


Figure 5. (a) Moisture content, and (b) Ash content of coconut sugar produced from coconut sap each day

Error! Reference source not found. displays ash content (%) of the produced coconut sugar. The ash concentration exhibits relative consistency during the observation period, varying within a narrow range of around 1.8% to 2.2%. Based on statistical analysis, there was no significant difference among sugar produces from coconut sap. The ash content of the produced coconut sugar consistently met the requirements of Indonesia National Standard (SNI 3743-2021) ((BSN), 2021) for palm sugar throughout the observation period. The minimal fluctuation signifies a consistent mineral content of the sugar generated during the process. The presence of ash, predominantly composed of minerals, enhances the nutritional value of sugar; but, excessive quantities can adversely affect its quality and flavor. The uniform ash content noted in this study indicates a well-regulated production process that reduces discrepancies in mineral integration.

Figure 5 illustrates the color analysis of coconut sugar, including hue, chroma, and brightness. Figure 5(a) and 6(b) illustrates the variations in chroma and hue. The hue values typically varies from 65 to 70, signifying a uniform yellowish-brown tint typical of coconut sugar. Minor variances were noted, especially on days 9 and 25, may be due to tiny alterations in processing conditions. The chroma values, which indicate color saturation or intensity, fluctuate within a range of approximately 15 to 25. This indicates that the color intensity of the sugar fluctuated throughout the production process. Lower chroma value signifies a less saturated, more subdued hue, whereas an increased value denotes a more vibrant color.

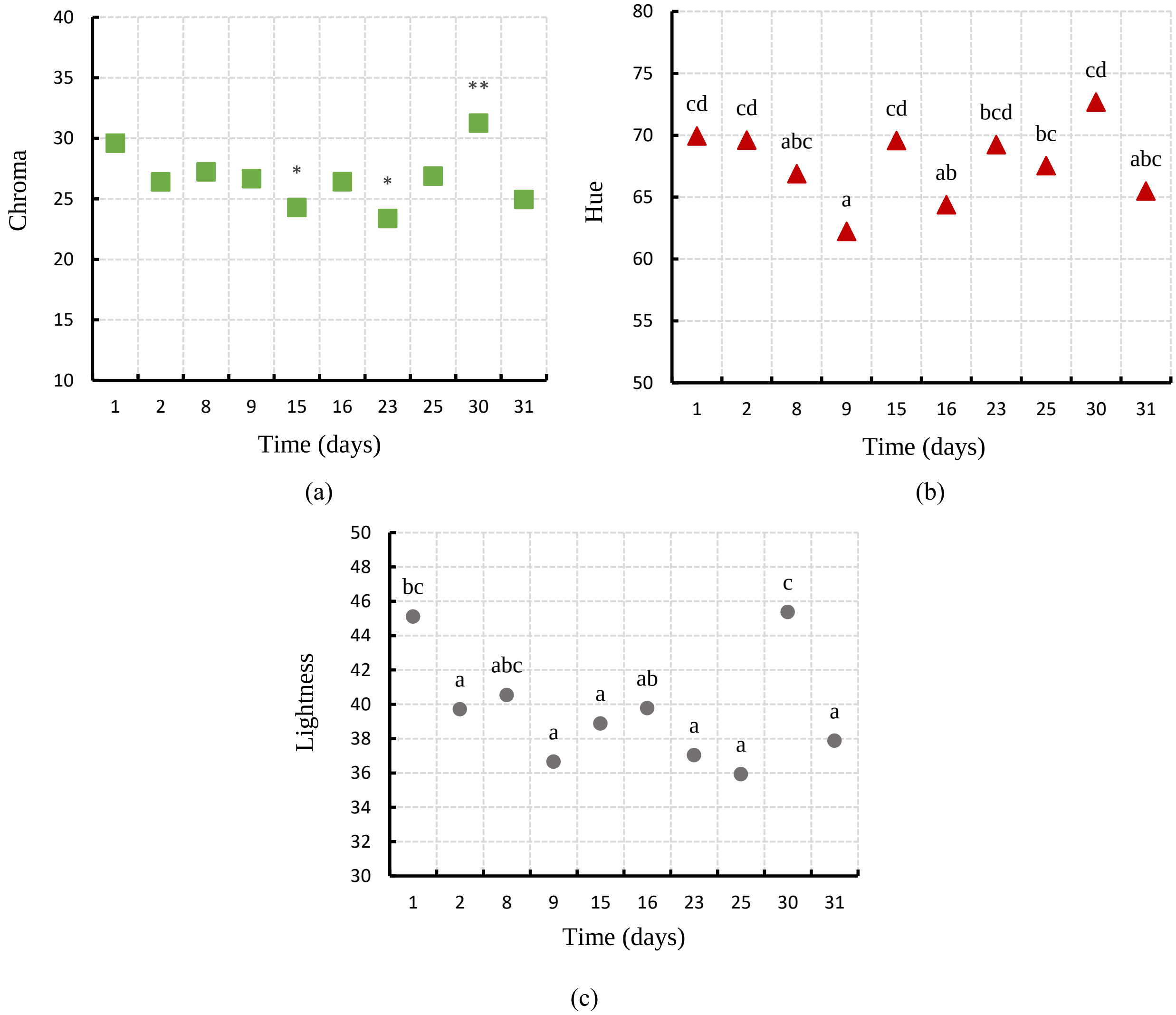


Figure 5. Color analysis of coconut sugar produced from coconut sap each day: (a) chroma, (b) hue, and (c) lightness

These fluctuations in chroma align with the understanding that the Maillard reaction, a key browning mechanism in sugar processing, is influenced by several factors, including pH and temperature (Karseno *et al*., 2017). El-Ghorab *et al*. (2010) specifically noted that increasing pH enhances browning in coconut neera (sap) due to increased availability of reactive amino groups for the Maillard reaction (El-Ghorab *et al*., 2010). Natural variations in the sap's initial pH could contribute to the observed chroma fluctuations. Although low pH can promote sucrose hydrolysis into reducing sugars (glucose and fructose), which are Maillard reaction precursors, the reaction rate itself is limited at low pH due to protonation of the amine group, making it less available for reaction (El-Ghorab *et al*., 2010).

Figure 5(c) depicts the variations in lightness (L*) of the coconut sugar. The variations in lightness (L*) of the coconut sugar. The lightness fluctuated between 35 and 45. Lower L* values indicate dark sugar, whereas larger values indicate light sugar. The observed variations signify alterations in the sugar's colour or brightness. The differences in lightness may be due to the degree of caramelization during processing or the presence of impurities. These differences in lightness may be due to variations in the degree of caramelization during processing, the presence of impurities, or potentially the same pH-related influences on the Maillard reaction discussed above.

4. CONCLUSIONS

This study demonstrates the importance of environmental conditions, particularly temperature and relative humidity, in determining the qualitative features of coconut sap and its produced sugar blocks. Increased relative humidity is associated with a modest drop in total soluble solids (TSS) and pH. While visual patterns suggested a potential influence of temperature on TSS, pH, and density, statistical analyses did not confirm significant correlations, possibly due to the narrow temperature range (19.9–22.34 °C) during the observation period. These findings underscore the importance of monitoring environmental conditions during postharvest handling. Maintaining relative humidity below 85% may help preserve sap quality by supporting higher TSS and pH values. Further studies with broader temperature variations are needed to better understand its role in sap quality dynamics.

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