MODIFICATION, FABRICATION, AND PERFORMANCE EVALUATION OF A COCO SUGAR PROCESSING (CCSP) MACHINE

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MODIFICATION, FABRICATION, AND PERFORMANCE EVALUATION OF A COCO SUGAR PROCESSING (CCSP) MACHINE

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Abstract: *This study outlines the design, development, and evaluation of a semi-automated Coconut Sugar Processing (CCSP) machine aimed at addressing inefficiencies in coconut sugar production. The machine integrates an automated temperature controller and dual heating (L.P.G. and AlChrome electric) to evaporate, granulate, and crush coconut sap. Tests at 105°C, 110°C, and 115°C (2 liters per trial) showed that higher temperatures reduced production time and increased cooking recovery. Treatment 3 (115°C) achieved the highest production rate (0.689 kg/h). Sensory evaluations confirmed consumer preference for higher-temperature samples, although the difference was minimal and statistically insignificant. The CCSP machine demonstrated a rated capacity of 162 kg/h and an operational efficiency of 87%. Its adoption is expected to enhance product quality, worker safety, and production efficiency, especially for small producer groups facing limited production capacity and economic challenges in the coconut sugar industry.*

Keywords: Coconut Sugar; Coconut Sap; Crystallization; Coco Sugar Processing Machine

1. INTRODUCTION

The coconut palm (*Cocos nucifera*), also known as the "Tree of Life," is a significant contributor to the Philippines' agricultural economy [1] [2]. The country is the world's second-largest producer of coconuts, with coconuts grown in 69 of its 82 provinces. The Philippine coconut production was 14.9 million metric tons in 2023, a 5% increase from 14.4 million metric tons in 2020 [1] [3]. This increase highlights the significance of coconuts to the agricultural economy and the potential of the coconut industry to foster and support national economic growth and rural livelihoods.

A wide range of research and development has been conducted on coconut-based high-value products, including coconut sugar, virgin coconut oil, desiccated coconut, and copra meal [4]. In coco sugar production, the sap from the coconut flower is collected when the tree is tapped, and follows a series of processing steps (heating, boiling, sieving, drying). Quality measures have been outlined as part of the process to ensure the commercial viability and production of high-value products. With the global demand for natural sweeteners increasing, coconut sugar has emerged as a viable product targeted for the health market. The popularity of coco sugar can be largely attributed to its unique taste and appearance, as well as a variety of health benefits, such as a lower glycemic index compared to other sweeteners and healthy substitutes [5].

The Philippines continues to experience growth in coconut sugar exports, but it is undergoing a transitional period, as the country has faced several structural and operational challenges related to the coconut sugar industry in recent years. One of the major issues facing the industry is the production process.

The traditional method of coco sugar production utilizes various manual tasks, which lower production capabilities, decrease the consistency of the quality of the final product, increase overall supply costs, and restrict the ability to participate in a larger market share in the coco sugar industry. Furthermore, micro, small, and medium-sized enterprises (MSMEs), which dominate the coco sugar industry, do not have immediate access to equipment, resulting in lower production output and a lack of economies of scale with traditional methods.

Although the coconut sugar industry is expected to yield considerable agricultural and economic value to the Philippines, the coconut sugar sector has a low adoption rate for the use of mechanized systems. It is reasonable to assume that producing a fully automated solution that takes into account the needs and wants of local producers will serve as an opportunity to change the way coco sugar is produced and consumed while promoting sustainability and reducing food waste.

The objectives of the study are to address these issues, specifically aiming to:

1. Develop a coconut sugar processing machine with an automated temperature control system.
2. Determine machine performance on
    a) Crystallizing Capacity
    b) Machine Output Capacity
    c) Machine Output Efficiency
3. Conduct a sensory evaluation to assess the overall acceptability of the produced cacao sugar.

The study intends to promote the sustainability and improvement of coco sugar production processes in the Philippines, ultimately to facilitate continued growth in local and export markets.

2. MATERIALS AND METHODS

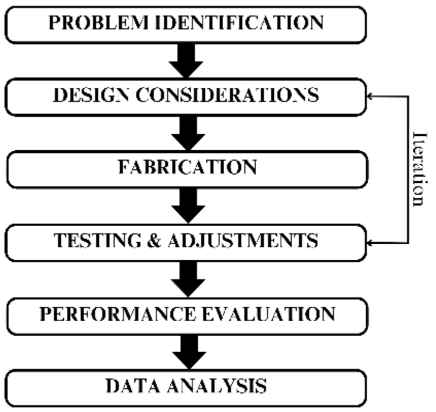


Fig. 1. Framework of the Study

A structured methodological framework was used in this study. This method was useful to steer the change procedure and evaluation steps on a coco sugar processing machine (Fig. 1). The initial step was to identify production inefficiencies, focusing on the limitations and gaps of existing coco sugar processing methods to identify some of the potential problems that coco sugar processors are experiencing (i.e., high manufacturing costs, labor-intensive process).
This diagnostic phase of research informed the design development phase, which included process-related considerations within the specified design, such as machine size, stirrer specifications, and the addition of a temperature control system.

After the design phase, the modified coco sugar processing machine was fabricated at Caraga State University with selected materials and techniques using recommended construction specifications made during the design phase. After the machine was constructed, it underwent experimental testing and iterations, with careful monitoring, logging, and adjustments to operational parameters to maximize performance.
Performance evaluation involved a number of quantitative measures of relevant operational parameters, such as crystallizing capacity, machine capacity, and machine output efficiency, as well as a sensory evaluation of the coco sugar produced. Finally, data analysis employed Analysis of Variance (ANOVA) to evaluate the appreciative machine's performance, and the economic analysis included NPV, BCR, and PBP in terms of its potential application in small- to medium-scale agro-industrial enterprises.

2.1 Design Considerations

The design and development of the Coco Sugar Processing Machine required the appropriate integration of design factors necessary to harness the unique properties of coconut sap, ensuring that processing efficiency, product quality, and operator safety were all achieved.

In ergonomic design, machines should be tailored to the physical characteristics of their users. Anthropometric data specific to Filipinos, such as the average adult height ranging from 150 cm to 160 cm, ensures comfort, safety, and efficiency. Studies report average heights of 159.96 cm for Filipino men and 149.85 cm for women [6].

Designing machines within these measurements, such as a proposed height of 157.8 cm (see Fig. 2), supports proper posture, reduces the risk of musculoskeletal disorders, and enhances productivity [7]. Due to ergonomic considerations, the machine was also designed with respect to cleaning and maintenance, featuring a modular component layout that allows for easy disassembly, cleaning, and sanitization after each batch.

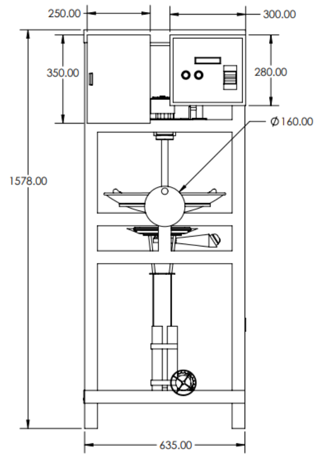


Fig. 2. Dimensions of the CCSP

A gear motor running at 50 rpm, as specified by PAES 236:2008, is used to support the evaporation and crystallization processes in coco sugar production. The stirrer shaft and paddle, made of food-grade stainless steel, ensure safety and durability. Since heat can reduce motor efficiency and lifespan—halving insulation life for every 10°C rise—the motor is mounted 40 cm above the heated wok with a plate barrier to minimize heat exposure.

Fig. 3. Two-Blade Paddle Stirrer Design in CCSP

The wok, modeled as a semicircular shape with a diameter of 48 cm (radius = 24 cm), was analyzed to determine geometric properties relevant to mixing and heat distribution. Using a central arc angle of 60° ($\pi/3$ radians), the chord length was calculated as 24 cm, and the sagitta (vertical rise) as 3.2 cm (see Fig. 3). Applying the sagitta formula, the resulting radius of curvature was confirmed to be approximately 24 cm, consistent with the wok's known radius, validating the assumed geometric profile. Testing revealed a maximum sugar depth of 2 mm at the wok center, so a 1 mm clearance was maintained between the stirrer paddle and wok surface to ensure effective mixing and support proper crystallization.

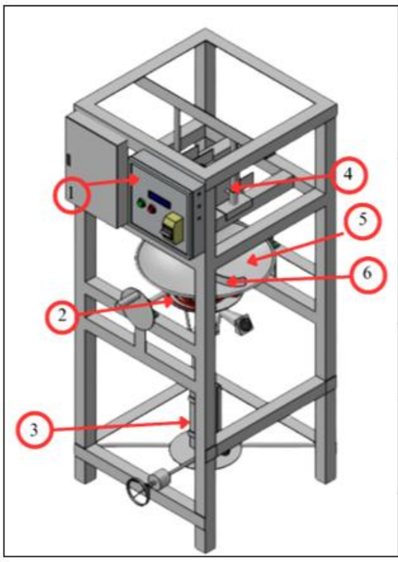
The machine would incorporate a temperature monitoring and control mechanism that would enable the operator to regulate the heat throughout the entire process. The heating system was designed to allow the heat source to be set to predetermined temperature settings of a range of 105°C to 115°C [8]. AlChrome (FeCrAl) wire was selected for heating due to its excellent high-temperature resistance, oxidation resistance, and durability, outperforming the initially tested NiCr wire [9]. To minimize heat loss and maintain consistent temperatures up to 115°C, refractory concrete cement was used as insulation for its high thermal resistance and low conductivity [10]. The designed cooking vessel material was selected based on food-grade stainless steel, which would provide sufficient cooking capacity while respecting food safety standards and maintaining thermal conductivity.

Regarding the automated temperature control system, the PID controller constants ($K_p = 4.0$, $K_i = 0.5$, $K_d = 0.01$) were tuned experimentally for a fast response rate with little overshoot and stability and exceeded what was originally produced with the Ziegler–Nichols tuning because of the nonlinear thermal dynamics of the system. The PID system uses a MAX6675 thermocouple with an Arduino Mega to stabilize temperatures whilst coconut sap caramelizes (105°C, 110°C, 115°C) by controlling relay systems that switch on and off heating elements. Due to the gradual switching of the heating elements to control the temperature, the temperature becomes more stable, allowing for the production of sugar with consistent quality. Currently, the system is threshold-based, but it can be enhanced to become a more sophisticated, proper PID-based switching system for regulating the temperature.

Sap characterization was conducted at three collection sites—Cabayawa, Tubay; Brgy. Masao, Butuan City; and Brgy. Aupagan, Butuan City—to analyze the pH levels of the samples. Monitoring pH served as a critical quality control parameter, ensuring that the sap entering the stock pot was free from contaminants and maintained within the optimal range for effective production of coco sugar.
Taking into account the technical specifications and operational parameters, the Coco Sugar Processing Machine was successfully developed to deliver consistent performance, ensure high product quality, and prioritize user-friendliness.

2.2 Design

The Coco Sugar Processing Machine (CCSP), as shown in Figure 4, is a semi-automatic machine designed for producing coco sugar from coconut sap. The machine is functional and easy to operate, providing an efficient, consistent, and controlled cooking process. The CCSP operates through the integration of several components, all of which are installed in a vertical frame, ensuring that everything is logically assembled and all processing functions are controlled from a single location.



No.	Name of Parts
1	Panel
2	Electric Burner
3	Lifting Mechanism
4	Motor
5	Stock Pot
6	Stirrer

Fig. 4. Coco Sugar Processing Machine (CCSP)

At the top of the machine is the control panel (1), which contains the electronic control for the entire operation, including controls for motor speed, gas burner ignition, and process timing. The electric burner (2) is directly below the stock pot, and it works with the gas burner system to ensure even heating and accurate temperature control. The electric burner is designed to be removable (3), so that it will allow for the space to pour out the cooked coco sugar from the stock pot. The mechanical agitation is generated by a DC gear motor (4) that drives a stirrer (6) inside the stock pot (5).

The stirrer continuously propels a complete mixing of the coconut sap during heating, preventing concentrated burning of the sap and allowing for uniform water evaporation. The stockpot (5) is the main cooking chamber and where the sap is evaporated down to a granular state. Stirring is a critical part of the converting process from sap to granulated coco sugar and maintains product quality and consistency. The overall design ensures the proper encasement of all machine components, thereby maintaining their operational capability and serviceability.

Other components not visible are the LPG tank, which is located at the base of the machine. Also located beneath the control panel is the solenoid valve, a device that regulates the gas supply from the LPG tank at the base of the frame, and it is used for safety and control purposes.

The systematic diagram of the coconut sugar processing machine demonstrates the integrated operation of electrical and thermal systems within the processing system. This will provide a comprehensive analysis with a systematic breakdown of the aspects underlying potential machine failures throughout this work. The Coco Sugar processing machine experimental procedures are as:

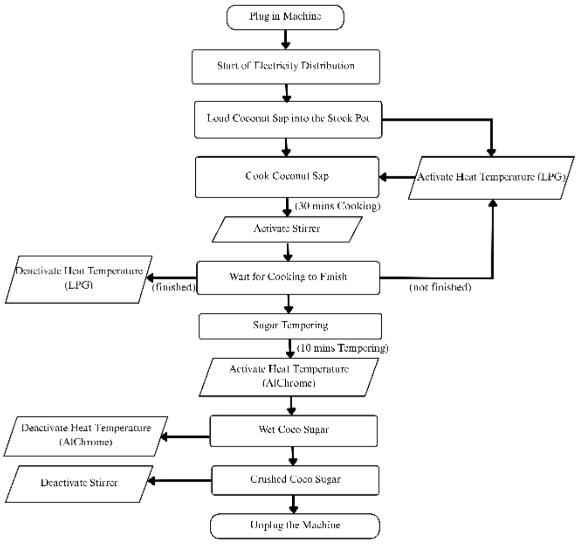


Fig. 5. System Flow Diagram

1. The process commences by plugging in the machine and starting the electricity flow.
2. The freshly harvested coconut sap is placed in the stockpot for processing.
3. The system engages the LPG heat for cooking the sap.
4. The stirrer engages (after 30 minutes)
5. The system monitors the cooking process.
6. When the sap is done cooking, the system turns off the LPG heat.
7. The process continues with tempering the sugar, which involves continuous stirring and heating that enhances texture and quality for ten minutes of stirring.
8. An AlChrome (electric) heating element is engaged for tempering (essentially a ten-minute duration).
9. When the sap turns into a very wet coco sugar, the AlChrome heating system is disengaged.
10. The output is coco sugar, which is crushed to get to the product, then the stirrer is disengaged.
11. We finished the operation by unplugging the machine.
12. Transfer the crushed sugar into a container.
13. Let it air dry.
14. Put inside the packaging.

The coco sugar processing machine has a multi-heat source system, using LPG for the cooking phase and AlChrome electric heating for the tempering phase, both ensuring the temperature is controlled throughout the process. The machine features element and stirrer activation and deactivation systems, which are set to operate with either a timed interval or a process status interval, thereby reducing the need for manual intervention. Furthermore, the flowchart illustrated a permanent order of sequential mechanical processing operations followed by thermal operations, which aided in the repeatability of the product.

Overall, the coco sugar processing machine is designed to achieve operational excellence in processing coco sugar, including accuracy, operational efficiency, and ease of control operation, with the distinction between manual completion of the initial setup and automated completion of the main processing operation.

2.2 Fabrication

The researchers utilized the tools and equipment available at the Caraga State University-Main Campus, Farmshop facility, in Brgy. Ampayon, Butuan City, to design and build the Modified Coco Sugar Processing Machine. The equipment was very limited, consisting of a drilling machine, wrenches, and hand and power tools necessary for machining and assembly.

2.3 Evaluation & Testing

To ensure reliability and the effective operation of the machine, evaluation and testing were conducted. This method of testing and evaluation plays a crucial role in identifying operational constraints, potential malfunctions, and system deficiencies. As a result, the researchers were able to provide suitable remedial actions.

2.4. Sample Preparation

Coconut sap was freshly harvested from Brgy. Aupagan, Butuan City, Agusan del Norte, Cabayawa, Tubay, Agusan del Norte, and Brgy. Masao, Butuan City. (see Figure 11). This was used in the evaluation of the coconut sugar processing machine.

(a) (b) (c)

Fig. 6. *Mananggites* from (a) Brgy. Aupagan, Butuan City, (b) Cabayawa, Tubay, and (c) Brgy. Masao, Butuan City, collecting fresh coconut sap.

The sap collected is available in different colors, depending on its pH. The lowest pH documented was 4.01, while the highest was 5.55. The sap was also available in different colors (see Fig. 6). Every batch of coconut sap collected is placed in refrigeration immediately to retain freshness and limit spoilage. Chilling the sap at a low temperature dramatically slows the natural fermentation process occurring due to microorganisms. This was essential to preserving the quality of the sap for processing.

2.5 Data Gathering and Testing Analytics

Controlled tests were done using a fixed coconut sap volume of 2L to maintain consistency across tests and were tested at three (3) treatments (105°C, 110 °, 115°C). The pH and other parameters were measured and recorded for each batch during the entire processing cycle. The data collected were analyzed statistically, primarily through analysis, which calculated averages and comparisons to evaluate the machine's capability and efficiency. Following the technical comparisons, an economic analysis was conducted to assess the cost-effectiveness and leverage factors for the potential investment in utilizing the machine for small- to medium-scale production.

Fig. 7. Freshly collected sap samples.

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3. RESULTS & DISCUSSION

This chapter explains the findings from the evaluation and testing of the coconut sugar processing machine. In this chapter, the discussion will encompass the performance objectives of total production time, total coco sugar yield, crystallizing capacity, overall machine output capacity, machine output efficiency, sensory evaluation, and economic analysis.

3.1 Total Production Time

There was a variation in the time taken for the evaporation and crystallization processes among the three treatments, with T1 taking the longest. The average time for evaporation of T1 was 75.99 minutes, and the crystallization time was 24.49 minutes, compared to T2 and T3. The reason for the longer time required for T1 may be due to its higher initial moisture content and lower pH, which affect the evaporation rate and sucrose crystallization [8] [11] .

The higher the temperature of the treatment, generally, the less time it takes for processing because water evaporates quickly and crystallizing sugar takes less time, which is what thermodynamic principles suggest: the greater the amount of heat, the faster the transition of the water and sugar phases will occur.

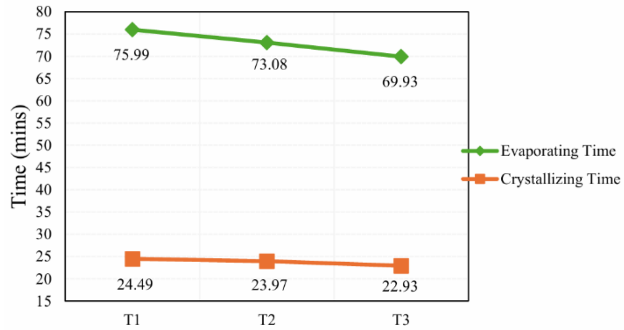

Fig. 8. Total Production Time per Phase of Coco Sugar Production

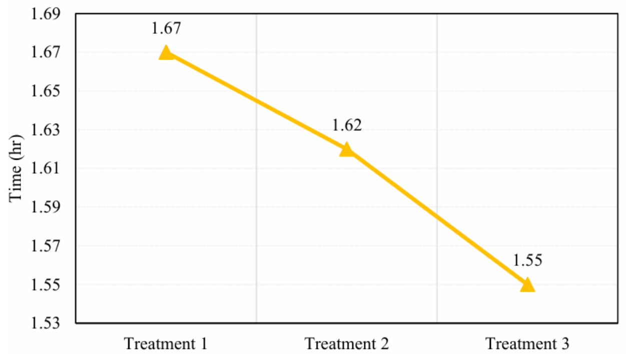

Fig. 9. Total Production Time of CCSP Machine

Generally, the higher the temperature, the better the efficiency will be; however, it also makes the sugar susceptible to burning or caramelization, which affects its flavor, color, and nutritional value [8]. As previously stated above, T1 took a total of 1.67 hours to process, as indicated in Figure 3. There are now innovations, such as vacuum rotary evaporation, which can reduce processing time at lower temperatures by lowering the boiling point of water and potentially improving product quality and efficiency [12]. Furthermore, automated temperature control systems support the maintenance of desirable conditions to keep the product stable without diminishing any allowable physicochemical properties [13].

3.2 Total Coco Sugar Yield

As observed in Figure 9, Treatment 3 yielded the greatest average final weight of coconut sugar (263 g), followed closely by Treatment 2 (260.7 g) and Treatment 1 (259.7 g). Likewise, Table 4 indicates that Treatment 3 had the greatest cooking recovery with a mean recovery of 87.66%. Treatment 2 and Treatment 1 had means of 86.88% and 86.55%, respectively. While the variation may not seem substantial, this adjustment could be meaningful from a profitability perspective, whether for small-scale use or commercial production. The greater cooking recovery ratio of Treatment 3 compared to Treatment 1 or Treatment 2 indicates that the product has likely experienced the most optimal temperature profile throughout the cooking process, facilitating moisture evaporation, sugar crystallization, and thus reducing the need for excessive heat, which can cause charring or caramelization and ultimately lead to product wastage.

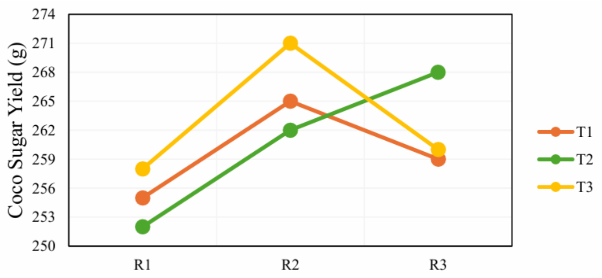

Fig. 10. Graphical Presentation of Coco Sugar Yield.

Muriel et al. (2019) suggest that improved control over processing parameters, specifically temperature application and endpoint detection, could enhance sugar recovery and mitigate the impact of thermal degradation. Under ideal circumstances, 1 kg of coconut sugar can be produced from "6-8 liters" of fresh sap [14] [15]. It is vital to control sweating and crystallization as closely as possible. Also consider the viscosity, initial sugar concentration (°Brix), and pH before cooking, as these factors also impact cooking efficiency and total yield. Take, for example, total soluble solids; the higher the total soluble solids, the less energy is required and the shorter the cooking time.

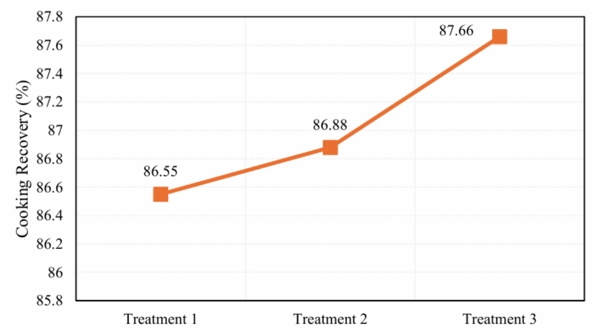

Fig. 11. Recovered Coco Sugar at the End of the Production.

A report that the temperature and pH appear to positively correlate with browning intensity and antioxidant activity, which are both derived from the biochemical reactions of the Maillard reaction that can depict the level of sugar production completeness and product quality, and highlights the importance of heat control throughout the temperature range [8].

3.3 Evaluation of Total Production Time

Table 1. Analysis of Variance for Evaporating Time

	SS	df	MS	F	α
Between Groups	55.054	2	27.527	1.556	0.285
Within Groups	106.129	6	17.688		
Total	**161.184**	**8**			

The results of the ANOVA tests on evaporation time are presented in Table 5. The ANOVA test yielded F (2, 6) = 1.556 and p = 0.285. The p-value was greater than 0.05; therefore, we conclude that there is no statistically significant difference in the average evaporating time of the treatments (T1, T2, and T3). While not statistically significant, T3 had the lowest evaporating time. One explanation could be the higher temperature of T3. Higher temperatures during food product processing increase the rate of water evaporation, which may account for the difference in evaporation times between T1, T2, and T3.

A study confirms that higher temperatures can optimally accelerate the evaporation process, resulting in a decreased production time for coconut sugar [11]. For crystallization time, the ANOVA test yielded F(2, 6) = 0.885 and p = 0.460, as shown in Table 6. Since the p-value is greater than 0.05, there was no statistically significant difference in average crystallizing time across treatments. The treatments had a minimal effect on crystal formation. Crystallization times can be influenced by several factors, including supersaturation levels, cooling rates, and agitation. These factors were imposed equally across the treatments in this study. The non-significant difference in crystallization indicates the treatments had similar applied parameters, which ultimately resulted in a common crystallizing time.

Table 2. Analysis of Variance for Crystallizing Time.

	SS	df	MS	F	α
Between Groups	3.789	2	1.895	.885	0.460
Within Groups	12.843	6	2.140		
Total	**16.632**	**8**			

This supports the recommendations in [8] that controlled processing parameters are crucial for ensuring a constant crystallization time when producing coconut sugar. In terms of total production time, the test produced F(2, 6) = 1.291 with a p = 0.342, as shown in Table 14. This value is much greater than 0.05, so we can conclude that there is no statistically significant difference. The mean total production time was not statistically significant for T1, T2, and T3. That means treatment variation did not have a large effect on the overall total production time. This indicates that although some production phases (evaporating and crystallizing) may exhibit detectable variations in time due to differences in treatment. This could be interpreted as meaning that the production times for the three treatments did not statistically differ in overall production time. This is consistent with [11], where the researchers stated that changes in production parameters can improve the quality of specific production phases without affecting the overall production time.

Overall, the ANOVA tests on evaporating time, crystallizing time, and total production time found no statistically significant differences between the three treatments. However, there were observable trends. T3 had a decreased evaporation time, which may be attributed to the processing conditions. This implies that effective temperature had an impact on the phases of the coconut sugar making.

Table 3. Analysis of Variance for Total Production Time.

	SS	df	MS	F	α
Between Groups	0.023	2	0.011	1.291	0.342
Within Groups	0.053	6	0.009		
Total	**0.076**	**8**			

These conclusions suggest that optimizing processing parameters at specific phases may influence the overall production time without a significant reduction in process time.

3.4 Evaluation of Crystallizing Capacity

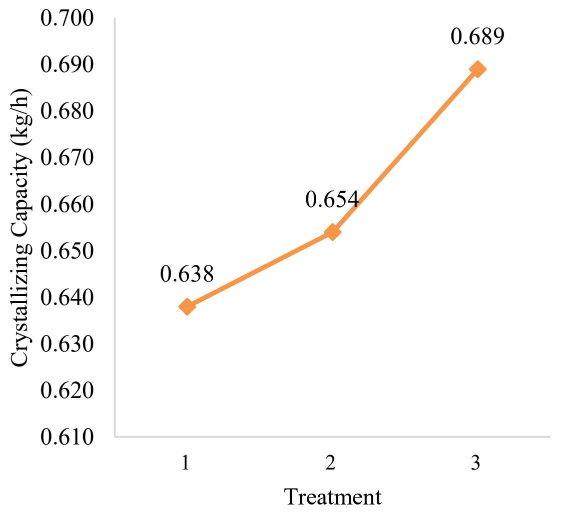

Fig. 12. Graphical Presentation of Crystallizing Capacity.

The ANOVA test for crystallizing capacity shows an $F(2, 6) = 2.525$ with a p-value of 0.160, indicating that no statistically significant difference exists among the three treatments. As presented in Fig. 8, T3 had the highest crystallizing capacity (0.689 kg/hr), followed closely by T2 (0.654 kg/hr) and T1 (0.638 kg/hr). While statistically insignificant, the trend observed for treatment 3 to perhaps benefit from better processing conditions, such as temperature and pH, was favorable for crystallization.

Table 4. Analysis of Variance for Crystallizing Capacity.

	SS	df	MS	F	α
Between Groups	0.006	2	0.003	2.525	0.160
Within Groups	0.008	6	0.001		
Total	**0.014**	**8**			

A study reported significant influences of temperature and pH on the crystallization of coconut palm sugar, as these factors affect the efficiency and quality of the product [11]. A study reported that both equipment and technical skillfulness are essential for creating crystallization; equipment such as stirring, temperature control, and rate control all affect the crystallization process [8].

3.5 Overall Machine Output Performance

The coco sugar processing machine achieved an overall machine output capacity of 0.162 kg/h and a machine output efficiency of 87%, indicating that it operated adequately (see Figure 9). This result supports the findings of [16], who reported increased product quality and higher efficiency when producing palm sugar using pan evaporators and crystallizers with rotating mechanisms.

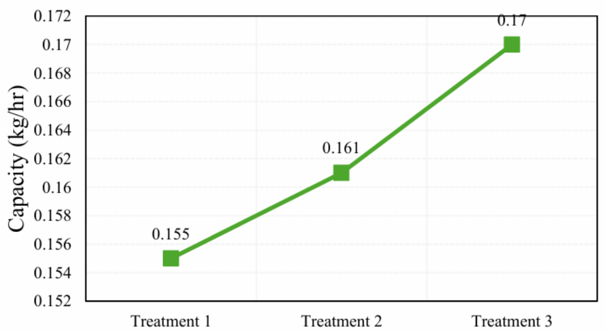

Fig. 13. Machine Output Capacity of CCSP

The coco sugar processing machine produced coconut sugar with an average fineness modulus (FM) of 3.72, which falls within the acceptable FM range of 3.08–5.97 [14]. A report showed slightly higher FM values (3.95–4.53), indicating that the average particle size of the granules was approximately acceptable for consumption or industrial applications [16]. Importantly, lower FM values imply that smaller particles were being produced, which is desirable in many processing applications.

The high output efficiency and acceptable granule size were primarily the result of the coco sugar processing machine's ability to maintain and regulate stirring and a consistent temperature, contractual conditions that are crucial for proper crystallization. The results from this current experiment demonstrate the role played by mechanics and thermodynamic principles in controlling the quality and output of coco sugar.

3.6 Sensory Evaluation

Nine (9) samples of coco sugar went through a sensory evaluation using a 5-Hedonic Scale, where five attributes were assessed: appearance, aroma, texture, taste, and overall acceptability. Sample H5J received the highest mean score (4.73), making it the most favored, particularly for taste, and also scoring well in appearance, aroma, and texture. Sample X7A yielded a mean score of 4.56, noted for its high appearance and texture ratings. Sample Q6N had a moderate score of 4.17, mainly affected by appearance. In contrast, sample Z4P had the lowest acceptability (mean score of 3.75), with low ratings in appearance and texture, indicating it was the least preferred by consumers.

These differences in sensory scores reflect variations in processing treatments, which influenced key quality attributes like texture, color, flavor, and aroma, factors that shape consumer perceptions of coco sugar. Further research into the functional properties of the samples would help explain these sensory outcomes and better assess overall product quality.

(a) (b)

Fig. 14. Coco sugar samples evaluated: (a) Coco Sugar bought from the market and (b) Sample H5J.

4. CONCLUSION

The testing and development of the coco sugar processing machine showed that heating and stirring automatically produced improved efficiencies, and more consistent production, with less time and labor input compared to the same production processes where heating and stirring were done manually. At processing temperatures of 105˚C, 110˚C, and 115˚C, the processing times and yields were similar, but the temperature of 115˚C yielded the best sugar recovery and sensory quality. This suggests that improving temperature optimization is an important way to improve the quality of coco sugar products. Ultimately, the coco sugar processing machine can modernize coco sugar production while maintaining product quality, with further improvement potential with greater precision, and refined thermal control measures.

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