UNIVERSITI PUTRA MALAYSIA

# *PROCESSING OF COCONUT SAP INTO SYRUP AND GRANULAR SUGAR USING DIFFERENT EVAPORATION TECHNIQUES FOR ECONOMICAL PRODUCTION*

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By

**ASGHAR MUHAMMAD TUSEEF**

**Thesis Submitted to the School of Graduate Studies, Putra Malaysia, in fulfilment of the requirement for the Degree of Doctor of Philosophy**

**October 2021**

**DEDICATION**

This thesis is dedicated to Almighty Allah, the Merciful, the Nourisher who created and gave me the privilege to start and complete my study, my esteemed father Asghar Ali Sandhu (Late), and my admired and precious mother Suryia Begham who raised me and provided the opportunity for me to become who I am today. Also, the dedication goes to my appreciated and beloved wife Sadaf Fatima, my cute daughter Tehreem Fatima and my lovely son Muhammad Affan Tuseef for their unbearable sacrifices.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the Degree of Doctor of Philosophy

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**Chairperson : Professor Yus Aniza binti Yusof, PhD**
**Faculty : Engineering**


Malaysia is the 6$^{th}$ major raw sugar importing country, to support domestic consumption. Producing sugar from coconut sap is an alternative to sugarcane; in fact, coconut sugar has entered the global marketplace with increasing consumption by a more health-conscious world population. In Malaysia, coconut sugar has limited use, primarily as an ingredient in traditional dishes. Commercial production of coconut sugar by open-heat evaporation exposes the sap to a high temperature (>100 °C) for a long time (3-5 hours), causing inconsistent and decreased quality of the coconut sugar produced. The overall objective of this research was to explore the use of coconut sap as an alternative sugar source by identifying a suitable processing method that can efficiently produce a high-quality product with the potential for commercialization.

Initially, fresh coconut sap, sugar palm sap, and sugarcane juice were analyzed and compared their properties and nutrient values. The concentrations of three sugars (fructose, glucose, and sucrose), six vitamins (vitamin C, B1, B3, B4, B2, and B10), and antioxidant activities were higher in coconut sap compared with the other two (2) sugar sources. Then, three evaporative processing methods [rotary (RE), microwave (ME), and open-heat (OHE) evaporation] with different conditions were used to produce coconut sugar. Rotary evaporation at 60 °C and 250 mbar vacuum pressure (RE-60) provided the suitable conditions, producing coconut sugar after a short processing time (12.2 min) at a lower processing temperature (54.8 °C), which contributed to lower energy requirements (0.35kWh).

Storage stability of the coconut sugar was evaluated at room temperature (25 °C) and elevated temperature (38 °C) for 8 weeks. Less change in moisture content, water activity, stickiness, lightness, colour, and browning index was observed for RE coconut sugar compared with those made using the other processing methods, suggesting greater quality stability of RE sugar. Morphology changes of sugar stored at elevated temperature compared with room temperature supported that room temperature is more appropriate for coconut sugar storage, and temperature excursions during shipping and warehousing should be avoided. Sensory evaluation showed higher scores for all attributes for RE compared with OHE sugar. The design, scale-up simulation, and cost analysis for commercial production of coconut sugar were also evaluated. The RE method was more time-efficient and economical compared with the ME and OHE methods. Production costs and pay-back period were more favourable, with a higher gross margin for coconut sugar produced with RE-60.

Coconut sugar production based on a minimum capacity of 750L/batch (2250L/day) can be a viable project in the Sabak Bernam district of Selangor state Malaysia. The coconut sugar price calculated for this project (RM35.76/kg) lower compared with commercially available coconut sugar price (RM45/kg) and the project is expected to payback invested capital in about 3.50 years. The project could generate local employment by producing sugar from local materials and could have an impact on foreign exchange by decreasing the sugar import price.

Overall, the study showed that coconut sap processed using RE can be an economical source of high-quality granular sugar. Rotary evaporation at 60 °C provided more suitable processing conditions, with minimal energy requirement. The production of marketable coconut sugar has the potential to supplement both local and international demand, generating additional income. Strategies to address the well-defined constraints and limitations of scale-up and commercialization are needed, and further research is warranted.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**PEMPROSESAN SAP KELAPA DALAM SIRAP DAN GULA GRANULAR MENGGUNAKAN TEKNIK PENGUAPAN BERBEZA UNTUK PENGELUARAN EKONOMI**

Oleh

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Malaysia merupakan pengimport gula mentah utama yang ke-6, terutamanya menyokong keperluan domestik. Pembuatan gula daripada sap kelapa merupakan alternatif selain daripada tebu; di mana gula kelapa telah memasuki pasaran global dengan peningkatan keperluan oleh golongan yang mementingkan kesihatan di dunia. Di Malaysia, penggunaan gula kelapa adalah terhad, dan hanya dimakan sebagai ramuan dalam masakan tradisional. Selain itu, pembuatan gula kelapa secara komersial dengan menggunakan kaedah penyejatan haba terbuka telah mendedahkan sap kelapa pada suhu tinggi (> 100 °C) untuk jangka masa yang panjang (3-5 jam). Ini menyebabkan kualiti gula kelapa yang dihasilkan terjejas dan tidak konsisten. Objektif keseluruhan kajian ini adalah untuk menelitikan penggunaan sap kelapa sebagai sumber gula yang alternatif dengan mengenalpastikan kaedah pemprosesan yang sesuai dan efisien untuk menghasilkan produk yang berkualiti tinggi dan berpotensi untuk dikomersialkan.

Sap kelapa segar, sap nira enau dan jus tebu telah dianalisis dan dibandingkan dari segi sifat dan nilai nutrien. Kepekatan gula utama (fruktosa, glukosa, dan sukrosa), vitamin (vitamin C, B1, B3, B4, B2, dan B10) dan aktiviti antioksidan untuk sap kelapa adalah lebih tinggi berbanding dengan dua (2) sumber gula yang lain. Kemudian, tiga kaedah pemprosesan evaporatif [penyejatan berputar (RE), ketuhar gelombang mikro (ME) dan penyejatan terbuka (OHE)] dengan kondisi yang berbeza telah digunakan untuk menghasilkan gula kelapa. Penyejatan berputar pada 60 °C dan tekanan vakum 250 mbar (RE-60) didapati adalah kondisi yang paling sesuai, di mana gula kelapa dihasilkan dalam tempoh pemprosesan yang singkat (12.2 min) pada suhu pemprosesan yang lebih rendah (54.80 °C), dan menyumbangkan keperluan tenaga yang lebih rendah (0.35kWh).

Kestabilan penyimpanan gula kelapa telah dinilai pada suhu bilik (25 °C) dan suhu tinggi (38 °C) selama 8 minggu. Perubahan yang minimal dari segi kandungan kelembapan, aktiviti air, kelekitan, keringanan, warna dan indeks pemerasan telah diperhatikan untuk gula kelapa RE, berbanding dengan gula kelapa yang dihasil menggunakan kaedah pemprosesan lain, memperlihatkan lebih stabiliti kualiti gula RE. Perubahan morfologi gula yang disimpan pada suhu tinggi telah diperlihatkan dan dibanding dengan penyimpanan pada suhu dan didapati bahawa suhu bilik adalah lebih sesuai untuk penyimpanan gula kelapa, dan perubahan suhu ketika perkapalan dan penggudangan harus dielakkan. Penilaian sensori menunjukkan bahawa lebih tinggi skor untuk semua atribut bagi gula kelapa RE berbanding dengan gula kelapa OHE. Reka bentuk, simulasi skala tambah, dan kos analisis bagi penghasilan gula kelapa secara komersial juga telah dinilai. Kaedah RE didapati lebih menjimatkan masa dan lebih ekonomikal. Kos pengeluaran dan tempoh bayaran balik adalah lebih menggalakkan dengan margin kasar yang lebih tinggi untuk gula kelapa yang dihasilkan dengan RE-60.

Pengeluaran gula kelapa berdasarkan kapasiti minimum 750L/kelompok (2250L/hari) dapat dilaksanakan di daerah Sabak Bernam, Negeri Selangor, Malaysia. Projek ini dapat menjana peluang pekerjaan tempatan dengan menghasilkan gula daripada bahan tempatan dan dapat memberikan kesan kepada pertukaran wang asing dengan menurunkan harga import gula.

Keseluruhannya, kajian ini menunjukkan bahawa sap kelapa yang diproses menggunakan RE dapat menjadi sumber ekonomi gula pasir yang berkualiti tinggi. Penyejatan putar pada suhu 60 °C adalah kondisi pemprosesan yang lebih sesuai, dengan keperluan tenaga yang minimal. Pengeluaran gula kelapa yang boleh dipasarkan mempunyai potensi untuk memenuhi kedua-dua permintaan tempatan dan antarabangsa, serta dapat menjana pendapatan tambahan. Strategi untuk mengatasi kekangan dan limitasi skala tambah yang jelas dan pengkomersialan diperlukan, berserta dengan penyelidikan yang lebih lanjut.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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**Declaration by Members of Supervisory Committee**

This is to confirm that:

- The research conducted and the writing of this thesis was under our supervision;
- Supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

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| | |
|---|---|
| ABTS | 2,2'-azino-bis-3-ethylbenzthiazoline-6-6sulfonic acid |
| ADA | American diabetes association |
| ANOVA | Analysis of Variance |
| AOAC | Association of Official Agricultural Chemists |
| ARP | Amadorire arranged products |
| aw | Water activity |
| BAFPS | Bureau of Agriculture and Fisheries Product Standards |
| BI | Browning index |
| C* | Chroma |
| CDB | Coconut development board |
| CI | Cohesion index |
| CIE | Commission Internationale de I'Eclairage |
| CIP | Cleaning in place |
| CPs | Caramelization products |
| CSS | Commercial coconut sugar |
| DFC | Direct fixed capital |
| DPPH | 2,2-diphenyl-1-picrylhydrzyl |
| EHT | Extra-high tension |
| EPC | Equipment purchase cost |
| ET | Elevated temperature |
| FAO | Food and Agriculture Organization |
| FCR | Folin-ciocalteu regent |
| FRAP | Ferric reducing antioxidant power |
| GI | Glycaemic index |

| | |
|---|---|
| H* | Hue angle |
| HMF | Hydroxymethyl furfural |
| HPLC | High-performance liquid chromatography |
| HRP | Heyns rearrangement products |
| HTF | Horizontal thin film |
| ISO | International Organization for Standardization |
| MC) | Moisture content |
| ME | Microwave evaporation |
| MRPs | Maillard reaction products |
| MT | Metric ton |
| ND | Not detected |
| OHE | Open-heat evaporation |
| OP | Open pan |
| PCA | Philippine coconut authority |
| PCARRD | Philippine Council for Agriculture, Forestry and Natural Resources Research and Development |
| PFA | Powder flow analyser |
| PFSD | Powder flow speed dependency |
| QA | Quality assurance |
| QC | Quality control |
| RE | Rotary evaporation |
| RID | Refractive index detector |
| RT | Room temperature |
| SEM | Scanning electron microscope |
| SMEs | Small and medium entrepreneurs |

| | |
|---|---|
| SPD | Superpro Designer (software) |
| TPC | Total phenolic contents |
| TPC | Total plant cost |
| TPDC | Total plant direct cost |
| TPIC | Total plant indirect cost Engineering |
| TSS | Total soluble solids |
| UEPC | Unlisted Equipment Purchase cost |
| USD | United States dollar |
| UV | Ultraviolet light |
| VTF | Vertical thin film |
| WCT | West coastal tall |
| WHO | World health organization |
| WSI | Water solubility index |
| $\Delta E$ | Colour difference |

# CHAPTER 1

# INTRODUCTION

Coconut sugar has been produced and consumed in Southeast Asia for centuries and, until recently, production has been primarily on small scale for the local market. Now, as the global economy continues to expand, concomitant with increasing health concerns about cane sugar, the demand for coconut sugar is growing across Asia and throughout the world. Other major coconut-producing countries have developed the capacity for large-scale coconut sugar production and have entered the international marketplace. At present, Malaysia is the 6$^{th}$ major importer of raw sugar in the world for its domestic needs (ISO, 2020) and has not undertaken a serious effort to enter the coconut sugar market.

Several challenges that should be overcome constrain the nascent, lucrative opportunity to explore a paradigm shift that should be possible in a country that is perpetually among the top 12 coconut-producing nations in the world (NM, 2020). The acceleration in global coconut sugar demand presents an opportunity for the significant growth of the sector, providing increased prosperity along the value chain, including to the smallholder farmers who dominate the bottom of the chain (Pranav, 2018).

## *The Coconut in Malaysia*

The coconut palm is one of the four (4) major crops (oil palm, rubber, rice, and coconut) grown in Malaysia (Yun, 2019). The most important coconut products in Malaysia are copra (including desiccated coconut, copra meal), coconut oil, and by-products such as coconut shell charcoal (Sivapragasam, 2008). Coconut sugar is not currently a prominent member of the Malaysian coconut product portfolio.

Coconut sugar is rich in antioxidants, minerals, and vitamins compared with sugars made from other sources, and has a lower glycaemic index, which has contributed to its popularity in a health-conscious world (CBI, 2020). Accordingly, the global coconut sugar market is undergoing rapid growth. The key players in the coconut sugar market are the Philippines, Indonesia, and Thailand, which account for approximately 80% of production, with fewer than 20 manufacturers capturing most of the business (CBI, 2020; ICC, 2020).

Entering the coconut sugar market would require a successful value chain shift in Malaysia (Section 2.2, Figure 2.2). The main constraint is the lack of an efficient, reproducible method for evaporation of coconut sap and producing thick coconut sugar syrup or granular coconut sugar.

## 1.1 Processing of Coconut Sugar Syrup and Granular Sugar

Traditional open-heat evaporation (OHE) is the most commonly used method for removing excess water from coconut sap to produce concentrated coconut sugar syrup, which can be further evaporated to produce granular coconut sugar. However, this conventional open-heat method results in an over-cooked sugar, leading to the deterioration of the physical and chemical properties of coconut sugar, with elevated cost due to longer processing time (Apriyantono et al., 2002). Accordingly, an improved coconut sap evaporation method is needed.

Different processing methods, including rotary evaporation (RE) and microwave evaporation (ME) under different processing conditions (different temperatures and microwave powers), were compared with OHE to determine their effects on the physicochemical, nutritional, and antioxidant properties of coconut sugar syrup, to find a better processing method for producing coconut sugar syrup or granular sugar. The physical and flow properties of granular coconut sugar produced in this research were compared with those of coconut sugar available in the market. In addition, storage studies were performed to examine changes in coconut sugar properties at normal and elevated temperatures. The elevated temperature was included to replicate extremes conditions that may be encountered during transportation and warehouse storage of coconut sugar in tropical climates. The results were expected to identify a robust method for producing granular coconut sugar that is suitable for retail sales and food product development, and use in the pharmaceutical and cosmetic industries.

Manufacturing simulations and economic analyses of granular coconut sugar were modeled using SuperPro Designer software incorporating the experimental data resulting from this research. In addition, due diligence was performed to define assumptions such as material costs, chemical costs, labour costs, and the market price of coconut sugar (Petrides, 2015). The approximate cost of coconut sugar production on a commercial scale, processing large volumes of coconut sap, was generated and compared with production costs of granular coconut sugar produced using the traditional method (available in the market) to examine the feasibility of the process chosen from this study. Finally, a plan layout for the coconut sugar industry in Sabak Bernam, Salengor, Malaysia was proposed, based on the simulation and economic analysis results.

## 1.2 Problem Statement

Evaporation during sugar processing (manufacturing) contributes the highest cost share in sugar production (Ensinas et al., 2007). The conventional OHE method requires high temperature ranging from 100-120 °C in an open-pan for 3-5 hours of continuous heating for evaporation (Srikaeo et al., 2019), producing over-processed coconut sugar syrup and granular coconut sugar that have deteriorated physical (appearance, colourcolour, aroma, etc.) and chemical (sugar and vitamin profile, antioxidants, etc.) quality (Apriyantono et al., 2002). This process eventually increases the production cost which will ultimately increase the product pricing.

Reduced processing time and lower temperatures were targeted because longer processing (3-5 h) at high temperatures may enhance the Caramelization and Maillard reaction, which may lead to dark coloured coconut sugar (Apriyantono et al., 2002; Karseno et al., 2018; Nurhadi et al., 2018), for which there is only a niche market in traditional dishes. Phisut (2010) also studied the effect of processing temperature on the browning of palm sugar syrup and palm sugar cake and found the involvement of Maillard in the browning of palm sugar during processing and storage; however, a limited study on coconut sugar syrup or granular coconut sugar manufacturing was found.

Rotary (vacuum) and microwave evaporation methods were accepted as feasible alternative approaches to be investigated for their impact on sugar quality during the processing of sugar. Before examining evaporation methods, laboratory investigations were necessary to establish baseline comparisons of coconut sap obtained from the resource identified for this project with other traditional sugar resources (sugar palm and sugarcane juices). Temperature, humidity, and storage time are important determinants of food quality which can decrease sensory characteristics and induce compositional deterioration (Apriyantono et al., 2002). Thus, it is essential to study the effects of processing methods of granular coconut sugar on the browning, sensory, and physicochemical stability of coconut sugar during storage (Naknean et al., 2013). Hence, the effect of processing/evaporation techniques on storage quality was also an essential component of this research, because the processing methods can influence the quality of granular coconut sugar during storage as reported by Phisut (2010). Stability was examined during conventional and high-temperature storage, envisioning worst-case conditions for coconut sugar product transportation. Economic evaluation is necessary to explore the feasibility of any project (Jiaxin et al., 2018; Lambert et al., 2018; Petrides, 2015). Investors must have valid data supporting potential return on investment across a range of manufacturing options to decide the investment in any project.

To date, there is limited scientific support for coconut sugar production strategies in Malaysia. Therefore, this research aimed to study the effect of evaporation techniques on the physicochemical, antioxidant, mechanical, and sensory properties of coconut sugar syrup and granular sugar along with identification of the evaporation technique that preserves quality with minimum production time and cost and maintains the quality during the storage. Further research is needed to investigate the efficiency and reproducibility of scale-up. Empiric data are necessary to test the model developed during this preliminary research.

## 1.3 Industrial Significance of Study

Converting a portion of Malaysia's coconut tree output to coconut sugar production could ultimately affect the trade balance through two (2) pathways. Entering the global coconut sugar market would increase export income and increasing domestic consumption of coconut sugar as an alternative to cane sugar might offset some of the dependence on sugar imports.

Continuous efforts on promoting the conversion of part of the Malaysian coconut industry to the production of coconut sugar will require a robust, reproducible, and efficient method for evaporating coconut sap. This research explored two (2) alternative approaches; 1) rotary and 2) microwave evaporation and compared them with the traditional OHE method for product composition and quality. A cost model was developed estimating the production cost of coconut sugar, compared with its market price. This research might be helpful for the industry to produce coconut sugar in Malaysia with local raw materials.

## 1.4 Objective

The objective of this research was to describe the effect of processing parameter modifications on the production of coconut sugar.

To achieve the objective of the study, the following specific objectives were set:

1. To evaluate the physicochemical, antioxidant, and nutritional properties of the three sugar raw materials including coconut sap, sugar palm, and sugarcane juices.

2. To evaluate the effects of different processing methods on the sugar profile, functional and physical properties of coconut sugar syrup.

3. To evaluate the effect of storage temperature on the physical properties, morphology, and sensory characteristics of granular coconut sugar.

4. To apply SuperPro designer software for simulation and cost analysis to establish a scenario-testing model designed to help strategize feasible and economical production of granular coconut sugar.

## 1.5 Scope and Limitations of the Study

The scope of this study was to produce coconut sugar syrup and granular sugar from coconut sap using two (2) novel evaporation techniques compared with the problematic traditional OHE method. This SuperPro design may be applicable for processing capacity of 400-800 L/batch coconut sap, in Sabak Bernam District of Selangor State, for 300 working days/year, on 7 years of depreciation, 20 years assumed project lifetime, 24% income tax at the rate, an inflation rate of 0.66-3.87%, and for the year 2022 with all capital received from bank debt.

Physical, vitamin, mineral, and antioxidant profiles of the resulting sugar syrups were compared, and processing data was considered to select a preferred method from the investigational approaches. The crude fiber was not determined in this study as previous findings showed that coconut sap and sugar palm juice contained a very low amount of crude fiber. In addition, phenolic acid, amino acids, flavonoids, and microbial analyses were not performed as they are not relevant to the project objectives. Consumer product characteristics and international standard compliance of sugar made from the preferred method were compared with that of sugar made using the OHE method and with commercial coconut sugar, acknowledging that the commercial sugar had a longer time the following manufacture and that it might have been adulterated. Stability at normal and elevated storage temperatures was examined for these three (3) sugars. Economic modeling was performed for the selected evaporation method, to consolidate the feasibility of the selected process in comparison with the other approaches.

Limitations of the research included small sample sizes and limited geographical and seasonal sap sampling. Additional small-scale studies are warranted to establish the robustness of the process among natural variations known to occur in the sap. One of the profitable objective marketing claims for coconut sugar is that it is not over-processed; accordingly, purchasers are prepared to accept some product variations that could only be removed by excessive processing. Therefore, in this setting, the coconut sugar manufacturing process should produce sugar that has good storage stability and sensory and physical characteristics, with acceptable variations in standard limits.

The need to modify the procedure during scale-up is also a limitation. The effect of the use of clarifying agents and crystallization aids on the composition of the sugar must be evaluated in a laboratory-based pilot scale-up investigation.

## 1.6 The Outline of Chapters

The study is presented in five chapters, including this introduction (Chapter 1). The literature review (Chapter 2) presents a brief historical and anatomical overview of the production and harvesting of coconut sap and describes the current state of the art for sap collection and processing. As warranted, relevant comparisons with sugar palm and sugarcane, two other “natural” sugar sources, are provided. Chapter 3 provides details of the processing methods examined, and the equipment and methods used for composition, quality, and procedural analyses. Chapter 4 provides details on the characteristics of coconut sap, palm sap, and cane juice as raw materials for sugar syrup and granular sugar production. The actual performance of the coconut sap processing methods that allowed reaching the defined evaporation endpoint is described in detail, followed by results of analyses of the output of each method. Characteristics of sugars prepared by the preferred and traditional methods after storage stability testing at normal and accelerated temperatures are described. Finally, manufacturing simulation and economic modelling outcomes, when relevant data from this research were integrated with that acquired from due diligent market and manufacturing research, are defined, and compared. Chapter 5 summarizes conclusions from the study and posits recommendations for the industry and overall implications of the findings for future research.

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