Process Design of Multifeed and Multiproduct Sugar Factories

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Abstract. Indonesia's journey toward food self-sufficiency faces challenges with declining sugar production from seasonal sugarcane harvesting. To overcome this, alternative year-round and abundant sources like coconut sap and sorghum offer potential solutions. This study tackles the decreasing trend in sugar production through the optimization of a miniplant utilizing multifeed sources sugarcane, coconut sap, and sorghum to produce white crystal, brown sugar, and syrup. The objective is to ensure year-round plant operation. The process design focuses on maximizing profits, considering total sales and operational costs related to raw materials, water, and steam. Constraints are implemented to production capacities for sugarcane (15,000 kg/day), coconut sap (6,000 kg/day), and sorghum (9,000 kg/day). Maximizing the potential of alternative biomass materials involves a combined feed of coconut sap and sorghum raw material. The design process flow involves sugar production using only sugarcane feed for the first 4 months and, for the subsequent 8 months, transitioning to a combined feed of coconut sap and sorghum to create multiproduct sugar. From the design process achieved maximum profit of Rp7,096,618,000.00. This research provides valuable insights into diversifying sugar production, promoting sustainability and economic viability in Indonesian sugar industry.

1 Introduction

One of the main agricultural commodities in Indonesia that has been designated as a special product in the Agreement on Agriculture (AoA) by the World Trade Organization (WTO), which can enhance the economy in Indonesia, is sugar [1]. Indonesia is planning to achieve food self-sufficiency by increasing domestic sugar production in order to strengthen food security and improve the quality of life for Indonesian communities, even in remote rural areas. However, these efforts have not been successful so far [2]. This is due to the fact that sugar production in Indonesia has tended to decline over the past decade [3]. Based on this, an analysis related to sugar production in Indonesia is necessary to achieve the target of sugar self-sufficiency in Indonesia by the upcoming year 2024. The data relationships between sugar consumption, production, and import can be seen in Figure 1.

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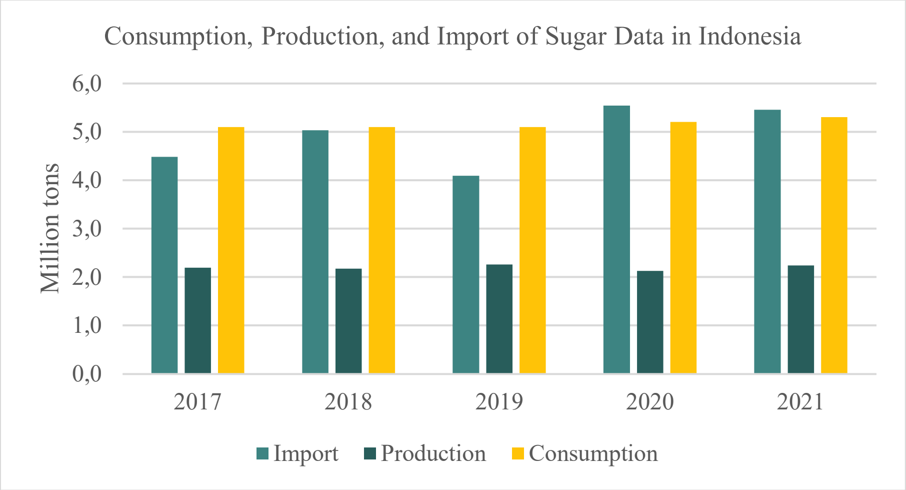

Fig. 1. Graphic Consumption, Production, and Import of Sugar Data in Indonesia [3]

From the graph, it is evident that sugar consumption is on the rise, while production remains steady or tends to decline, resulting in high sugar imports to Indonesia. This situation can be attributed to the prevalent use of sugarcane as the main raw material in Indonesia's sugar industry. Sugarcane is a seasonal crop, harvested optimally for about 10 months [4], leading conventional sugar mills to operate during the harvest season for 4-6 months. It is essential to complete sugarcane harvesting and milling within a maximum of 36 hours to maintain sugar quality, as prolonged time may lead to a decrease in juice due to evaporation of water content, resulting in increased solids and reduced productivity [4], contributing to the overall decline in sugar production.

In recent times, there has been extensive research indicating that sugar can be derived not only from sugarcane but also from other materials with the potential to produce sugar. One such alternative is coconut sap, a sweet liquid obtained from pressing the stem or sap of the flower cluster. Coconut sap is widely used in the sugar industry due to the abundant and wild growth of coconut trees throughout Indonesia [5]. Coconut sap is often utilized in sugar production, yielding both brown sugar and sugar ant. However, the processing of coconut sap is susceptible to contamination by wild yeast, producing sucrase enzymes that break down sucrose into glucose and fructose [6]. Another potential raw material is sorghum, known to contain approximately 12.7% sucrose [7]. In Indonesia, sorghum production ranges from 4,000 to 6,000 tons per year, with a relatively short harvest period of 3-4 months and year-round availability [8]. Given the lengthy process of obtaining coconut sap and the underutilization of sorghum in Indonesia, combining feeds of coconut sap and sorghum can maximize the potential of alternative raw materials. This strategy aims to complement the strengths of both materials and achieve maximum profitability in the mini-plant's operational process.

The challenges faced by conventional sugar mills, particularly the seasonal shortage of sugarcane supply, and the potential use of alternative abundant raw materials, such as coconut sap and sorghum, prompt the optimization of a sugar miniplant. This involves using multifeed sources, including sugarcane, and combining feeds of coconut sap and sorghum to produce multiple products like crystal sugar, brown sugar, and syrup. The process design aims to ensure year-round mini-plant operation by leveraging the abundance of alternative raw materials. Additionally, it evaluates whether process design multifeed and multiproduct processes, coupled with year-round operation, results in maximum profitability compared to using sugarcane alone as conventional sugar factory. This process design will determine the optimal quantities of feeds and products to achieve maximum profitability in the sugar production process.

2 Methods

This research presents a block flow diagram illustrating the multiproduct sugar manufacturing process, encompassing white sugar, brown sugar, and syrup, derived from sugarcane, coconut sap, and sorghum. The initial preparation stage involves the temporary storage of raw materials like sugarcane and sorghum stalks, emphasizing the critical need for prompt sugarcane processing within a 36-hour window to maintain sugar quality. Coconut sap, another raw material, undergoes immediate processing upon arrival to prevent pH reduction due to yeast fermentation. Milling processes, featuring grinding-filtration units, are employed for sugarcane and sorghum stalks to extract sap efficiently. The multistage milling ensures maximal sap extraction from diverse raw materials, maintaining high-quality sap for subsequent processing.

For coconut sap, the process advances directly to the juice heater phase, initiating a meticulous purification process. Preheating with Juice Heater to 100°C triggers the defecation process, followed by lime milk addition through the hot liming technique to achieve optimal pH. Subsequent steps involve flocculant addition for impurity removal and sap clarification through sedimentation in a clarifier. The clarified sap undergoes evaporation in a triple-effect evaporator under vacuum conditions, ensuring careful purification and concentration for subsequent cooking and crystallization steps, ultimately resulting in the production of high-quality sugar products.

After evaporation, the concentrated sap undergoes reheating in the cooking pan until it achieves supersaturation. In the Cooking Pan stage, red sugar products are molded and left to solidify, while liquid sugar is packaged. The process for white crystal sugar products proceeds to crystallization with the addition of fondant. Following sufficient crystallization, the subsequent step involves Na-Crystallization to continue the crystallization process initiated in the cooking pan. This step aims to decrease cooking temperature and increase saturation value, facilitating the adherence of sucrose to the already formed crystals.

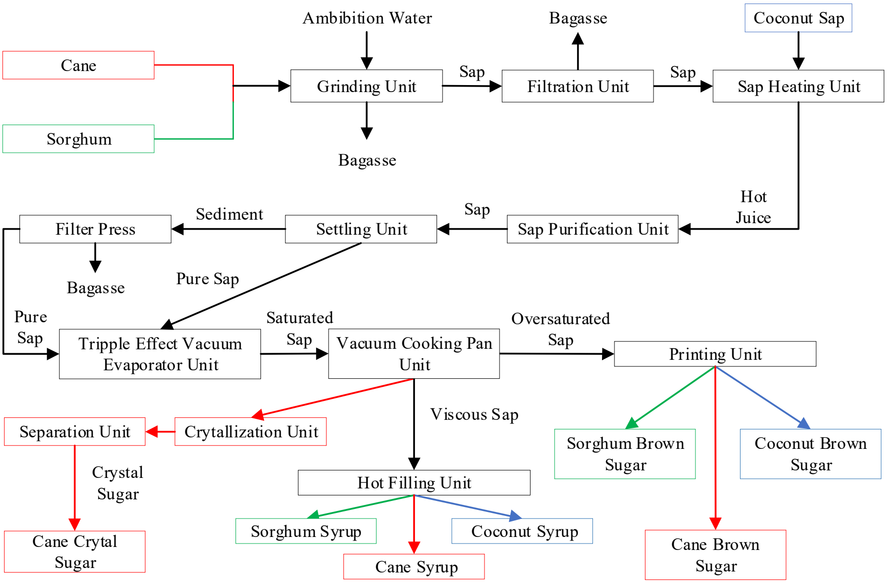

Fig. 2. Block Flow Diagram Miniplant

2.1 Data Collection

The required data for this research includes information on the harvest period for each feed, chemical composition data of sugarcane, coconut sap, and sorghum feeds, as well as data on raw material prices and product selling prices.

Table 1. Harvest Period Data for Each Feed

Raw Material	Harvesting Season	Production/yr	Ref.
Sugarcane	Seasonal Plant, harvested when they reach the age of 10 - 12 month.	17.362.620 ton (2022)	[3]
Sorghum	Throughout the year, harvested when they reach the age of 80 – 100 days.	2.182 ton	[9,10]
Coconut Sap	Throughout the year, harvested once a month.	48.989,4 kg/day *33% from availability	[3]

Table 2. Chemical Composition of Sugarcane [11]

Parameter	Composition (%w/w)	Parameter	Composition (%w/w)
Sugarcane Component		**Sap Components**	
Water	70.0	Organic Acids	2.96
Dissolved solids	17.5	Carboxylic Acid	1.10
Fiber	12.5	Amino Acid	0.50
Sap Components		**Organic non-sugar**	
Sucrose	75.00	Protein	0.500
Glucose	4.00	Starch	0.001
Fructose	4.00	Gum	0.300
Salt	4.00	Wax, fat, phosphate	0.050
Inorganic Acids	1.50	Others	0.500

Table 3. Chemical Composition of Coconut Sap and Sorghum [7, 12]

Coconut Sap		Sorghum	
Components	**Composition (%w/w)**	**Components**	**Composition (%w/w)**
Water Content	85.15	Water Content	71.90
Sucrose	13.85	Sucrose	12.70
Glucose	0.22	Glucose	3.60
Fructose	0.44	Fructose	2.60
Protein	0.20	Cellulose, Hemicellulose, Lignin	8.80
Ash	0.15	Ash	0.40

Table 4. Price of Raw Material Used and Product

Raw Material	Price(/kg) in Rupiah	Raw Material	Price(/kg) in Rupiah	Product	Price(/kg) in Rupiah
Sugar Cane	605	Limemilk	17,500.00	Crystal Sugar	12,420.00
Coconut Sap	4,000.00	Flocullant	7,467.00	Brown Sugar	24,900.00
Sorghum	200.00	Fondant	63,000.00	Syrup	28,870.00

2.2 Algorithm

In the design of the Mini sugar plant with multifeed and multiproduct, mass balance and energy balance calculations are required. Material balance is commonly referred to as a mass balance. Mass balance is a quantitative calculation of all the materials entering and leaving a system, as well as accumulated within the system based on their mass. In general, mass balance can be formulated using equation (1).

Input – Output + Generation – Consumption = Accumulation (1)

Mass balance is divided into total mass balance and component mass balance. Under steady-state conditions, the accumulation term is zero. Thus, the total mass balance can be formulated using equation (2).

$$\sum M_{in} = \sum M_{out} \tag{2}$$

Meanwhile, the component mass balance can be formulated using equation (3).

$$[\sum Mx_i]_{in} = [\sum Mx_i]_{out} \tag{3}$$

Where:

M: total mass entering/leaving the system

x_i : mass fraction of component i

However, energy balance, or energy balance, is a quantitative calculation for the energy entering and leaving a system, as well as the heat generated in a process.

2.3 Economic Analysis

Economic analysis is one of the methods that can be employed to assess the feasibility of whether a factory can engage in production. In this study, economic analysis is conducted to measure the profits gained by a miniplant over the course of one year of operation. The economic analysis comprises two aspects: the total sales of the produced products and their operating costs. From these two aspects, the maximum revenue of the sugar miniplant can be obtained. Revenue represents the profit a factory gains from selling its products to consumers and does not include the capital investment costs [13]. This economic analysis will also determine whether the optimization efforts undertaken have been successful and have reached their optimal point. As a result, the hope of this economic analysis is that the factory can implement the developed optimization approaches due to their economic viability.

3 Result and Discussion

In the results of the mass and energy balance calculation, the produced products consist of crystal sugar, brown sugar, and syrup from sugarcane material. Meanwhile, a combined feed of coconut sap and sorghum is created to optimize the abundance of renewable biomass materials, resulting in the production of brown sugar and syrup with a capacity of 9 tons/day for sorghum and 6 tons/day for coconut sap.

Based on the calculations in the mass balance process design that has been conducted, the respective results of each product from the raw materials of Sugarcane, Coconut Sap, and Sorghum stalks with a feed of 15 tons/day can be observes in Table 5. Meanwhile, for each component in each product can be observed in Table 6 and Table 7.

Table 5. Mass and Energy Balance Calculation

Feed	Capacity (kg/day)	Persentage	Product	Product (kg/day)	Steam (kg/day)	Water (kg/day)
Sugarcane	15,000	100%	Crystal Sugar	1,437	15,807.46	4,464.52
		100%	Brown Sugar	2,150	15,962.36	4,464.38
		100%	Syrup	2,485	15,597.83	4,461.20
Coconut Sap	15,000	100%	Brown Sugar	2,501	17,406.35	793.90
		100%	Syrup	2,891	16,982.17	790.21
Sorghum	15,000	100%	Brown Sugar	1,531	13,679.81	4,457.27
		100%	Syrup	1,770	13,420.16	4,455.01
Combine Feed Coconut Sap and Sorghum	9,000 kg Sorghum + 6,000 kg Coconut Sap	100%	Brown Sugar	1,531	13,679.81	4,457.27
		100%	Syrup	1,770	13,420.16	4,455.01

Table 6. Mass Fraction Sugarcane Product of Sugar

Sugarcane Product	Brown Sugar	Syrup	Sugarcane Product	Brown Sugar	Syrup
Component	**Mass Fraction**		**Component**	**Mass Fraction**	
Water	0.1100	0.2300	Amino Acid	0.0131	0.0114
Sucrose	0.6705	0.5801	Ash	0.0350	0.0303
Glucose	0.0262	0.0227	Protein	0.0044	0.0038
Fructose	0.0262	0.0227	Starch	0.0000	0.0000
Salt	0.0262	0.0227	Gum	0.0035	0.0030
Inorganic Acids	0.0219	0.0189	Wax, fat, phosphate	0.0009	0.0008
Organic Acids	0.0437	0.0378	$Ca(OH)_2$	0.0008	0.0007
Carboxylic Acid	0.0175	0.0151	Flocculant	0.0000	0.0000
Total	**1.0000**	**1.0000**	**Total**	**1.0000**	**1.0000**

The brown sugar products from sugarcane, produced at a rate of 15 tons per day, were evaluated against the Indonesian National Standard (SNI) specifications. The moisture content and ash content in the produced brown sugar do not comply with SNI standards, recording 11% moisture content (above the 10% standard) and 3.5% ash content (exceeding the 2% standard). However, the reducing sugar content, including glucose and fructose, met the SNI standard of 10%, with a calculated content of 5.24%. Similarly, the syrup products from sugarcane, also produced at a rate of 15 tons per day, were assessed against SNI quality standards. The moisture content and ash content in the syrup do not align with the standards, recording 23% moisture content (beyond the 20% standard) and 3.03% ash content (above the 1% standard). Nevertheless, the reducing sugar content in the syrup, consisting of glucose and fructose, meets the SNI standard of 30%, with a calculated content of 4.5%. This discrepancy in the results is due to the moisture content aligning with the Brix value at CV 'X' in East Java.

The results of brown sugar products from coconut sap (nira) for a production yield of 15 tons per day can also be compared to the standard quality of SNI. Similar to the case of sugarcane brown sugar, the obtained results for moisture content do not meet the SNI standard, being at 11%. However, the standards for reducing sugar content and ash content are met. From Table 7, it can be observed that the reducing sugar content obtained is 3.86%, which is still below the SNI standard of 10%. Furthermore, the ash content also complies with the SNI standard, measuring at 0.8%.

Table 7. Mass Fraction Coconut Sap and Sorghum Product of Sugar

Coconut Sap Product	**Brown Sugar**	**Syrup**	**Sorghum Product**	**Brown Sugar**	**Syrup**
Component	**Mass Fraction**		**Component**	**Mass Fraction**	
Water	0.1100	0.2300	Water	0.1100	0.2300
Sucrose	0.8301	0.7182	Sucrose	0.8702	0.7529
Glucose	0.0130	0.0113	Glucose	0.0102	0.0088
Fructose	0.0256	0.0221	Fructose	0.0073	0.0064
Protein	0.0118	0.0102	Ash	0.0011	0.0010
Ash	0.0088	0.0076	$Ca(OH)_2$	0.0011	0.0010
Limemilk	0.0007	0.0006	Flocculant	0.0000	0.0000
Flocculant	0.0000	0.0000			
Total	**1.0000**	**1.0000**	**Total**	**1.0000**	**1.0000**

For the results of liquid sugar (syrup) products from coconut sap (nira) for a production yield of 15 tons per day, the obtained results for moisture content do not meet the SNI standard, being at 23%. However, the standards for reducing sugar content and ash content are met. It can be observed that the reducing sugar content obtained is 3.34%, which is still below the SNI standard of 30%. Additionally, the ash content also complies with the SNI standard, measuring at 0.76%.

The results of brown sugar products from sorghum stalks for a production yield of 15 tons per day can also be compared to the standard quality of SNI. Similar to both sugarcane and coconut sap brown sugar, the obtained results for moisture content do not meet the SNI standard, being at 11%. However, the standards for reducing sugar content and ash content are met. It can be observed that the reducing sugar content obtained is 1.75%, which is still below the SNI standard of 10%. Additionally, the ash content also complies with the SNI standard, measuring at 0.11%.

For the results of liquid sugar products from sorghum stalks for a production yield of 15 tons per day, the obtained results for moisture content do not meet the SNI standard, being at 23%. However, the standards for reducing sugar content and ash content are met. It can be observed that the reducing sugar content obtained is 1.52%, which is still below the SNI standard of 30%. Additionally, the ash content also complies with the SNI standard, measuring at 0.10%.

From the analysis, it is evident that certain product components do not meet SNI standards. This discrepancy can impact the quality of the products in terms of color, shape, and taste. The adherence to SNI standards is crucial as it signifies the product's suitability for consumption, ensuring it meets the required food quality standards for public consumption.

Moving on to the results of the energy balance process design, the steam and water requirements needed during the production process are obtained. The smallest steam requirement is needed for the multiproduct sugar production process from sorghum feed, with a steam requirement of 17,208.5619 kg/day. However, for the other materials, the steam requirements are not significantly different from the sorghum feed. Meanwhile, the smallest water requirement is needed for the multiproduct sugar production process from coconut sap feed, with a water requirement of 792.0580 kg/day. However, for sugarcane and sorghum materials, a much larger water requirement is necessary compared to coconut sap, as sugarcane and sorghum undergo milling processes. Coconut sap, on the other hand, goes directly into the juice heater process.

In this study, a multiproduct sugar production process was implemented, utilizing sugarcane as the raw material for 4 months and transitioning to a combined feed of coconut sap and sorghum for the subsequent 8 months. The product split ratio for sugarcane included 50% white sugar, 45% brown sugar, and 5% syrup, while the ratio for the combined feed comprised 15% brown sugar and 85% syrup. This ratio showcased the higher pricing of brown sugar from sugarcane compared to sugarcane syrup, while brown sugar in the combined feed was priced lower than the syrup. Profit calculation incorporated a product split ratio for each raw material, favoring the more expensive product. This strategic approach played a pivotal role in maximizing the profit over the one-year duration of sugar production, with operational costs deducted from total multiproduct sugar sales. Operational cost considerations were streamlined to three main aspects, based from and aligning with the practices of CV 'X' in East Java, which serves as a reference for multiproduct sugar production equipment. The fixed operational costs, encompassing raw material requirements, steam, and water, were the primary focus. The resulting profit from this miniplant's one-year production of multiproduct sugar from multifeed raw materials amounted to IDR 7,096,618,000.00.

Comparing the obtained profit from the conventional plant, which exclusively uses sugarcane feed for 4 months, with common harvesting and milling practices, a profit of IDR319,110,389.24 was achieved. This underscores the significant enhancement in profit value resulting from the multifeed process design, tapping into the abundance of biomass materials. The higher prices of products derived from combined coconut sap and sorghum, adjusted to market rates, contributed to this improvement. Additionally, the perceived health benefits of products from coconut sap and sorghum, suitable for individuals with diabetes, further justified their higher pricing. In contrast, lower prices for sugarcane products were attributed to their failure to meet SNI quality standards. Consequently, our product prices were strategically set at approximately 90% of the market price.

4 Conclusion

In this research, a multifeed and multiproduct sugar miniplant design process has been successfully implemented, resulting in profitability. The production process covers 4 months using sugarcane feed with a capacity of 15 tons/day, followed by the subsequent 8 months of multiproduct production from a combined feed of coconut sap and sorghum with capacities of 6 tons/day for coconut sap and 9 tons/day for sorghum. For sugarcane feed, the split fraction of products includes GKP, brown sugar, and syrup with ratios of 0.50, 0.45, and 0.05, respectively. Meanwhile, for the coconut sap and sorghum feed, a split fraction is used for brown sugar and syrup at 0.15 and 0.85, respectively. With an incoming feed capacity of 15 tons/day, a profit of IDR 7,096,618,000.00 has been achieved. This profit is calculated by subtracting product sales from operational costs, including raw material requirements, steam, and water during the production process for one year. In comparison, the profit obtained from a conventional sugar plant using sugarcane feed for 4 months according to the harvest and sugarcane milling period is IDR 319,110,389.24. This finding indicates that the multifeed process design efficiently utilizes biomass, significantly increases profit value, and enables year-round sugar production without being constrained by sugarcane harvest periods.

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