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Analysis of Energy and Material Efficiency in Traditional Sugar Mills Using STEM-Based Approaches

Analisis Efisiensi Energi dan Material di Pabrik Gula Tradisional Menggunakan Pendekatan Berbasis STEM

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ABSTRAK
Pabrik gula tradisional menghadapi tantangan dalam meningkatkan efisiensi produksi untuk tetap kompetitif dan memenuhi permintaan pasar yang terus meningkat. Penelitian ini mengadopsi pendekatan inovatif berbasis STEM (*Science, Technology, Engineering, and Mathematics*) untuk menganalisis aliran material dan energi dalam proses produksi gula. Pendekatan ini tidak hanya mengidentifikasi inefisiensi tetapi juga menawarkan solusi berbasis data dan teknologi modern untuk optimalisasi operasional. Penelitian melibatkan pemetaan aliran material dan energi menggunakan metode keseimbangan massa dan energi, serta analisis sebab akibat untuk mengidentifikasi akar masalah inefisiensi di setiap tahap produksi, mulai dari persiapan, penggilingan, pemurnian, hingga kristalisasi. Hasil penelitian menunjukkan rendemen produksi sebesar 6,63%, jauh di bawah target perusahaan sebesar 10%, dengan inefisiensi utama disebabkan oleh kualitas bahan baku yang rendah, pengaturan suhu proses yang tidak standar, dan keterampilan operator yang kurang memadai. Rekomendasi berbasis STEM meliputi integrasi teknologi sensor untuk pemantauan *real-time*, perawatan mesin secara berkala menggunakan algoritma prediktif, pembuatan pedoman digital untuk operator, serta optimalisasi bahan baku melalui data agronomi. Implementasi pendekatan ini diharapkan tidak hanya meningkatkan rendemen dan efisiensi produksi tetapi juga mendukung keberlanjutan operasional dengan mengurangi limbah dan emisi.

Kata kunci — analisis proses produksi, efisiensi energi, keseimbangan massa, pabrik gula tradisional, STEM,

ABSTRACT
Traditional sugar factories face challenges in improving production efficiency to remain competitive and meet growing market demand. This research adopts an innovative STEM (Science, Technology, Engineering, and Mathematics) approach to analyze material and energy flows in the sugar production process. This approach not only identifies inefficiencies but also offers data-driven solutions and modern technology for operational optimization. The research involved material and energy flow mapping using the mass and energy balance method, along with causal analysis to identify the root causes of inefficiencies at each stage of production, from preparation, milling, refining, to crystallization. The results showed a production yield of 6,63%, far below the company's target of 10%, with the main inefficiencies caused by low raw material quality, non-standard process temperature settings, and inadequate operator skills. STEM-based recommendations include integrating sensor technology for real-time monitoring, regular machine maintenance using predictive algorithms, creating digital guidelines for operators, and optimizing raw materials through agronomic data. Implementing this approach is expected to improve yield and production efficiency and support operational sustainability by reducing waste and emissions.

Keywords — *energy efficiency, mass balance, production process analysis, STEM, traditional sugar factory*

1. Introduction

Efficiency in the utilization of raw materials, energy, and by-products is a major factor in maintaining the sustainability of industrial operations, including the sugar industry. In sugar production, each stage of the process involves interconnected material and energy flows. Material flow analysis includes mapping all raw material inputs to the main product or by-product, taking into account potential losses due to waste or loss of materials during the process [1]. On the other hand, energy flow analysis aims to identify and regulate the rate and distribution of energy in the production system, to improve efficiency and reduce energy waste.

The traditional sugar industry in Indonesia faces major challenges in maintaining operational efficiency and competitiveness amidst increasing market demand. The production process takes place during the intensive milling season, with 24-hour operations divided into three work shifts [2], is often characterized by material and energy wastage. The stages of milling, refining, evaporation, crystallization, and centrifugation, which transform sugarcane into ready-to-consume sugar, have the potential to generate inefficiencies that have a significant impact on production costs and contribute to environmental pollution [3]. To address these issues, a STEM (Science, Technology, Engineering, and Mathematics))-based approach was introduced as an innovation capable of providing systematic and data-driven solutions. By integrating sensor technology, real-time data analysis, and predictive algorithms for process monitoring and optimization, this approach enables the reduction of material and energy waste, improves production efficiency, and supports environmental sustainability. This not only reduces operational costs but also strengthens the competitiveness of Indonesia's sugar industry in the global market.

2. Target and Output

The application of a STEM (Science, Technology, Engineering, and Mathematics) based approach in analyzing material and energy flows in the sugar industry provides the ability to identify critical points of waste and develop solutions based on data and the latest technology [4]. This approach integrates scientific methods, technological engineering, and mathematical analysis to understand and optimize material and energy flows at every stage of production. Using tools such as smart sensors, energy flow modeling, and big data analysis algorithms, this research not only helps improve operational efficiency but also introduces innovations in real-time process monitoring and control systems. Through systematic evaluation of material and energy flows, companies can reduce waste, lower operating costs, and improve production quality to achieve the standard targets set by the company [5]. This STEM-based innovation has the potential to transform the traditional sugar industry, increasing its competitiveness in the global market, in addition to driving sustainability and more efficient waste management, making it more environmentally friendly and sustainable.

3. Research Methodology

This research uses a mixed method approach that combines qualitative and quantitative methods to measure and analyze material and energy flows during the May to August 2023 sugar production process at Madukismo Sugar Factory, Bantul, Yogyakarta. The focus of this research includes material and energy flow analysis starting from sugarcane cultivation, and processing in the factory, to waste handling for three observations of the entire process chain. The main objective is to understand the flow of material and energy from inputs to production outputs, identify efficiency values, and calculate the resulting yield.

3.1. Data Collection

Primary data collection was obtained through direct observation, measurement of materials involved in the process, and interviews with relevant parties in the field, including sugarcane farmers and factory operators. Information collected included the flow of sugarcane cultivation, crop productivity, processing at the factory, energy and material usage, and waste handling during the production process. In addition, validation and verification of data and interview results were conducted with the production manager, technicians, and environmental department to get a complete picture of operational practices and resource efficiency. Secondary data was obtained from company records and documents, including sugarcane supply data from farmers to the mill, daily milling during the 2018-2023 period, electricity consumption data, and production machinery specifications. Secondary data also includes reports on the use of sugar production materials, along with records on waste management and treatment systems implemented by the company.

3.2. Data Processing

Data processing begins with the calculation of the mass balance and energy balance used at each stage of the production process, starting from the receipt of sugarcane to the final product. This calculation aims to calculate the conversion ratio of raw materials into products and to identify potential material waste at each stage of production. Sugarcane supplier data comes from the main supplier areas, namely Bantul, Kulon Progo, Sleman, and other areas in Central Jawa, such as Magelang, Klaten, and Purworejo. The sugarcane used comes from a partnership pattern with smallholder sugarcane farmers and independent farmers. These partnerships are focused on enhancing both yield and the quality of raw materials delivered to the factory, which is essential to ensuring the production of high-quality sugar.

3.3. Data Analysis

Calculation and analysis of mass balance and energy balance using the basis of fluid mass flow rate based on latent heat value and specific heat capacity [6]. After completing the calculation of the mass balance, the research continued with the calculation of the energy balance in the form of energy balance values. Calculation of energy balance can be done using the following equation:

$$Q\ Input = Q\ Output$$
$$Q\ Latent = mx\ \lambda$$
$$Q\ Reasonable = mx\ Cp\ x\ \Delta T$$

Notes:
m : Fluid mass flow rate (kg/h)
λ : Latent heat (kcal/kg)
Cp : Specific heat capacity (kcal/kg °C)

Calculation of electrical energy consumption is done to find out how much electricity is used by tools and machines at each workstation. Energy consumption is calculated by multiplying the power of the equipment by the duration of its use in the production section [7]. The results of this calculation are used to evaluate the energy efficiency at each stage of sugar production. Waste Management Analysis is also conducted to identify potential waste of energy and materials. For analyzing the processing of wastes in sugar industries, identify and quantify the waste generated, such as bagasse (solid) and effluents (liquid), and characterize their physical-chemical properties. Current management practices will be reviewed, focusing on recycling, treatment, and disposal methods, including any environmental impacts associated with such emissions or pollution. Identify inefficiencies such as energy losses or material leakages and propose improvements like the adoption of advanced treatment technologies, enhancing recycling processes, or reducing waste at source. Monitor and report on the efficacy of measures to reduce wastes that support environmental sustainability.

4. Result and Discussion

Based on the latest data from the Indonesian Ministry of Agriculture, by 2022 the area of sugarcane plantations in Indonesia will reach around 488.900 hectares, with significant contributions from the Central Java and Yogyakarta regions. For Central Java and Yogyakarta, data shows that the sugarcane area in Yogyakarta is recorded at around 2.900 hectares, which is supplied to Madukismo Sugar Factory. National white crystal sugar (GKP) production in 2022 was recorded at 2,45 million tons, an increase of 2,34% compared to the previous year, although the yield in that year decreased slightly.

4.1. Material and Energy Flow Analysis

In material flow analysis, mass balance determines how much material enters and leaves a production process. Mass balance applies the law of conservation of energy, where the input flow is equal to the output flow if there is no accumulation in the equipment or machinery involved in the process. The mass balance calculation is done through the following equation:

$$\textit{Mass Input} = \textit{Mass Output}$$

Based on the mass balance analysis, sugarcane processed at the mill amounted to 2.901.071 kg/day, which was added with imbibition water of 919.143 kg/day at the milling station. This stage produces an average raw juice of 2.885.714 kg/day and solid waste in the form of pulp totaling an average of 934.500 kg/day. This pulp is used as boiler fuel to produce steam energy, which is converted into electrical energy by a turbine generator. At the refining station, raw nira together with chemicals such as lime milk (5.079 kg/day), sulfur (1.364 kg/day), and phosphoric acid (225 kg/day) produce clear nira of 2.803.188 kg/day and blotong liquid waste of 89.204 kg/day. The clear juice is then evaporated into concentrated juice of 558.461 kg/day through the evaporation station, with evaporation water loss reaching 2.244.728 kg/day. The crystallization and centrifugation process produces 192.414 kg/day of SHS sugar and 114.737 kg/day of molasses. Liquid waste in the form of blotong is processed into liquid fertilizer, while bagasse is used for steam energy, showing relevant material and energy efficiency measures. The STEM approach to this analysis shows opportunities to improve efficiency at stations with the largest material losses, such as evaporation, through technology optimization and data-driven process control [8]. This can support the sustainability of factory operations and improve overall efficiency. In the sugar production process, the mass balance at each stage is shown in Figure 1.

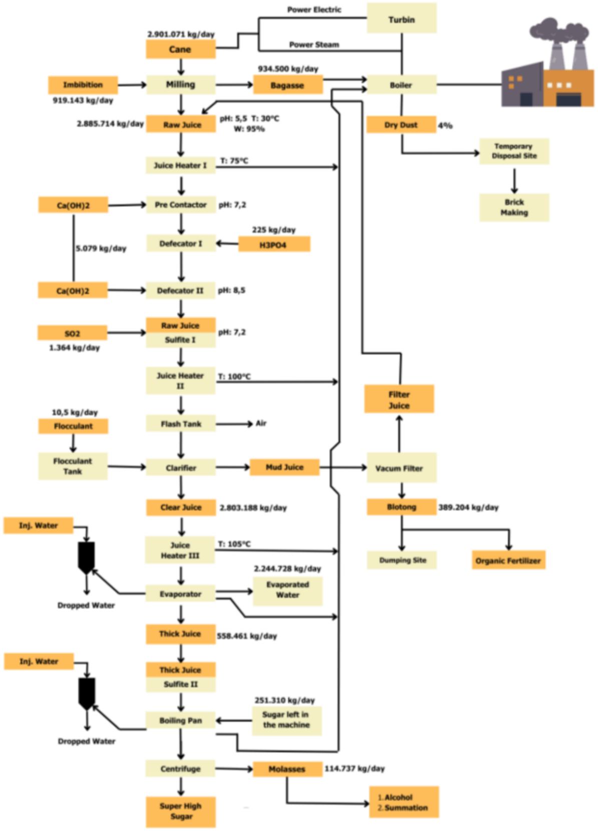

Figure 1. Material Flow of Sugar Production at Madukismo Sugar Factory

Based on the mass balance analysis, the production capacity of sugarcane in the short stable period, namely period 10 (July 10 - July 16, 2023) is 2.901.071 kg/day, resulting in an average SHS (Superium Hoofd Suiker) of 192.414 kg/day (Super High Sugar). Based on this analysis, the sugarcane yield value, which is the ratio of crystal sugar output to the weight of milled sugarcane multiplied by 100% [9], was set at 6,63%. In addition, the amount of output is different from the amount of input, where the final output is only 6,63%, not 100%, because the production process solid wastes, which include bagasse or fibrous balance, filter mud or succus dross, ash from the combustion of bagasse, and sugarcane tops and leave-taking ; liquid wastefulness, which admit molasses from crystallization and effluent containing constituent and inorganic impurities that need to be treated ; and gaseous emissions, which include flue gases from boiler, mainly frame of CO_2 and particulate matter matter, besides dust from jam and handling. Proper management of these waste watercourse is all important for reducing environmental impact and heighten resource efficiency. As a result, the final mass is much lower than the initial mass at each stage of the sugar production process.

Based on the energy balance calculation, thermal energy analysis was conducted at each stage of the evaporation process using the STEM approach. The heat received by the nira in evaporator I is 14.609.273,6 kcal/hour, with an output of 10.592.393,3 kcal/hour, showing an efficiency of 72,51%. In evaporator II, the heat received is 10.592.393,3 kcal/hour, with an output of 6,905,763 kcal/hour, giving an efficiency of 65,18%. Evaporator III has an efficiency of 56,39%, with an inlet heat of 6.397.174,48 kcal/hour and an outlet of 3.607.650,78 kcal/hour. Finally, evaporator IV shows low efficiency with inlet heat of 3.607.650,78 kcal/h and inconsistent output (939.532.704 kcal/h). Data discrepancies in evaporator IV indicate the need for a review of measurements and data validation. A simulation and algorithm-based STEM approach was used to evaluate the overall energy efficiency, identify optimization opportunities, and evaluate the energy efficiency of the evaporator [10]. These findings highlight the importance of equipment maintenance and process parameter settings to maximize energy efficiency in traditional sugar mills, ultimately supporting sustainability and operational efficiency.

4.2. Electricity Consumption Analysis

After the calculation of the heat balance is completed, the calculation of the flow of electrical energy is carried out. Electrical energy can be generated by other forms of energy and can even serve as a source of other types of energy which can subsequently be transformed into other energy forms [11]. To determine the value of consumption or use of electrical energy of a device, the following equation can be used:

$$W = P \times t$$

Notes:
W : Electric energy consumption (kWh)
P : Machine power (watt)
t : Time interval (hour)

Calculation of electrical energy input and output using machine specification data on each production process with a STEM approach, specifically energy flow analysis. Electrical energy consumption in the preparation stage amounted to 18.264,24 kWh, with an efficiency of 82,89% due to electricity losses of 3.125,42 kWh. At the milling stage, electricity consumption reached 59.040 kWh, with an efficiency of 82,45% and losses of 10.362,13 kWh. The refining stage showed an efficiency of 80,09%, with electricity consumption of 1.641,12 kWh and losses of 326,76 kWh. In the evaporation process, electricity consumption was 3.600 kWh, efficiency was 80,09%, and losses were 716,72 kWh. The cooking process recorded the lowest efficiency of 78,79%, with electricity consumption of 12.690 kWh and losses of 2.565,98 kWh. This analysis shows that there are significant opportunities to improve energy efficiency through the optimization of electrical systems and process controls, particularly at the cooking stage. STEM-based approaches through improved electrical system design, machine control optimization, improved operator training, and database flows to reduce electricity losses will improve the operational sustainability of sugar mills [12]. The flow of electrical energy in the Sugar Production Process at PG Madukismo is shown in Figure 2.

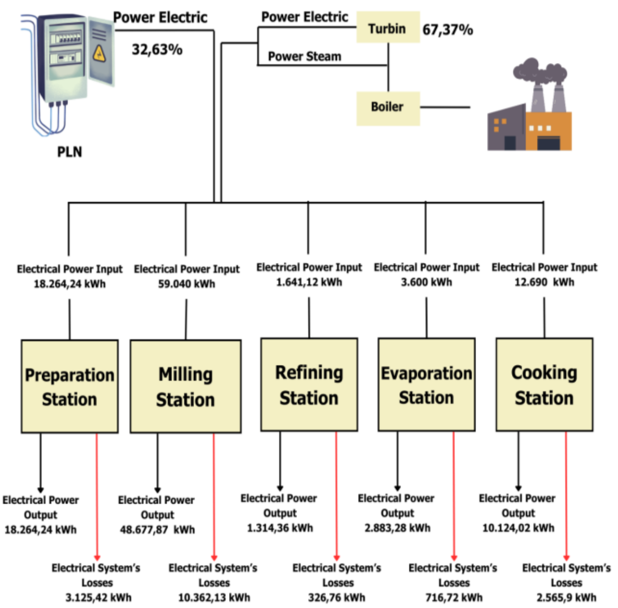

Figure 2. Electric Energy Flow of Sugar Production at Madukismo Sugar Factory

Based on the analysis of the flow of electrical energy in the factory, factory operations utilize steam as fuel to drive turbines to produce electrical energy to drive several factory machines. In addition, the factory also utilizes electrical energy from the PLN network to operate every machine and equipment used in the sugar production process. The utilization of steam generated during production to generate electricity in the factory is a common and efficient practice known as Cogeneration Heat and Power (CHP), where the heat generated during the production process is used to generate electricity, thus improving overall energy efficiency [13].

Based on the analysis of short-term electricity consumption for period 10, electricity consumption from three turbines accounts for 67,37% of the total electricity consumption of 45.857 kWh. The turbine electricity consumption comes from three driving turbines namely TG 1, TG 2, and TG 3 which produce 14.800 kWh, 15.286 kWh, and 15.771 kWh respectively. Electricity consumption from PLN accounts for 32,63% of the total consumption, with details of 9.357 kWh from PLN North and 12.857 kWh from PLN South, totaling 22.214 kWh. The average total electricity consumption for the factory's sugar production process is 68.071 kWh per day. Based on this data, the factory is able to consume more electricity from steam and can maximize resource utilization while reducing electricity dependence from external sources such as PLN [11].

4.3. Realization of Production Yields with Defined Yield Values

The main problem with material flow is that the yield rate of the sugar production process is still very low. The company's desired target is 10%, but the actual yield rate achieved is still below the company's target as shown in Figure 3.

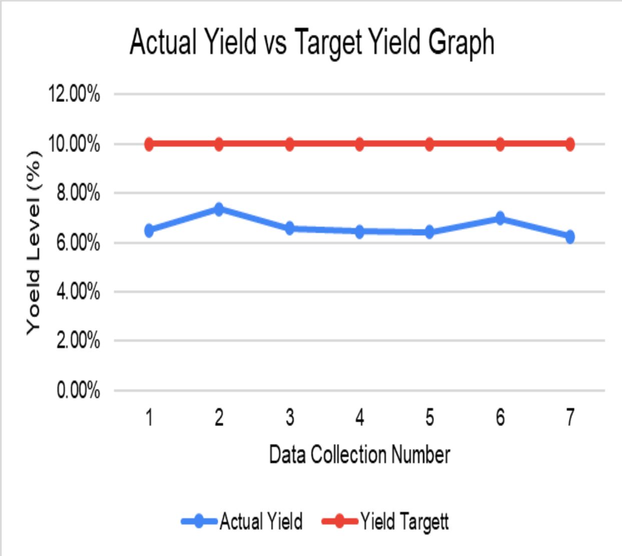

Figure 3. Electric Energy Flow of Sugar Production at Madukismo Sugar Factory

Figure 3 shows the sugar mill's average yield of only 6,63%, well below the company's target of 10%, indicating inefficiencies in material and energy flows during the production process. With an average daily milling capacity calculated from the receiving process of 3.293,5 tons of sugarcane, the factory produces approximately 230,545 tons of sugar and 11,2 liters of denatured alcohol per ton of sugarcane, along with a large amount of waste in the form of bagasse, blotong, combustion ash, liquid waste, and gas. Through STEM-based analysis, particularly using mass and energy balances, these inefficiencies can be quantitatively identified to identify potential waste utilization (Table 1), low raw material quality, suboptimal machine configuration, or inefficient energy management [14]. With this approach, factories can develop data-driven solutions to improve the efficiency of the production process [15], minimize waste [16], and support operational sustainability [17], while increasing the yield of sugar produced [18].

Table 1. Identification of the Proportion and Potential Utilization of Sugar Production Waste

Type of Waste	Amount per Ton of Sugar	Total Amount per Day (Ton)	Description
Solid Waste			
Bagasse	0.25 - 0.30 ton	57.636 - 69.164	Used as fuel.
Blotong	0.05 - 0.08 ton	11.527 - 18.444	Used as fertilizer or biogas material.
Bagasse Combustion Ash	0.01 - 0.02 ton	2.305 - 4.611	Combustion products in steam boilers.
Liquid Waste			
Condenser Water	4 - 6 m³	922.18 - 1.383,27 m³	Water from cooling and condenser.
Filter wash Water	4 - 6 m³	922.18 - 1.383,27 m³	Used wash water.
Limbah Cair Klarifikasi	4 - 6 m³	922.18 - 1.383,27 m³	Water mixed with organic waste.
Gas Waste			
Emissions from Bagasse Combustion	-	Tergantung konsumsi bahan bakar	CO_2 and combustion particles.

Observation and FGD data (2023)

4.4. Ishikawa Diagram

Factors affecting sugar production yield are grouped into four main causes, namely people, raw materials, machinery, and methods. These factors are illustrated in the Ishikawa Diagram in Figure 4 below.

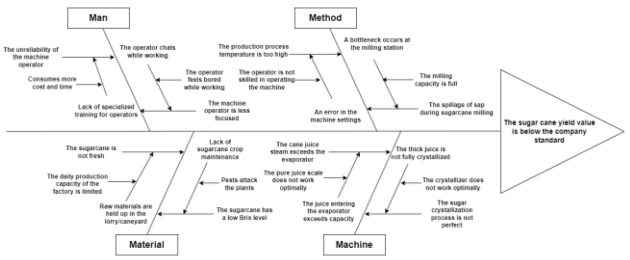

Figure 2. Cause-Effect Diagram of Factors Causing Substandard Sugarcane Yields

Based on the Cuase-Effect Diagram, the low yield of sugarcane in the company can be explained through a causal analysis involving internal and external factors. In terms of labor factors, the unreliability of machine operators is due to a lack of specialized training and low work focus caused by communication breakdowns during work. In terms of raw materials, the unfreshness of sugarcane due to prolonged storage in trucks or plantations and low Brix levels are caused by sub-optimal maintenance. For the method factor, process temperatures that do not meet standards are caused by machine settings errors, while spillage of sugarcane juice at the mill occurs due to congestion at the milling station. The machine factor also plays an important role, where the incomplete crystallization process is caused by the suboptimal performance of the crystallizer, in addition to the steam from the sugarcane juice that exceeds the evaporator capacity due to the entry of more juice than its holding capacity or limit. By using the STEM approach [8] and mass and energy flow analysis, this analysis can go more in-depth to identify potential energy and material wastage [19], along with providing technical solutions for operational improvements, increasing efficiency, and optimizing the sugar production process.

Achieving a high sugar yield will result in the production of more SHS (Super High Sugar) in the sugar production process. Increasing sugar production yield can be achieved by improving the internal and external factors of the factory. For internal factors, regular machine maintenance, operational monitoring, and regular process evaluation need to be implemented, using the STEM approach and mass and energy flow analysis to improve efficiency and reduce energy and material wastage [20]. Meanwhile, external factors focus on improving the quality of sugarcane raw materials through improved pre-harvest and post-harvest processes, in addition to partnerships with farmers to increase yields. The implementation of these recommendations, supported by mass and energy flow analysis, is expected to reduce wastage and increase sugar yields sustainably.

This innovation will not only improve energy efficiency, but also help minimize wastage, reduce operational costs, and speed up production processes. With these STEM-based measures, the factory can improve efficiency, sugar yield, and operational sustainability, creating a more environmentally friendly and sustainable production system. STEM-based approaches are proving to be highly relevant and innovative in addressing the energy and material efficiency challenges of the traditional sugar industry.

5. Conclusions

The sugar factory's production efficiency is below the 10% target, with a yield of only 6,63%. The evaporation station is the main energy source, with the turbine dominating electricity consumption. The preparation station has the highest efficiency (82.89%), while the cooking station has the lowest (78.79%). Low yields are attributed to poor machine operators, low Brix levels, non-standard temperatures, nira spillage, and a non-optimal crystallization process. Internal improvements like maintenance and operator training are recommended, while external improvements, particularly in raw material management, are needed. STEM-based technology can optimize material and energy flows.

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