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Chemical Plant Design Production of Essential Oil from Robusta Coffee Beans with a Capacity of 200 Metric Tons/Year

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ABSTRACT
This study aims to develop a preliminary design of a Robusta coffee bean essential oil plant with a production capacity of 200 tons/year in Turen Subdistrict, Malang Regency. The design considers raw material availability, site selection, solid–liquid extraction process, purification, material flow diagram, mass balance, and heat balance analysis. The extraction process was conducted at 70–80°C for 2 hours, followed by purification using distillation and n-hexane washing. The mass balance analysis showed a steady-state condition with total input and output streams of 19,661.42 kg/h, supported by effective solvent recovery and an essential oil production rate of 33.67 kg/h. Heat balance analysis indicated that the extractor contributed the highest energy requirement of 524,779 kJ/h (44%), followed by the distillation column (35%) and rotary dryer (21%). The results suggest that heat integration and thermal insulation strategies are necessary to improve energy efficiency and reduce steam consumption.

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INTRODUCTION

Indonesia is one of the world's largest coffee-producing countries, with a total plantation area of 1.29 million hectares in 2022 (Afnaria & Nurhayati, 2021). The coffee varieties cultivated include Arabica, Robusta, Liberica, and Excelsa, with Robusta being the most widely produced due to its high productivity, higher caffeine content, and relatively lower cost. Global demand for essential oils has increased significantly. In 2021, Indonesia's essential oil exports reached USD 248.4 million, growing by 15.09% compared to the previous year, with major export destinations including the United States, India, France, Spain, and the Netherlands (Trisnawati & Julianto, 2022). However, domestic production capacity has not yet fully met market demand, indicating strong opportunities for industrial development, particularly for value-added products derived from agricultural commodities such as coffee.

Malang Regency in East Java has strong potential as a location for developing a robusta coffee-based industry, supported by a plantation area of approximately 19,000 hectares and productivity of around 1 metric ton per hectare. In addition to abundant raw materials, supporting factors such as solvent availability (ethanol), transportation infrastructure, utilities, labor, and community readiness further strengthen the feasibility of establishing a processing facility in Turen Subdistrict.

Despite numerous studies on coffee composition and extraction methods, most previous research focuses on laboratory-scale extraction efficiency and product characterization. Limited studies have addressed the integration of these findings into a comprehensive industrial plant design, particularly those incorporating detailed mass and heat balance analysis for process optimization. In addition, existing studies often emphasize either product yield or energy aspects separately, without considering their combined impact on overall process efficiency and feasibility.

Therefore, this study aims to develop a preliminary design of a robusta coffee bean essential oil plant with a capacity of 200 metric tons per year by integrating mass balance and heat balance analysis. The novelty of this work lies in the combined evaluation of material and energy requirements within a single design framework, providing a more comprehensive assessment of process efficiency and industrial feasibility. This approach is expected to contribute to the development of a sustainable and economically viable essential oil industry in Indonesia, while enhancing the added value of robusta coffee as a national commodity.

LITERATURE REVIEW

Chemical Composition and Bioactivity of Robusta Coffee

Robusta coffee (Coffea canephora) contains major bioactive compounds such as caffeine, chlorogenic acids, tannins, and saponins, which contribute to antioxidant and antimicrobial activities (Wigati et al., 2018; Amiliyah et al., 2015). Compared to Arabica, Robusta generally has higher caffeine and chlorogenic acid content, resulting in stronger antioxidant capacity but also higher bitterness.

Several studies indicate that chlorogenic acids are sensitive to thermal degradation during roasting, leading to reduced antioxidant activity but increased formation of aroma compounds through Maillard reactions. This creates a trade-off between bioactivity and sensory quality. Therefore, from an industrial perspective, the selection of processing conditions must balance functional properties and desired product characteristics.

1. Coffee Bean Essential Oil and Its Utilization

Coffee bean oil (10–15%) consists mainly of fatty acids, diterpenes, and volatile compounds responsible for aroma (Firyanto & Mulyaningsih, 2020). Compared to steam distillation, solvent extraction generally provides higher oil yield but may risk solvent residues, while supercritical CO_2 extraction produces higher purity oil but requires higher investment cost. Thus, method selection depends on economic and quality considerations.

Previous studies highlight that temperature and solvent polarity significantly influence extraction efficiency. Higher temperatures can increase yield but may degrade volatile compounds, reducing aroma quality. This indicates the need for optimized operating conditions to achieve a balance between yield and product quality.

In industrial applications, coffee oil is used in food flavoring, cosmetics, and aromatherapy due to its antioxidant and emollient properties (Aziz et al., 2009; Calligaris et al., 2009). The growing demand for natural products further strengthens its commercial potential, particularly in countries with abundant raw materials such as Indonesia.

2. Mass Balance and Heat Balance in Process Design

Mass and heat balances are fundamental tools in process design to ensure efficiency and feasibility. The mass balance follows the conservation of mass principle:

$$\sum m_{in} = \sum m_{out} + \text{accumulation} \quad \ldots\ldots\ldots\ldots\ldots (1)$$

For steady-state processes (common in industrial plants), accumulation is zero:

$$\sum m_{in} = \sum m_{out} \quad \ldots\ldots\ldots\ldots\ldots (2)$$

This equation is used to determine material flow rates in each unit operation, such as extraction and separation, ensuring minimal material loss and optimal resource utilization.

Heat balance is based on energy conservation:

$$Q - W = \sum m(h_{out} - h_{in}) \quad \ldots\ldots\ldots\ldots\ldots (3)$$

In many chemical processes where shaft work (W) is negligible:

$$Q = \sum m\Delta h \quad \ldots\ldots\ldots\ldots\ldots (4)$$

Heat balance analysis is crucial in operations involving temperature changes, such as heating and evaporation, where improper control may reduce product quality or increase energy consumption.

Previous studies emphasize that integrating mass and heat balance improves process efficiency through energy optimization and utility system design. However, many small-scale designs overlook heat integration, leading to higher operational costs. Therefore, incorporating both balances in the early design stage is essential to achieve an economically viable and energy-efficient essential oil plant.

METHODOLOGY

This research methodology encompasses various systematically designed stages, beginning with the collection of data on plant design as the primary basis, followed by the application of equations formulated sequentially based on the literature in the previous chapter to serve as a design model.

1. **Analysis of Raw Material Availability**

The main raw materials are Robusta coffee beans and ethanol. East Java is a significant producer of Robusta coffee, with a production of 45.8 thousand metric tons in 2022. Malang Regency has approximately 19 thousand hectares of Robusta plantations with a productivity of approximately 1 metric ton per hectare.

2. **Site Selection**

Site selection takes into account raw materials, marketing, utilities, transportation, labor, and regulations. The Turen subdistrict was chosen because it is close to a coffee-producing center (Dampit), has good transportation access, adequate water, electricity, and fuel supplies, and a community ready for industrial development.

3. **Production Process**

The main processes include:

- Solid-liquid extraction: Roasted coffee beans are ground and extracted with ethanol at 70–80°C for approximately 2 hours.
- Purification: Distillation to separate the ethanol, followed by treatment with n-hexane to increase the purity of the essential oil.

4. **Flow Diagram**

The process begins with roasting, grinding, sieving, solid-liquid extraction, filtration, distillation, n-hexane blending, and final distillation. A flow diagram was created to map the flow of materials from raw materials to the final product.

5. **Mass Balance**

Operating basis: 330 days/year (24 hours/day, 3 batches/day). Production capacity: 200 metric tons/year or ±33.67 kg/hour. The mass balance is calculated for the rotary dryer, hammer mill, vibrating screen, extractor, and distillation column.

6. **Heat Balance**

The heat balance analysis uses the equation: $Q = m \cdot Cp \cdot \Delta T$. The specific heat capacity (Cp) for each component is taken from standard thermodynamic sources: ethanol (2.44 kJ/kg°C), hexane (2.26 kJ/kg°C), coffee beans (1.6 kJ/kg°C). ΔT is calculated from the unit's operating temperatures (dryer 25→150 °C, extractor 25→80 °C, distillation 25→90 °C). An assumed thermal efficiency of 80 % is applied to account for heat loss.

RESEARCH RESULT

The availability of raw materials and supporting resources was evaluated as the basis for the preliminary design of the Robusta coffee essential oil plant. Malang Regency was selected as the potential raw material source due to its significant Robusta coffee production. In 2022, Malang Regency had approximately 19,000 hectares of Robusta coffee plantations with a productivity of around 1 metric ton per hectare (Afnaria & Nurhayati, 2021). The selected plant location in Turen Subdistrict is strategically positioned near the Dampit coffee production center, which is located approximately 10 km from the plant site, ensuring efficient raw material transportation. In addition, the availability of ethanol as an extraction solvent is supported by domestic bioethanol production. The selected location also provides access to essential utilities, including clean water supply from PDAM, electricity from PT PLN Turen Substation, and energy sources from gas and LPG suppliers.

The designed production process of Robusta coffee bean essential oil consists of raw material preparation, solid–liquid extraction, solvent recovery, and purification stages. The extraction process utilizes ethanol as a solvent at a temperature range of 70–80°C for approximately 2 hours. The extracted oil is subsequently separated from the solvent through distillation, followed by purification using n-hexane washing and final distillation. The process flow diagram illustrates the sequence of operations and material transfer between process units, serving as the basis for equipment design and process evaluation.

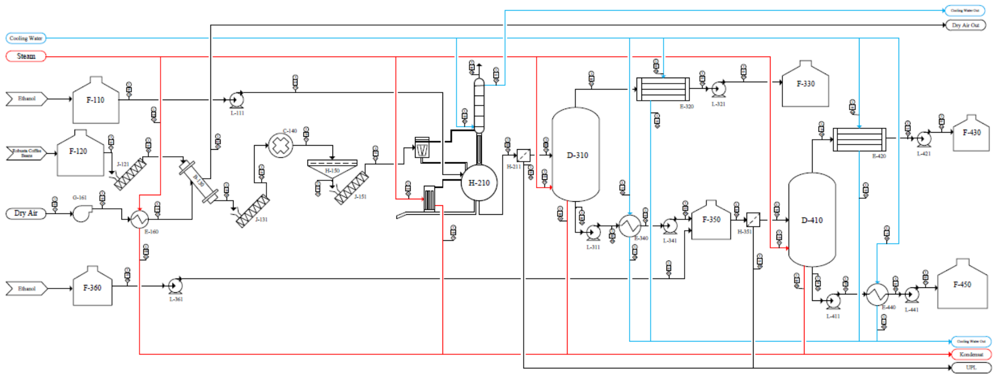
The mass balance calculation showed that the designed process reached steady-state conditions, with total input and output streams of 19,661.42 kg/h. The main raw materials consisted of Robusta coffee beans, ethanol, and n-hexane, while the primary product obtained was essential oil with a production rate of approximately 33.67 kg/h. The solvent recovery process resulted in ethanol and n-hexane outputs of approximately 13,742.87 kg/h and 4,150.69 kg/h, respectively, indicating effective solvent utilization within the system.

The heat balance analysis was conducted to determine the energy requirement of each major process unit. The highest energy demand was observed in the extractor, requiring 524,779.04 kJ/h, followed by the distillation column and rotary dryer with energy requirements of 414,656.27 kJ/h and 245,010.99 kJ/h, respectively. The extractor contributed approximately 44% of the total heat requirement, while the distillation column and rotary dryer accounted for 35% and 21%, respectively.

DISCUSSION

The availability of Robusta coffee raw materials in Malang Regency provides a strong foundation for the development of an essential oil processing industry. The proximity of the plant location to coffee production centers reduces transportation costs and minimizes the risk of raw material supply limitations. This finding supports the industrial location principle proposed by Peters et al. (2003), which emphasizes that accessibility to raw materials and logistical efficiency are key factors in determining plant feasibility. Furthermore, the availability of ethanol from domestic production supports the sustainability of the process by reducing dependence on imported solvents. The presence of adequate utilities and human resources in the Malang region also enhances the technical feasibility of the proposed plant, in accordance with chemical plant design criteria described by Towler and Sinnott (2013).

Figure 1. PFD Production of Essential Oil from Robusta Coffee Beans



The selected solid–liquid extraction method using ethanol provides a technically feasible approach for recovering essential oil from Robusta coffee beans. Compared with more advanced extraction technologies, such as supercritical fluid extraction, solvent extraction offers advantages in terms of simpler equipment requirements and lower investment costs. However, the extraction process requires careful optimization because temperature and extraction time significantly influence both oil yield and volatile compound preservation. Previous research reported that coffee oil extraction yield varies between 1–8%, depending on raw material characteristics and extraction conditions (Firyanto & Mulyaningsih, 2020). Therefore, maintaining the extraction temperature within the designed range of 70–80°C is important to achieve a balance between extraction efficiency and product quality.

Table 1. Mass Balance

Komponen	Input				Output						
	Laju Massa (kg/jam)										
	<3>	<8>	<15>	<34>	<4>	<20>	<25>	<38>	<46>	<51>	<52>
Mineral	-	75,59	-	-	-	2,06	-	-	-	-	-
Kafein	-	39,51	-	-	-	7,73	-	-	-	-	-
Trigonelline	-	12,88	-	-	-	1,72	-	-	-	-	-
Lipid	-	161,48	-	-	-	127,81	-	-	-	-	-
Asam amino	-	202,71	-	-	-	2,58	-	-	-	-	-
Karbohidrat	-	870,95	-	-	-	3,44	-	-	-	-	-
Chologenic acid	-	170,07	-	-	-	4,29	-	-	-	-	-
H_2O	0,98	184,67	-	-	104,96	80,69	-	-	-	-	-
N_2	38,73	-	-	-	38,73	-	-	-	-	-	-
O_2	10,29	-	-	-	10,29	-	-	-	-	-	-
Hexane	-	-	-	4150,69				-	4150,69	-	-
Ethanol	-	-	13742,87	-	-	-	11750,15	-	618,43	-	1374,29
Ekstrak Kopi	-	-	-	-	-	-	-	1349,89	-	-	-
Minyak	-	-	-	-	-	-	-	-	-	33,67	-
Jumlah	**50,00**	**1717,86**	**13742,87**	**4150,69**	**153,98**	**230,32**	**11750,15**	**1349,89**	**4769,12**	**33,67**	**1374,29**
Total	**19661,42**				**19661,42**						

The mass balance results demonstrate that the proposed plant design achieves efficient material utilization, as indicated by the equilibrium between input and output streams. The high recovery of ethanol and n-hexane contributes to reducing solvent consumption, operational costs, and waste generation. This condition is essential in industrial-scale essential oil production because solvent recovery efficiency directly affects both economic performance and environmental sustainability (Towler & Sinnott, 2013). The obtained essential oil production rate of 33.67 kg/h is also consistent with the targeted annual production capacity of 200 metric tons, indicating that the proposed process configuration is technically appropriate.

The heat balance analysis indicates that the extraction and purification stages are the dominant energy-consuming operations. The extractor showed the highest energy requirement due to the need to maintain elevated temperatures during the extraction process, while the distillation column required significant energy for solvent separation. Similar findings have been reported in essential oil industries, where extraction and purification units contribute the largest proportion of energy consumption (Trisnawati & Julianto, 2022). Therefore, energy optimization strategies are necessary to improve plant efficiency. Heat integration, such as utilizing waste heat from the distillation condenser to preheat incoming feed streams, can reduce external energy requirements. In addition, improving insulation performance in distillation equipment and heat transfer pipelines may reduce heat losses by approximately 15–20% (Sinnott & Towler, 2009).

Overall, the preliminary design demonstrates that the Robusta coffee essential oil plant has potential for sustainable operation through efficient raw material utilization, solvent recovery, and energy management. However, further studies involving economic analysis, process optimization, and environmental assessment are required to evaluate the overall feasibility of large-scale implementation.

CONCLUSIONS

Based on the analysis of raw material availability, location, processes, mass balance, and heat balance, it can be concluded that the preliminary design of a robusta coffee bean essential oil plant with a capacity of 200 metric tons per year in Turen Subdistrict, Malang Regency, is technically and economically feasible. The abundant potential of Robusta coffee beans—with production in East Java reaching 45.8 thousand metric tons and Malang contributing approximately 19 thousand hectares of productive land—along with the availability of ethanol from national producers, ensures a continuous supply of raw materials. The selection of a solid-liquid extraction process at 70–80°C yields a high (1–8 %) and stable yield, while the purification process involving distillation and washing with n-hexane demonstrates the ability to effectively separate and purify essential oil components. The mass balance shows an input = output equilibrium (19,661.42 kg/h) and high solvent recovery, resulting in minimal waste. In terms of energy, the extractor unit requires 524,779 kJ/h (44 % of the heat load), followed by distillation at 414,656 kJ/h (35 %) and the rotary dryer at 245,011 kJ/h (21 %). The high heat consumption in the extractor underscores the need for thermal optimization to reduce operating costs and emissions.

RECOMMENDATIONS

1. **Heat Integration**

   Implement a heat recovery strategy by utilizing hot steam from the distillation condenser to preheat the feed entering the extractor or rotary dryer, thereby reducing steam consumption by 15–20 %.

2. **Thermal Insulation**

   Improve thermal insulation on the surfaces of distillation columns and hot process piping to minimize heat loss to the environment and maintain stable operating temperatures.

3. **Extractor Operation Optimization**

   Consider using intensive mechanical agitation or varying the solid–solvent ratio to reduce extraction time without lowering yield, while also reducing the heat load.

4. **Energy Monitoring and Control**

   Install flow and temperature instruments at critical points (steam inlet/outlet, ethanol vapor, cooling water) to monitor the heat balance in real time and make operational adjustments for maximum efficiency.

5. **Advanced Economic Analysis**

   Conduct a detailed economic analysis (CAPEX, OPEX, NPV, IRR, POT) that incorporates energy and raw material price scenarios, as well as potential green financing options, to ensure long-term financial viability.

6. **Renewable Energy Study**

   Explore options for using boilers fueled by coffee waste biomass or solar thermal panels to reduce reliance on fossil fuels and lower the plant's carbon footprint.

ADVANCED RESEARCH

This study is limited to a preliminary plant design based on raw material assessment, process design, mass balance, and heat balance analysis. Economic feasibility, pilot-scale validation, and environmental impact assessment have not been evaluated. In addition, the process parameters were developed based on literature data, which may differ from actual operating conditions due to variations in raw material characteristics and extraction performance. Further research should focus on experimental optimization of extraction parameters, economic analysis, and energy integration strategies to improve process efficiency, sustainability, and commercial feasibility of Robusta coffee essential oil production.

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REFERENCES

Afnaria, & Nurhayati. (2021). *Produksi kopi di Indonesia*. Badan Pusat Statistik.

Aziz, T., Ratih, C., & Sari, P. (2009). *Teknologi minyak atsiri*. Balai Penelitian Tanaman Obat.

Calligaris, S., Munari, M., Arrighetti, G., & Anese, M. (2009). Insights into the physicochemical properties of coffee oil. *Food Chemistry, 115*(1), 301–306. https://doi.org/10.1016/j.foodchem.2008.11.091

Firyanto, & Mulyaningsih. (2020). *Teknologi ekstraksi minyak atsiri*. UGM Press.

Geankoplis, C. J. (2003). *Transport processes and separation process principles* (4th ed.). Prentice Hall.

Kumar, S., Singh, R., & Sharma, S. (2020). Extraction and characterization of bioactive compounds from coffee by-products: A review. *Food Chemistry, 309*, 125719. https://doi.org/10.1016/j.foodchem.2019.125719

Mussatto, S. I., Machado, E. M. S., Martins, S., & Teixeira, J. A. (2011). Production, composition, and application of coffee and its industrial residues. *Food and Bioprocess Technology, 4*, 661–672. https://doi.org/10.1007/s11947-011-0565-z

Peters, M. S., Timmerhaus, K. D., & West, R. E. (2003). *Plant design and economics for chemical engineers* (5th ed.). McGraw-Hill.

Sinnott, R., & Towler, G. (2009). *Chemical engineering design: Principles, practice and economics of plant and process design*. Butterworth-Heinemann.

Towler, G., & Sinnott, R. (2013). *Chemical engineering design: Principles, practice and economics of plant and process design* (2nd ed.). Butterworth-Heinemann.

Trisnawati, & Julianto. (2022). *Statistik ekspor minyak atsiri Indonesia*. Badan Pusat Statistik.

Wigati, D., Anwar, K., & Sudarsono. (2018). Chemical composition and phytochemical properties of Robusta coffee (*Coffea canephora*) beans. *Jurnal Kimia dan Pendidikan, 3*(2), 101–109.