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MATERIAL FLOW ANALYSIS OF WHITE BREAD PRODUCTION: CASE STUDY AT A HOME-SCALE BAKERY PRODUCTION IN SURABAYA

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ABSTRACT

Bread production in urban areas of Indonesia requires significant resource inputs (total 150 kg: 85.21 kg flour, water 52.33 kg, sugar 4.26 kg, salt/yeast 1.74 kg each, oil 1.40 kg, butter 1.32 kg, eggs 2.00 kg for 135 kg/day of bread ready for distribution) while also producing solid waste and emissions, thus requiring an efficiency assessment through Material Flow Analysis (MFA) for sustainability. This study applied MFA with a gate-to-gate approach to seven operational units: weighing, mixing, fermentation, dough forming, baking, cooling, and packaging at a home industry in Surabaya, using primary data from structured interviews (October 29, 2025) and secondary data from the literature. The results showed high efficiency, with a Product Yield of 90%, Organic Waste of 3.34%, Non-Product Output Ratio (NPOR) of 10.01%, and total emissions and steam of 6.67%. The main losses were 7.6 kg CO_2 (mixing/fermentation), trim waste 3 kg, exhaust 2.4 kg, and steam 1.7 kg (mass imbalance of 0.515 kg due to rounding/evaporation). MFA effectively supports sustainable bakery production through process optimization and waste valorization.

Keywords: Material Flow Analysis, White Bread Production, Mass Balance, Ecoefficiency.

ABSTRAK

Produksi roti di wilayah urban Indonesia memerlukan input *sumber daya besar (total 150 kg: tepung 85,21 kg, air 52,33 kg, gula 4,26 kg, garam/ragi masing-masing 1,74 kg, minyak 1,40 kg, mentega 1,32 kg, telur 2,00 kg untuk 135 kg/hari roti siap distribusi) sekaligus menghasilkan limbah padat dan emisi, sehingga memerlukan penilaian efisiensi melalui* Material Flow Analysis (MFA) *untuk keberlanjutan. Penelitian ini menerapkan MFA dengan pendekatan* gate-to-gate *pada tujuh unit operasi penimbangan, pencampuran, fermentasi, pembentukan adonan, pemanggangan, pendinginan, pengemasan pada sebuah industri rumahan di Surabaya, menggunakan data primer dari wawancara terstruktur (29 Oktober 2025) dan data sekunder dari literatur. Hasil menunjukkan efisiensi tinggi dengan* Product Yield *90%,* Organic Waste *3.34%, NPOR (*Non-Product Output Ratio*) 10,01%, emisi dan uap total 6,67%; kehilangan utama: 7,6 kg CO_2 (pencampuran/fermentasi),* trim waste *3 kg,* exhaust *2,4 kg, uap 1,7 kg (ketidakseimbangan massa 0,515 kg akibat pembulatan/evaporasi). MFA efektif mendukung produksi* bakery *berkelanjutan melalui optimalisasi proses dan valorisasi limbah.*

Kata kunci : Material Flow Analysis*, produksi roti tawar, neraca massa,* eco-efficiency.

INTRODUCTION

Bread products are a fast-food industry made from wheat flour. According to the Indonesian National Standard (SNI 01-3840-1995), bread is a product made with wheat flour as the main ingredient, made through a fermentation process with yeast and the addition of permitted food additives, then baked (BSN, 1995). Bread products also have a shelf life of two to three days, are not easily stale, and are readily available on the market. Bread is widely consumed as a breakfast item, particularly in urban areas (Poh and Hendrawan, 2013).

According to data from the Central Statistics Agency (BPS) in 2023, bread consumption in Indonesia reached 3.01 kilograms (kg) per capita annually (BPS, 2023). In fact, bread sales in Indonesia are the highest in Southeast Asia, reaching IDR 2.6 trillion. However, the Indonesian bread market is said to still require a supply of 68 percent. This gap can be exploited by startups that launch bakery businesses. Bread is a widely recognized bakery product (Musyarofa et al., 2025). This has led to a new habit in the community, namely, consuming bread as a healthy and practical breakfast option by replacing rice, which is known to be a source of carbohydrates (Al-Hakkak and Al-Hakkak, 2010; Mesta-Corral et al., 2024).

Bread is one of the world's major staple foods, and its production chain, from raw material cultivation, processing, transportation, baking, to distribution, requires substantial inputs of water, energy, and mineral fertilizers. For example, research shows that more than half of the environmental impact of bread production arises at the wheat cultivation stage, largely owing to fertilizer use and energy demand. Because the bakery industry is resource-intensive and generates waste streams (such as emissions, solid residues, and packaging waste), mapping material and energy flows through a "gate-to-gate" model offers a structured way to identify where inputs are highest, where losses occur, and where process improvements may yield the greatest benefits (Todd and Faour-Klingbeil, 2024).

In this context, the Material Flow Analysis (MFA) approach can be used to evaluate the sustainability aspects of the bread production process. Evaluating the sustainability aspects of bread production is important because the production process uses various resources, such as wheat flour, water, and energy, and produces waste and emissions that can impact the environment (Brostow et al., 2016; Brown and Waldron, 2013). MFA is a quantitative method used to identify and measure material flow in a production system. Through MFA, the amount of material input, output, and loss at each stage of the process can be determined, thereby identifying potential inefficiencies that need improvement. This approach provides a comprehensive understanding of resource efficiency and material balance in production.

Several studies in Indonesia have applied the MFA approach to the food industry, such as in the tofu (Musyarofa et al., 2025) and spice flour industries (Farahdiba et al., 2024), showing that this method can be used to evaluate potential inefficiencies and resource utilization in small and medium enterprises (SMEs). However, the application of MFA in the Indonesian bread industry is still limited, especially in urban areas with intensive production and distribution activities, such as Surabaya. Surabaya was chosen as the research location because it is one of the largest cities in Indonesia with significant growth in the food processing sector and an increase in bread consumption (BPS, 2023; Suflani et al., 2024). This indicates a critical research gap that must be filled to support the food industry's transition to a more sustainable production system.

Based on this background, the purpose of this study is to evaluate the sustainability of bread production at a home-scale white bread bakery through the application of Material Flow Analysis (MFA). Specifically, this study aims to (i) identify and map material flows (inputs, outputs, and losses) in the bread production process at a home-scale white bread bakery production, (ii) analyze the efficiency and potential material losses at each stage of the production process using the MFA approach, and (iii) provide strategic recommendations to improve resource efficiency and reduce material losses in bread production in urban Surabaya.

This research has two main benefits. Academically, this study is expected to enrich the literature on the application of MFA in the context of the Indonesian food industry, especially for medium-scale bread products (Denham et al., 2016). Practically, the results of this study can be used as a basis for home-scale white bread bakery production to formulate more efficient and environmentally friendly production strategies, as well as a reference for other food industry players in Indonesia to apply the principles of sustainable production. The production process of traditional food in small industries can have significant environmental impacts owing to energy consumption, agricultural inputs, and emissions generated during production (Manik et al., 2025).

METHODOLOGY

This study focuses on analyzing the bread production process at a home-scale white bread bakery in Surabaya, Indonesia, using the Material Flow Analysis (MFA) approach. This method is used to understand material and energy flows and evaluate the efficiency of resource use and potential material losses generated during the production process.

Data Collection

The primary data in this study were collected through structured online interviews conducted on October 29, 2025, with the production manager, procurement staff, and production workers at a home-scale white bread bakery production. The interviews were conducted via online communication platforms, such as WhatsApp Chat, depending on the respondents' availability and convenience. The information obtained covered various aspects of the production process, including the types and quantities of raw materials (such as flour, sugar, eggs, butter, and other additives), energy and water consumption at each production stage, types and quantities of waste generated (solid, liquid, and packaging), and the types of packaging materials and product distribution systems. In addition to the primary data, secondary data were collected from the literature, industrial reports, and online databases to complement and verify the technical information required for the Material Flow Analysis (MFA).

Goal and Scope

The goal of this Material Flow Analysis (MFA) study is to assess the sustainability of bread production through a systematic analysis of material and energy flows in a "gate-to-gate" model. The inventory data was based on inputs such as wheat flour, water, yeast, sugar, salt, oil, and electricity, while the outputs included bread, wastewater, solid residues, and air emissions. The scope of this study covers all stages in the production of bread, ranging from the receipt of raw materials, mixing, fermentation, baking, cooling, and packaging, until the bread is ready for distribution.

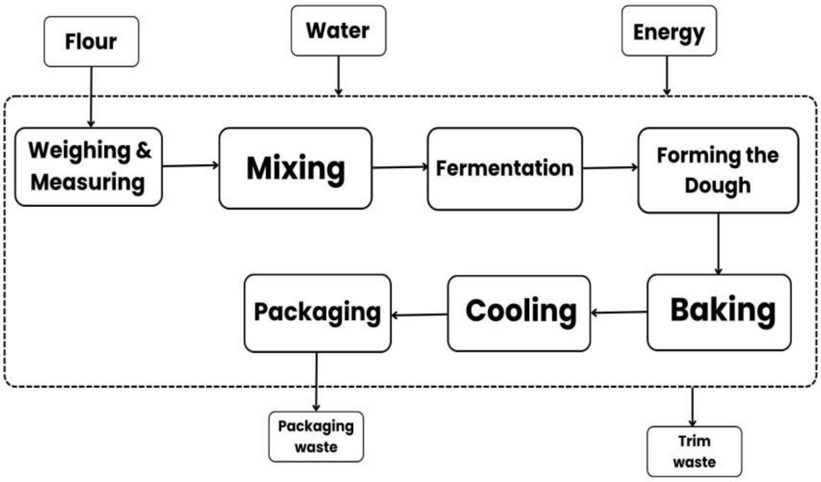

Figure 1. System Boundary of The Study

System Boundary

The system boundary of the bread production model covers all unit processes using a gate-to-gate approach, which can be grouped as follows: receipt and storage of raw materials, mixing and kneading, fermentation, baking, cooling, and packaging. These processes account for the main flows of materials and energy, as well as the generation of residues and emissions within the production system.

Emission Estimation Assumption

CO_2 emissions from electricity use were estimated by multiplying the amount of electrical energy consumed during the process by the average grid emission factor. For example, the average CO_2 emission factor for electricity supplied from the Indonesian grid is approximately 0.785 kg CO_2/kWh of electricity generated, reflecting the carbon intensity of the national electricity mix, with a significant contribution from fossil fuel generation (Climatiq, 2025). Similarly, CO_2 emissions from oven fuel use were estimated by multiplying the amount of Liquefied Petroleum Gas (LPG) consumed during baking with an emission factor derived from national energy statistics, where LPG combustion corresponds to an average emission factor of 65.41 kg CO_2/TJ of energy content, equivalent to approximately 3 kg CO_2/kg of LPG when converted using its net calorific value (Kementerian ESDM, 2017).The steam waste generated during the cooling stage was not estimated using emission factors, as it did not originate from fuel combustion or energy use. Instead, it was quantified using a material flow and mass balance approach, where the reduction in product mass between the end of baking and the end of cooling was assumed to represent the moisture released as water vapor. This assumption is consistent with the food engineering and baking process literature, which identifies evaporative moisture loss as the dominant mechanism of mass reduction during cooling. No direct steam flow measurements were conducted, and all estimated steam losses were reconciled through mass balance closure within the material flow model.

RESULT

Functional Unit

The functional unit in this study was defined as 135 kg/day of bread ready for shipping.

Material Flow Model

In a home-scale white bread bakery production, the Material Flow Model illustrates the movement of raw materials throughout the entire production process. This diagram shows each stage, starting with weighing and measuring raw materials, followed by mixing, fermentation, shaping, baking, cooling, and packaging. Each stage of the process shows the inputs, outputs, and corresponding waste streams, such as flour residue, eggshell waste, CO_2 emissions, trimmings, and packaging waste. This model provides an overview of how materials are transformed and utilized during production, enabling the identification of potential inefficiencies and material losses that may occur throughout the process of production.

The home-scale white bread production process consists of several sequential stages that transform raw materials into finished products. The process begins with weighing and measuring, where all ingredients, such as flour, sugar, salt, yeast, oil, butter, eggs, and water, are measured precisely according to the production formula. Accurate measurements at this stage are crucial to ensure product consistency and quality. Small material losses, such as flour residue and eggshell waste, may occur during the process.

After weighing, the ingredients proceed to the mixing stage, where all ingredients are mixed to form a homogeneous dough. The mixing process ensures that yeast and other components are evenly distributed throughout the mixture. Minor material losses may occur because of the dough sticking to the mixing equipment, whereas CO_2 emissions may occur naturally because of yeast activation. The next stage is fermentation, where the dough is left to rest for a certain period to allow yeast activity and gas formation to occur. This stage significantly affects the texture, volume, and softness of bread, with CO_2 emissions being a natural byproduct of the process.

After fermentation is complete, the dough moves on to the shaping stage, where it is formed into the desired shape. At this stage, waste scraps are often produced as excess dough is discarded to achieve a uniform size and shape. The shaped dough then enters the baking stage, where it is baked at a controlled temperature until fully cooked. This process produces exhaust gas and water vapor emissions, which are part of the energy and material flow during production.

After baking, the bread was cooled at room temperature to stabilize its structure and prevent condensation during packaging. This stage also produces a small amount of waste steam. Finally, the cooled bread is sent to the packaging stage, where it is wrapped in paper to maintain its quality during storage and distribution. Packaging activities can generate waste from cutting materials and sealing processes. Overall, these stages describe the complete material flow from raw materials to finished bread, providing a basis for analyzing efficiency and identifying potential material losses in the production system.

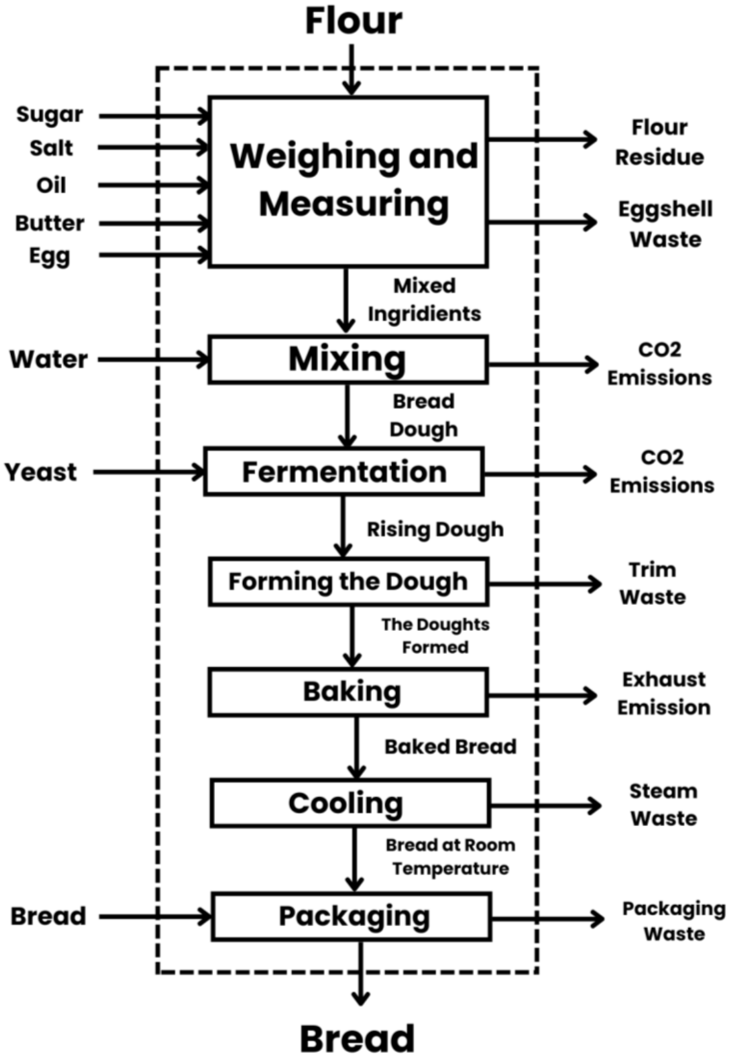

Figure 2. Material Flow Model of Bread Production

Material Balance

To provide a clear understanding of the material flows in the bread production system, a mass balance assessment was conducted across all unit operations involved in daily processing (Laurence et al., 2018). This analysis quantifies the transformation of raw materials into intermediate and final products. It also identifies waste and emissions generation at each stage. The evaluation includes seven sequential processes: weighing and measuring the ingredients, mixing, fermenting, dough forming, baking, cooling, and packaging. For each unit operation, all material inputs and outputs were recorded and reconciled to ensure consistency and accuracy in the overall production flow. The resulting mass balance, summarized in Table 1, offers a detailed view of the material conversion efficiency and loss distribution. This forms a critical basis for further environmental assessment, process improvement, and resource management in the bakery production line.

The overall mass balance for the bread production process was compiled to provide a consolidated representation of all material inputs and outputs across the entire processing sequence (Vistanty et al., 2020). This table integrates the cumulative quantities recorded at each unit operation including weighing, mixing, fermentation, baking, cooling, and packaging into a single comprehensive framework. By summarizing the transformation of raw materials into final products, by-products, and process-related losses, the overall mass balance enables a systematic evaluation of material flows and the efficiency of resource utilization throughout the production cycle (Li et al., 2020).

Table 1. Mass Balance for Unit Process

No.	Input		No.	Output	
	Material	Quantity (kg/d)		Material	Quantity (kg/d)
		Weighing and Measuring			
1	Flour	85.210	1	Flour Residue	0.015
2	Sugar	4.260	2	Eggshell Waste	0.30
3	Salt	1.740	3	Mixed Ingredients	95.615
4	Oil	1.400			
5	Butter	1.320			
6	Egg	2.000			
	Total	95.930			95.930
		Mixing			
1	Mixed Ingredients	95.615	1	CO_2 Emission	3.800
2	Water	52.330	2	Bread Dough	144.150
	Total				
		Fermentation			
1	Bread Dough	144.150	1	CO_2 Emission	3.800
2	Yeast	1.740	2	Rising Dough	142.100
	Total	145.900			145.900
		Forming the dough			
1	Forming the Dough	142.100	1	Trim Waste	3.000
			2	The Dough is Formed	139.100
	Total	142.100			142.100
		Baking			
1	Baking	139.100	1	Exhaust Emission	2.400
			2	Baked Bread	136.700
	Total	139.100			139.100
		Cooling			
1	Cooling	136.700	1	Steam Waste	1.700
			2	Bread at room	135.000
	Total	136.700			
		Packaging			
1	Bread	135.000	1	Bread	135.000
2	Paper packaging	0.550	2	Paper Packaging	0.500
	Total	135.500		Total	135.500

CO_2 emissions from the mixing and fermentation processes were calculated using an electricity-based emission factor approach to verify the values reported in the material mass balance table. The Indonesian electricity grid emission factor was assumed to be 0.785 kg CO_2 per kWh. The equivalent electricity consumption was obtained by back calculating the reported CO_2 emissions as follows:

Electricity use = Emission Factor × Consumption (kWh)

Electricity use = 0.785 kg CO_2/kWh × 4.84 kWh = 3.8 kg CO_2

This electricity demand is consistent with typical power requirements for industrial dough mixers and fermentation systems, confirming the plausibility of the reported CO_2 emissions.

Exhaust CO_2 emissions from the baking process were calculated using a stoichiometric combustion approach for liquefied petroleum gas (LPG), which was approximated as propane (C_3H_8). The complete combustion reaction is expressed as:

$$C_3H_8+5O_2 \rightarrow 3CO_2+4H_2O$$

Based on molar masses (C_3H_8 = 44 g/mol; CO_2 = 44 g/mol), the reaction indicates that 1 kg of LPG produces approximately 3 kg of CO_2. Therefore, the LPG consumption corresponding to the reported exhaust emission was calculated as:

LPG = Emission Factor × Consumption
LPG = 3 kg CO_2 × 0.8 kg LPG = 2.4 kg CO_2

This result is consistent with the national emission factor issued by the Indonesian Ministry of Energy and Mineral Resources, validating the reported exhaust CO_2 emissions.

Steam waste generated during the cooling stage was calculated using a mass balanced approach. The amount of steam released was determined as the difference between the mass of baked bread entering the cooling stage and the mass of bread after cooling:

$$m_{\text{steam}} = m_{\text{in}} - m_{\text{out}}$$
$$m_{\text{steam}} = 136.7\ \text{kg} - 135.0\ \text{kg} = 1.7\ \text{kg}$$

As no trimming or material removal occurs during cooling, this mass reduction was assumed to represent moisture released as water vapor. The calculation confirms the internal consistency of the material flow model.

Table 2. Overall Mass Balance

No.	Input		No.	Output	
	Material	Quantity (kg/d)		Material	Quantity (kg/d)
1	Flour	85.210	1	Finished Bread (Packaged)	135.000
2	Water	52.330	2	Packaging	0.500
3	Sugar	4.260	3	Organic Waste	5.015
4	Salt	1.740	4	Emission/Vapor	10.000
5	Yeast	1.740			
6	Oil	1.400			
7	Butter	1.320			
8	Egg	2.000			
	Total	150.000		Total	150.515

The total output derived from the overall mass balance does not fully match the initial 150 kg of input, resulting in a minor discrepancy of approximately 0.515 kg. Such deviations are common in mass balance assessments and are attributable to several factors, including rounding adjustments during intermediate calculations, small unquantified losses that occur during material handling, and moisture evaporation that is not explicitly measured. Variations in CO_2 release during fermentation and water vapor loss during baking or cooling may also contribute to marginal differences in recorded mass. Given the scale of the process and the inherent limitations of measurement precision, the observed imbalance is considered acceptable and does not compromise the reliability of the overall material flow evaluation.

DISCUSSION

Based on the application of the Material Flow Analysis (MFA) framework, this study successfully established a comprehensive and balanced mass balance for the entire bread production system, confirming the validity of the fundamental principle of mass conservation. This analysis reveals the structure of material flows by identifying four main components of the system (Qu et al., 2021; Nurjana et al., 2025). First, the input sources consisting of raw materials (flour, water, sugar, salt, yeast, oil, butter, egg) with precise quantification. Second, the chain of transformation processes consists of interconnected unit operations, namely weighting & measuring, mixing, fermentation, forming, baking, cooling, and packaging. Third, the economically valuable output flows (products), in the form of packaged bread as the system output. Fourth, the non-desirable output flows (residual flows), which include gas emissions (CO_2 from fermentation, exhaust from baking, steam from cooling) and solid waste (eggshell waste, flour residue, and dough trim waste).

Quantification at each process node shows that the largest mass loss occurs in the form of CO_2 emissions during the fermentation stage, which is a direct consequence of the biochemical processes involving yeast metabolism. Meanwhile, the generated solid waste, such as trim waste, indicates an opportunity for improving material efficiency through optimization of the forming process. Thus, MFA does not only serve as a tool for verifying compliance with the mass principle but further acts as a powerful diagnostic instrument for mapping material efficiency, quantifying waste generation at each critical stage, and providing an empirical basis for formulating process optimization strategies towards cleaner production and a circular economy in the food industry (Ren, 2018).

To ensure analytical transparency in evaluating the production system, each eco-efficiency indicator in this study is calculated using standardized formulas that represent the relationship between total inputs, final outputs, and material losses. The Total CO_2 Emissions indicator specifically accounts for emissions generated during key production stages, namely the mixing, fermentation, and baking processes. Meanwhile, the Non-Product Output Ratio (NPOR) captures all forms of material losses that do not contribute to the final product, including emissions, energy waste such as steam loss, solid waste such as eggshells and trim waste, as well as handling residues such as flour residue accumulated during processing. The formula used to calculate each indicator includes:

$$\text{Emission/Vapor} = \frac{\text{Emission/Vapor (kg)}}{\text{Total Input (kg)}} \times 100\% \quad (1)$$

$$\text{Organic Waste} = \frac{\text{Organic Waste (kg)}}{\text{Total Input (kg)}} \times 100\% \quad (2)$$

$$\text{NPOR} = \frac{\text{Total Non-Product Output (kg)}}{\text{Total Input (kg)}} \times 100\% \quad (3)$$

$$\text{Product Yield} = \frac{\text{Finished Bread (kg)}}{\text{Total Input (kg)}} \times 100\% \quad (4)$$

NOPR = Non-Product Output Ratio

Tabel 3. Calculation of Eco-efficiency Indicators

Indicators	Calculation	Result (%)
Emission/Vapor	$\frac{10\ kg}{150\ kg} \times 100\%$	6.67
Organic Waste	$\frac{5.015\ kg}{150\ kg} \times 100\%$	3.34
Non-Product Output Ratio (NPOR)	$\frac{15.015\ kg}{150\ kg} \times 100\%$	10.01
Product yield	$\frac{135\ kg}{150\ kg} \times 100\%$	90.00

As shown in Table 3, the emission/vapor ratio of 6.67% indicates that only a small fraction of the total input is released as emission-related output during the mixing, fermentation, and baking stages. The Non-Product Output Ratio (NPOR), calculated at 10.01%, reflects the combined contribution of CO_2 emissions, steam waste, eggshell waste, trim waste, flour handling residues also the packaging. The Organic Waste, calculated at 3.34%, there is contribution of steam waste, trim waste, eggshell waste and flour residue. This value is comparable to findings from MFA and MFCA assessments in the bakery sector, where non-product outputs typically range between 8–15% of total input depending on process efficiency and waste-handling practices (Yoddee and Chompu-inwai, 2023). For instance, a Material Flow Cost Accounting (MFCA) study on bread production in Thailand reported material losses of approximately 11.3%, dominated by dough trimming, baking losses, and handling residues. The NPOR in this study is slightly lower than that range, suggesting relatively effective waste management and controlled processing conditions.

The Product Yield of 90% fall within the efficiency range reported in previous MFA/MFCA evaluations of bakery operations, where yields between 85–92% are commonly observed (Tran and Herzig, 2020; Yoddee and Chompu-inwai, 2023). The slightly higher yield in this study indicates that most raw materials are successfully converted into final output, with minimal losses during handling and processing. This performance may be attributed to consistent dough portioning, reduced trimming waste, and efficient material handling. These results collectively demonstrate that the production process analyzed in this study achieves strong material conversion efficiency with relatively low non-product output compared to reported ranges in existing Material Flow Analysis studies within bakery industries (Todd and Faour-Klingbeil, 2024).

Beyond the quantitative indicators, the MFA results also highlight how closely process control and shop-floor practices influence overall eco-efficiency in home-scale bakery production. The relatively low Non-Product Output Ratio indicates that simple operational measures, such as careful weighing, disciplined handling of dough, and standardized baking times, already contribute significantly to minimizing material losses without requiring major technological investments.

At the same time, the identified loss streams, especially trim waste, eggshells, flour residue, and evaporative losses during baking and cooling represent tangible entry points for future cleaner production initiatives. For example, trim waste can potentially be reincorporated into new dough within safe quality limits, eggshells can be valorized as calcium-rich material for other applications, and flour residues may be reduced through improved housekeeping or captured for secondary use. By systematically linking each loss category to a realistic improvement option, MFA evolves from a diagnostic tool into a practical roadmap for incremental process optimization in small and medium-sized food enterprises.

Furthermore, situating this case study within the broader context of Indonesia's urban food system underscores the strategic value of MFA for local policy and SME support programs. The approach can be replicated in other micro and small bakeries to generate comparable indicators, enabling benchmarking of material efficiency and supporting targeted capacity-building efforts on waste reduction and resource conservation. In the long term, integrating MFA outcomes with economic and social metrics can help decision-makers design interventions that are not only environmentally sound but also financially viable and socially acceptable for home-scale producers in rapidly growing cities such as Surabaya.

This study has several limitations that should be acknowledged. First, the research was conducted at a single bakery, representing a single case study; therefore, the findings may not be fully generalizable to other bakeries with different production scales, technologies, or operational practices. Second, the primary data was collected through interviews with production staff, which may introduce self-reporting bias due to estimation errors or subjective responses. Third, this study focused exclusively on material flow analysis (MFA) and did not include an energy analysis or a full life cycle assessment (cradle-to-gate). As a result, the environmental implications discussed are limited to material flows and process-related losses, and do not represent the overall environmental impact of bread production.

CONCLUSION

The efficiency evaluation showed that the home-scale white bread bakery operated with strong material performance, with a Product Yield of 90%, which indicates that most of the raw materials are successfully converted into finished bread. While a Non-Product Output Ratio of 10.01% and an emission/vapor ratio of 6.67% reveal that the majority of losses occur naturally during fermentation, baking, and cooling, with smaller solid losses originating from weighing, mixing, and forming steps. The performance of the bakery is comparable to the industry norms.

REFERENCES

Al-Hakkak, J., Al-Hakkak, F., 2010. Functional egg white–pectin conjugates prepared by controlled Maillard reaction. Journal of Food Engineering 100(1), 152–159. https://doi.org/10.1016/J.JFOODENG.2010.03.040

BPS, 2023. Statistik Penyediaan Makanan dan Minuman 2023. Badan Pusat Statistik, Jakarta.

BSN, 1995. SNI 01-3840-1995 Roti. Badan Standardisasi Nasional, Jakarta.

Brostow, W., Chetuya, N., Hnatchuk, N., Uygunoglu, T., 2016. Reinforcing concrete: comparison of filler effects. Journal of Cleaner Production, 112, 2243–2248. https://doi.org/10.1016/J.JCLEPRO.2015.09.105

Brown, C., Waldron, S., 2013. Agrarian change, agricultural modernization and the modelling of agricultural households in Tibet. Agricultural Systems 115, 83–94. https://doi.org/10.1016/J.AGSY.2012.09.008

Climatiq, 2025. Emission Factor: Electricity Supplied from Grid in Indonesia. https://www.climatiq.io/data/emission-factor/de2ea62f-c1dc-43f2-8dd3-d6e7c884516a [2 December 2025

Denham, F.C., Biswas, W.K., Solah, V.A., Howieson, J.R., 2016. Greenhouse gas emissions from a Western Australian finfish supply chain. Journal of Cleaner Production, 112, 2079–2087. https://doi.org/10.1016/J.JCLEPRO.2014.11.080

Farahdiba, A.U., Franciscus, Y., Yuniarto, A., Hermana, J., 2024. Food Waste Flows for Energy Recovery: A Material Flow Analysis Approach in Urban Cities of Indonesia (Study Case: Surabaya City). Evergreen 11(3), 2728–2741. https://doi.org/10.5109/7236912

Kementerian ESDM, 2017. Kajian Penggunaan Faktor Emisi Lokal (Tier 2) dalam Inventarisasi GRK Sektor Energi. Pusat Data dan Teknologi Informasi ESDM, Kementerian Energi dan Sumber Daya Mineral, Jakarta.

Laurence, Hartono, N., Christiani, A., 2018. Case study of life cycle assessment in bread production process. The 2nd Internasional Conference on Eco Engineering Development 2018 (ICEED 2018). IOP Conference Series: Earth and Environmental Science 195, 012043. https://doi.org/10.1088/1755-1315/195/1/012043

Li, W.J., Liu, X., Wang, J.Z., Wu, J.X., Sheng, S., Wu, F.A., Wang, J., 2020. Synthesis and characterization of structural lipids with a balanced ratio of n-6/n-3 from mulberry seed oil and α-linolenic acid using a microfluidic enzyme reactor. Food and Bioproducts Processing, 120, 21–32. https://doi.org/10.1016/J.FBP.2019.12.008

Manik, Y.B.S., Putri, B.M., Arsanti, A., Sarmento, A.P., 2025. Life cycle assessment of indonesian traditional food: A case study of Lumpia Semarang. Food ScienTech Journal 7(2), 205-216. https://doi.org/10.33512/fsj.v7i2.31940

Mesta-Corral, M., Gómez-García, R., Balagurusamy, N., Torres-León, C., Hernández-Almanza, A.Y., 2024. Technological and nutritional aspects of bread production: An overview of current status and future challenges. Foods 13(13), 2062. https://doi.org/10.3390/foods13132062

Musyarofa, A.A.S., Nuraeni, M.I., Rohmania, Q., Asyiah, I.N., Nuriman, 2025. Analisis Produksi bersih berbasis *Life Cycle Assessment* (LCA) pada industri tahu di Lumajang. Eduproxima: Jurnal Ilmiah Pendidikan IPA 7(1), 136-146. https://doi.org/10.29100/.v7i1.5887

Nurjana, A., Rasyid, A., Uloli, H., 2025. Minimasi waste pada proses produksi roti menggunakan metode value stream mapping di UMKM Massempo Bakery. Jurnal Teknik Industri Terintegrasi (JUTIN) 8(1), 32-41. https://doi.org/10.31004/jutin.v8i1.36173

Poh, S.I., Hendrawan, B., 2013. Perilaku konsumsi dan faktor-faktor yang mempengaruhi masyarakat Surabaya dalam mengkonsumsi produk-produk pastry dan bakery. Jurnal Hospitality dan Manajemen Jasa 1(1), p.16. https://media.neliti.com/media/publicati ons/82500-ID-perilaku-konsumsi-dan-faktor-faktor-yang.pdf

Qu, Z., Tang, Z., Liu, F., Sablani, S. S., Ross, C.F., Sankaran, S., Tang, J., 2021. Quality of green beans (*Phaseolus vulgaris* L.) influenced by microwave and hot water pasteurization. Food Control, 124, 107936. https://doi.org/10.1016/J.FOODCONT.2021.107936

Ren, J., 2018. Multi-criteria decision making for the prioritization of energy systems under uncertainties after life cycle sustainability assessment. Sustainable Production and Consumption 16, 45–57. https://doi.org/10.1016/J.SPC.2018.06.005

Suflani, S., Komarudin, M.F., Suganda, A., Purwatisari, A., Rezky, R.P.O., Amri, S., Darmawan, M.R.N., Andini, A., 2024. Peningkatan kreativitas dan inovasi dalam pengemasan roti bagi UMKM di Kelurahan Sawah Luhur Kecamatan Kasemen Kota Serang. Indonesian Journal of Engagement, Community Services, Empowerment and Development 4(2), 244-254. https://doi.org/10.53067/ijecsed.v4i2

Todd, E.C.D., Faour-Klingbeil, D., 2024. Impact of food waste on society, specifically at retail and foodservice levels in developed and developing countries. Foods 13(13), 2098. https://doi.org/10.3390/foods13132098

Tran, T.T., Herzig, C., 2020. Material flow cost accounting in developing countries: A systematic review. Sustainability 12(13), 5431. https://doi.org/10.3390/su12135413

Vistanty, H., Malik, R.A., Mukimin, A., 2020. Performance of a full-scale anaerobic digestion on bakery wastewater treatment: Effect of modified distribution system. Jurnal Riset Teknologi Pencegahan Pencemaran Industri 11(1), 12-18. https://doi.org/10.21771/jrtppi.2020.v11.no1.p12-18

Yoddee, B., Chompu-inwai, R., 2023. Loss analysis in bread production process using material flow cost accounting technique. MATTER: International Journal of Science and Technology 9, 85–100. https://doi.org/10.20319/mijst.2023.9.85100