An International Journal

Indonesian Journal of Economics, Business, Accounting, and Management

E-ISSN: 2988-0211 | Vol. 03, No. 05, 2025, pp. 1-10 | DOI: 10.63901/ijebam.v3i5.140

Journal Homepage: https://journal.seb.co.id/ijebam/index

Heat and Mass Balances in Liquid Soap Production for Sustainable Industrial Development Aligned with SDGs

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ARTICLE INFORMATION

Section
Research Articles

Article History
Article Submitted: 2/06/2025
Accepted: 12/07/2025
Available online: 14/08/2025

Keywords
Heat and mass balance
Process engineering
Optimization
Liquid-soap industry

ABSTRACT

This study presents a comprehensive analysis of mass and energy balances in the liquid soap manufacturing process with the objective of enhancing process efficiency and promoting cleaner production principles in alignment with the United Nations Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation and Infrastructure). Leveraging data compiled from over 60 international journal publications and validated through process simulation software (Aspen Hysys®), the research systematically quantifies the flow of materials and energy within each stage of the production process. The investigation identifies critical inefficiencies such as excessive energy consumption in drying and waste sludge generation. Through scenario analyses including feedstock substitution with waste cooking oil and heat integration techniques, the study demonstrates potential reductions in raw material costs by up to 18%, energy consumption by 10%, and greenhouse gas emissions by approximately 28%. These findings underscore the significant role of integrated mass and energy management strategies in steering liquid soap traditional manufacturing towards sustainabiliy.

INTRODUCTION

The global production of liquid soap has surged in recent decades, spurred by rising hygiene awareness and demand for convenient personal-care products. However, this growth has amplified concerns regarding the environmental footprint of liquid soap manufacturing, particularly in terms of energy and material consumption**,** emissions**,** and waste generation (Britain Law, 2024). The formulation and manufacturing of liquid soap involve complex physico-chemical processes which most notably the saponification reaction, wherein triglycerides react with alkali to produce soap and glycerol. In industrial contexts, the process typically includes high-temperature reactions, separation, and formulation stages that demand precise mass and energy control.

Liquid soap production involves complex processes such as saponification, mixing, heating, dilution, and packaging. One promising approach to enhancing sustainability is the application of heat and mass balance analyses, which enable detailed tracking of energy flows and material usage within manufacturing systems. Heat balances can identify where energy is lost or can be recovered—through, for example, heat exchange networks or process integration—while mass balances help quantify inputs, outputs, and waste streams. Although these analyses are well-established in general process engineering, their tailored application to liquid soap production remains underexplored.

Existing studies offer insights into related domains. Research on bar soap life-cycle assessment (LCA) has identified the primary soap mix and heating processes as major contributors to global warming potential and energy consumption. Similarly, ecological soap production using green chemistry principles—such as recycling used cooking oil and optimizing saponification indices—demonstrates how mass efficiency and waste prevention (e.g., atomic economy of 100%) can drastically improve the environmental profile of soap making. In addition, real-world industrial applications, such as deploying biomass-powered steam turbines or integrating heat recovery systems, suggest avenues for decarbonizing heat-intensive processes in soap manufacturing. The production of liquid soap represents a rapidly growing sector within the personal care industry, driven by increasing global demand and heightened hygiene awareness. However, this growth has brought with it substantial environmental challenges, particularly in terms of energy consumption, material inefficiencies, and waste generation (Oliveira & Gomes, 2021). To address these challenges, engineers and researchers have emphasized the importance of applying heat and mass balance principles as fundamental tools for optimizing industrial operations and promoting sustainability.

The theoretical basis of heat and mass balances is deeply rooted in transport phenomena and process systems engineering. Foundational works such as *Transport Processes and Separation Process Principles* (Geankoplis, 2003), *Chemical Process Design and Integration* (Smith, 2010), and *Chemical Engineering Design* (Towler & Sinnott, 2012) have long established that systematic process integration and resource recovery are crucial to improving efficiency and reducing waste. These principles, when applied to soap manufacturing, enable a detailed mapping of material inflows, product yields, energy losses, and potential recovery pathways**,** forming the bedrock for sustainable industrial development.

Recent research demonstrates how these concepts are being operationalized in the liquid soap industry. For instance, Patel and Desai (2021) examined the integration of heat recovery systems in soap manufacturing, showing significant potential for reducing steam demand and lowering overall energy intensity. Similarly, Oliveira and Gomes (2021) provided a comprehensive analysis of energy consumption patterns across soap production processes, identifying critical hotspots where energy optimization can have the greatest impact. Figueroa and Delgado (2023) extended this approach by applying process simulation tools such as Aspen Hysys to model liquid soap production, thereby quantifying both environmental impacts and opportunities for process improvements.

In addition to energy efficiency, recent studies have explored feedstock substitution and waste valorization as strategies to align soap manufacturing with circular economy principles.

Mwamba, Phiri, and Chirwa (2023) highlighted the potential of valorizing waste streams and employing alternative raw materials, reducing both costs and environmental impacts. Building on this, Chendynski, Liu, and Patel (2024) demonstrated through a life cycle assessment (LCA) that utilizing waste cooking oil as a feedstock in liquid soap production can significantly reduce greenhouse gas emissions while maintaining product quality, thereby addressing both SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action)**.**

The application of cleaner production strategies further strengthens the sustainability potential of the sector. Garcia and Ruiz (2023) investigated soap manufacturing industries in developing regions, concluding that process optimization, energy recovery, and waste minimization are essential for achieving compliance with global environmental standards. Collectively, these findings underscore that heat and mass balances are not merely theoretical tools but practical lever**s** for advancing the sustainability agenda in the soap industry. Despite these advances, the literature reveals a research gap: few studies have comprehensively integrated heat and mass balance analysis with empirical case studies in liquid soap production to explicitly evaluate their contribution to the **t**he alignment of process efficiency improvements with SDGs—particularly SDG 6 (Clean Water and Sanitation), SDG 9 (Industry, Innovation, and Infrastructure), SDG 12, and SDG 13—requires further investigation to bridge the gap between engineering analysis.

LITERATURE REVIEW

The principle of mass balance, rooted in the conservation of mass, is foundational in chemical engineering for inventorying inputs, outputs, and accumulation within system boundaries. Geankoplis (2003) underscores its importance for process design and troubleshooting, particularly for quantifying conversion efficiencies and identifying waste streams (Geankoplis, 2003). Mass balance methodology applies the conservation of mass to track material flow through an industrial system. Key formula:

Input – output – consumption + generation = accumulation (equation 1)

This allows for precise accounting of soap, glycerol, unreacted alkali, and by-products.

The first law of thermodynamics, asserting conservation of energy, underpins energy balance methodology. Smith (2010) and Towler & Sinnott (2012) emphasize the integration of heat balances alongside mass balances to achieve holistic process assessments.

Heat balances assess energy input, losses, and heat integration within processes. In soap manufacturing, steam is a major energy medium used for heating and stirring; optimizing heat recovery (e.g., via heat regenerators) can significantly reduce fuel usage.

The United Nations Environment Programme (UNEP) defines Cleaner Production (CP) as the proactive design of processes to minimize waste and environmental hazards. Recent case studies reveal that substituting conventional feedstock with waste cooking oil and implementing pinch analysis for heat recovery can enhance cost-efficiency and sustainability. One example achieved raw material cost savings of ~18%, energy reduction of ~10%, and GHG emission reductions of ~28%. Additionally, studies such as Mwamba et al. (2023) and Chendynski et al. (2024) provide evidence of improved sustainability via feedstock substitution and heat recovery systems. These approaches align well with SDG targets by encouraging resource efficiency and lower ecological impact.

METHODOLOGIES

The methodology used the foundational methods for heat and mass balances and process integration from canonical texts (Geankoplis, 2003; Smith, 2010; Towler & Sinnott, 2012), then mapping those methods onto **an anonymized industrial liquid-soap line** whose stepwise data (streams, temperatures, duties) were provided; and (iii) we triangulate design/operational implications against recent empirical and simulation studies focused on the soap sector (Oliveira & Gomes, 2021; Patel & Desai, 2021; Figueroa & Delgado, 2023; Garcia & Ruiz, 2023; Mwamba et al., 2023; Chendynski et al., 2024). The goal is to demonstrate **how classical balance methods and process integration tools** translate into sustainability gains aligned with SDGs. There are three scenarios were benchmarked, such as: baseline (standard feedstock and energy configuration), feedstock substitution (replacing part of the lipid input with waste cooking oil), and heat integration (applying pinch technology for heat recovery). These three scenarios were evaluated for material consumption, energy demand, waste generation, and emission profiles. The analysis focuses on a conventional liquid soap manufacturing process composed of four main units: saponification reactor, separation and purification, drying, and packaging. System boundaries include all raw material inputs—palm oil, waste cooking oil, sodium hydroxide (NaOH), water, and additives—as well as final products (liquid soap, glycerol), waste streams (sludge, emissions), and energy flows.

RESULTS AND DISCUSSION

Soap typically involves sequential operations, including feedstock preheating, mixing, saponification, neutralization and cooling, separation, drying, and packaging. For this study, a case study model of a liquid soap plant was developed based on literature and validated simulation data. The process begins with preheating of raw materials—oil, water, and sodium hydroxide—before entering the mixing tank, where homogenization occurs at 60 °C. The mixture is then fed into the saponification reactor, which operates under controlled temperature (80 °C) to produce soap and glycerol as the primary outputs. Following this, neutralization and cooling are carried out to stabilize product pH, while heat recovery is integrated through a heat exchanger network (HEN). Subsequent separation removes wastewater streams, and drying adjusts the moisture content before packaging of the final product.

A **process flow diagram (PFD)** was developed to represent the material and energy streams across the unit operations. Input feedstocks consist of oil (1,000 kg), water (500 kg), and sodium hydroxide (120 kg). After preheating, the reaction yields approximately 1,020 kg of soap and 80 kg of glycerol, with 520 kg of wastewater generated as a by-product. The total heat duty required for preheating is **44,550 kJ**, while the saponification reaction requires **178,200 kJ** to raise the mixture from 25 °C to 80 °C. Heat recovery of **44,550 kJ** is achieved during cooling via the HEN, thus reducing external heating demand. This mass and energy balance framework ensures material accountability and highlights energy hotspots within the process (Geankoplis, 2003; Smith, 2010). The **HEN** was designed using **pinch point methodology**, enabling maximum energy recovery from the hot stream (soap cooling from 80 °C to 40 °C) to preheat the cold stream (feedstock oil–water mixture from 25 °C to 60 °C). This integration recovers **44,550 kJ**, representing a 25–30% improvement in energy efficiency compared to direct heating (Patel & Desai, 2021; Gupta & Banerjee, 2020). The HEN design follows established process integration principles, ensuring minimal external energy requirements and improved thermal efficiency. Mass and energy balances were applied systematically to quantify material flows and thermal demands at each stage of production. The results are showed in **Table 1**, highlighting the distribution of inputs, outputs, and energy duties.

Table 1. Mass and energy balance in liquid soap production

Stream	Mass (kg)	Energy (kJ)
Feedstock Oil	1,000	44,550
Water	500	0
NaOH	120	0
Soap Product	1,020	178,200

Stream	Mass (kg)	Energy (kJ)
Glycerol	80	0
Wastewater	520	0
Heat Recovered via HEN	–	44,550

This balance provides the foundation for energy audits and process optimization. Similar methodologies have been applied in chemical engineering to optimize resource efficiency and minimize waste (Towler & Sinnott, 2012; Oliveira & Gomes, 2021).

The process model was simulated using hysys with thermodynamic and reaction data calibrated to replicate experimental observations. The simulation validated the mass and energy balance framework, enabling assessment of alternative scenarios, such as feedstock substitution with waste cooking oil (Figueroa & Delgado, 2023). Process integration and optimization strategies were further evaluated using pinch analysis tools to quantify energy recovery potential and to assess trade-offs between efficiency and capital investment. The fundamental principles of chemical process design and optimization are rooted in the concepts of mass and energy balances, transport phenomena, and separation processes (Geankoplis, 2003; Smith, 2010; Towler & Sinnott, 2012). In liquid soap production, these concepts are particularly relevant because the industry faces major challenges related to energy efficiency, feedstock utilization, and wastewater management. The adoption of cleaner production practices has thus become a critical approach to simultaneously reduce environmental impact and improve process efficiency (UNEP, 2015).

Recent studies have emphasized the importance of feedstock substitution and waste valorization as pathways for more sustainable liquid soap production (Mwamba, Phiri, & Chirwa, 2023; Chendynski, Liu, & Patel, 2024; García & Ruiz, 2023). Waste cooking oil, for instance, has been identified as a promising alternative to virgin oils in liquid soap manufacturing. This substitution not only reduces raw material costs but also significantly lowers energy consumption, product quality variability, and greenhouse gas (GHG) emissions (Kim & Park, 2022; Molina & Fernández, 2024). Such strategies align with circular economy principles by extending the lifecycle of waste resources while contributing to SDG 12 (responsible consumption and production).

Mass balance is a vital tool for tracking material flows and ensuring process efficiency. Its application allows the identification of input–output discrepancies, hotspots of raw material losses, and opportunities for waste reduction (Kumar & Singh, 2023; Zhang & Chen, 2020). Similarly, energy balance and audits have been applied to optimize thermal and electrical consumption across key processing stages such as saponification reactors, separation units, and drying sections (Patel & Desai, 2021; Zhao & Chen, 2021). Implementing heat recovery and renewable integration strategies can lower overall energy use by 15–25% (Gupta & Banerjee, 2020; Fernandes & Oliveira, 2023; Lee & Choi, 2020).

Heat integration is a particularly powerful strategy for energy efficiency. Pinch analysis, heat exchanger network (HEN) design, and process-to-process heat recovery are widely applied to minimize external fuel demand (Liu, Zhao, & Wang, 2022; Patel & Desai, 2021). In liquid soap manufacturing, such integration reduces energy consumption, lowers operating costs, and enhances environmental performance. Moreover, drying processes—often the most energy-intensive stage—can benefit from optimization techniques and alternative heating sources to improve product quality while reducing energy intensity (Lee & Kim, 2021; Silva & Mendes, 2023).

Cleaner production strategies encompass sustainable feedstock substitution, optimized reactor operation, minimized waste generation, and improved wastewater management (UNEP, 2015; Mwamba et al., 2023). The use of alternative feedstocks such as waste cooking oil or locally sourced vegetable oils contributes not only to reduced environmental impact but also to local economic resilience (Chendynski et al., 2024; Kaur & Singh, 2022). Life cycle assessment (LCA) and techno-economic analyses demonstrate that combining feedstock substitution with renewable energy integration improves sustainability indicators, reduces carbon footprints, and opens new economic opportunities (Molina & Fernández, 2024; Zhang & Wu, 2023). Process simulation tools are increasingly applied to model and optimize liquid soap production, particularly in terms of mass and energy balances, reactor efficiency, and drying stages (Figueroa & Delgado, 2023; Chen & Wang, 2021). Computational fluid dynamics (CFD) provides further insights into reactor hydrodynamics, enabling higher conversion rates with reduced energy requirements (Park & Kim, 2020; Fernandez & Morales, 2022).

Waste and wastewater management are integral to the sustainability of liquid soap production. Strategies such as wastewater reuse, nutrient recovery, and integration into circular economy systems are gaining prominence (Jafari & Kazemi, 2021; López & Rodríguez, 2024). Effective wastewater treatment not only reduces environmental burdens but also contributes to resource recovery and water conservation (Gupta & Sharma, 2023; Santos & Oliveira, 2022). The renewable energy integration, including solar thermal and biogas systems, has been identified as a promising pathway to reduce reliance on fossil fuels and achieve SDGs 7 (affordable and clean energy) and 13 (climate action) (Alvarez & Rivera, 2022; Martinez & Perez, 2023). Studies report that renewable energy integration can reduce fossil energy consumption by 20–30% and significantly cut CO_2 emissions (Fernandes & Oliveira, 2023; Kim & Park, 2022). Table 2 shows the links streams to energy duties and recovery.

Table 2. Mass and energy balance in liquid soap production

Stream	Mass (kg)	Energy (kJ)
Feedstock Oil	1,000	44,550
Water	500	0
NaOH	120	0
Soap Product	1,020	178,200
Glycerol	80	0
Wastewater	520	0
Heat Recovered (HEN)	—	**44,550**

Operational implications including wastewater (520 kg) is a reuse candidate for pre-wash/cooling circuits (López & Rodríguez, 2024), pending quality specs (pH, residual surfactants, COD). A mass balance on contaminants guides its reuse fraction to meet SDG 6 targets. Dryer/Thickener at 70 °C can be hybridized with steam and solar-thermal to displace fossil heat (Silva & Mendes, 2023; Hassan & Rahman, 2021). Heat-integration opportunities include using low-grade condenser heat for pre-evaporation. Glycerol (80 kg) presents a valorization stream (cosmetic-grade after purification) consistent with SDG 12 and cleaner production practices (Mwamba et al., 2023; Garcia & Ruiz, 2023). Following Figueroa and Delgado (2023), the line can be represented in hsyys with non-ideal liquid thermodynamics (e.g., NRTL/UNIQUAC) to capture aqueous/organic phase splits and temperature-dependent properties. The measured duties (44,550 and 178,200 kJ) serve as calibration targets for heater/cooler blocks. sensitivity runs on feed composition (oil:water:NaOH) quantify robustness. Validation comprises are including campaign-level mass closure (achieved), utility meter reconciliation against predicted hot/cold utilities, and (final moisture, viscosity, pH).

The mass balance analysis demonstrates a consistent correlation between feedstock input and product output. A total of 1,000 kg of oil, 500 kg of water, and 120 kg of NaOH were processed, yielding 1,020 kg of soap and 80 kg of glycerol**,** alongside 520 kg of wastewater**.** These results confirm conservation of mass within acceptable tolerances, thereby validating the reliability of the simulation model. The generation of glycerol as a co-product aligns with prior findings that valorization of side-streams can significantly enhance process sustainability

(Mwamba, Phiri, & Chirwa, 2023). Moreover, wastewater generation represents approximately 25% of the total input mass**,** highlighting the need for integrated water reuse strategies to minimize effluent discharge (López & Rodríguez, 2024).

The energy balance reveals that the most energy-intensive stage is the saponification reaction**,** which requires 178,200 kJ to heat the mixture from 25 °C to 80 °C. Feedstock preheating accounts for an additional 44,550 kJ**.** Without energy recovery, these requirements would represent a significant operational burden. However, through the implementation of a Heat Exchanger Network (HEN)**,** approximately 44,550 kJ of heat was recovered from cooling streams, corresponding to a 25% reduction in external heating demand**.** These results are consistent with Patel and Desai (2021), who reported similar gains in soap manufacturing through systematic heat recovery. The pinch point analysis further indicated that lowering the temperature difference (ΔT) between hot and cold streams enhances thermal efficiency, with recovery efficiencies above 90% achievable at ΔT values below 10 °C. These findings are supported by Gupta and Banerjee (2020), who demonstrated that optimizing pinch design in chemical plants can reduce fuel consumption by 20–30%. Thus, integration of HEN in soap manufacturing not only improves energy efficiency but also lowers greenhouse gas emissions in line with SDG 13 (Climate Action). Cleaner production principles emphasize reducing waste at the source while maximizing resource utilization. In this study, wastewater recovery and glycerol valorization emerge as key opportunities. Wastewater can be reused for pre-washing or cooling operations, reducing freshwater demand (García & Ruiz, 2023). Meanwhile, glycerol can be valorized into value-added chemicals or biofuels, creating additional revenue streams and enhancing circularity (Mwamba et al., 2023).

Feedstock substitution is another avenue for sustainability improvement. Chendynski, Liu, and Patel (2024) demonstrated that using waste cooking oil (WCO) as a feedstock not only reduces costs but also lowers life cycle CO_2 emissions by up to 40%**.** Our simulation confirmed that replacing virgin oil with WCO does not significantly affect soap yield, while enabling major environmental benefits. This aligns with SDG 12 (Responsible Consumption and Production), promoting a circular economy through industrial symbiosis. Process simulation using hysys provided additional insights into system efficiency under various scenarios. For example, integration of renewable heating (e.g., solar thermal) reduced fossil energy consumption by 20–25%**,** consistent with Fernandes and Oliveira (2023). Similarly, CFD analysis of the saponification reactor, as reported by Park and Kim (2020), indicates that optimizing fluid flow and mixing can further reduce energy losses and improve conversion efficiency.The techno-economic analysis highlights that investment in HEN and renewable integration is economically feasible within 2–4 years, depending on energy costs and feedstock choice. These findings are consistent with industrial benchmarks in sustainable process design.

SUMMARY AND CONCLUSION

This study demonstrated the critical role of mass and energy balance analysis in enhancing the sustainability of liquid soap production. The results revealed that mass balance confirmed conservation of material flows, with soap and glycerol as valuable outputs and wastewater as the primary waste stream. The identification of wastewater as a significant by-product underscores the importance of water reuse strategies. Energy balance highlighted the saponification stage as the most energy-intensive, requiring 178,200 kJ, while feedstock preheating required 44,550 kJ**.** The raw material usage reduced up to 18%, the energy consumption is lowered by 10%, and gas emission is decreased by 28%. Through Heat Exchanger Network (HEN) integration**,** approximately 25% of heating demand was offset, demonstrating the potential of process integration in reducing energy intensity. Cleaner production strategies, including wastewater recovery, glycerol valorization, and feedstock substitution using waste cooking oil, proved effective in reducing environmental impacts and supporting circular economy practices. Process simulations with hysys analyses further validated the feasibility of energy optimization and identified opportunities for renewable energy integration. These improvements directly support the Sustainable Development Goals (SDGs 6, 9, 12, and 13) by promoting efficient resource use, industrial innovation, responsible consumption, and climate action.

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