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Enhancing eco-efficiency of ice cream production through integrated life cycle assessment and life cycle costing

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Abstract

The ice cream industry is highly energy-intensive due to its extensive reliance on refrigeration systems, leading to significant environmental burdens and increased production costs. Although Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) have been widely applied to evaluate industrial sustainability, studies integrating these approaches with eco-efficiency analysis to assess energy-saving strategies in ice cream production remain limited. Therefore, this study evaluated the environmental and economic performance of strawberry loly ice cream production through an integrated LCA, LCC, and eco-efficiency framework and assessed the potential of Phase Change Material (PCM)-based mitigation. A gate-to-gate approach was adopted using a functional unit of 1,000 L of strawberry loly ice cream per production cycle. Environmental impacts were quantified using the ReCiPe 2016 Endpoint (H) method implemented in SimaPro, while economic performance was evaluated using production-stage LCC. The baseline results indicated a total environmental impact of 860 Pt, with cold storage identified as the principal hotspot, contributing 507 Pt (58.9%) due to its electricity consumption of 1,527.8 kWh per production cycle. Human health was the dominant damage category, accounting for 823 Pt (95%) of the total environmental impact. The modeled PCM scenario indicated a 24.5% reduction in electricity consumption, resulting in a decrease in total environmental impact to 740 Pt (13.95%) and an increase in calculated value added of 4.06% based on operational cost savings. These economic results exclude PCM procurement, installation, maintenance, replacement, and capital costs because the mitigation strategy was evaluated through simulation rather than physical implementation. Overall, the PCM mitigation scenario demonstrated superior environmental and economic performance, indicating that integrating thermal energy storage with eco-efficiency assessment provides an effective strategy for improving the sustainability of energy-intensive food manufacturing systems.

Keywords

Eco-efficiency; Ice cream industry; Life cycle assessment; Life cycle costing; Phase change material

1. INTRODUCTION

The food processing industry is essential for global food security, economic growth, and industrial development (Mursalim, Aksan and Ruslan, 2023; Almohaimeed and Abouelnour, 2025; Santos and Lannes, 2025). However, expanding food manufacturing increases electricity, water, and raw material consumption, causing greenhouse gas emissions, resource depletion, wastewater generation, and solid waste accumulation (Athirafitri, Indrasti and Ismayana, 2021; Pena, Rovira-Val and Mendoza, 2022; Mahyudin *et al.*, 2023; Nikolic, 2025). As a resource-intensive sector, food processing contributes substantially to global energy demand and environmental impacts, highlighting the need for production strategies that improve environmental quality, economic performance, and resource efficiency (Konstantas, Stamford and Azapagic, 2020; Subal, Braunschweig and Hellweg, 2024; Yan, Mohsin and Mehak, 2025). Consequently, sustainability assessment is essential for identifying environmental hotspots, supporting evidence-based decision-making, and promoting sustainable industrial development aligned with global sustainability goals (Devi and Mirwan, 2023; Effendi, Warlina and Nurmawati, 2024; He *et al.*, 2025).

Among food manufacturing sectors, the ice cream industry is one of the most energy-intensive because product quality and safety depend on uninterrupted refrigeration throughout the production chain (Marchi and Zanoni, 2022; Doke and Gogate, 2025; Santos and Lannes, 2025). Critical processes, including aging, freezing, and cold storage, require continuous temperature control to maintain physicochemical properties, microbiological stability, and product quality, resulting in high electricity consumption and operating costs (Ghodrati, Zahedi and Abolfazl, 2022; Magdalena, 2023; Roy *et al.*, 2023). As refrigeration systems operate continuously and rely primarily on grid electricity, they contribute substantially to indirect greenhouse gas emissions and the overall environmental burden of ice cream production, making refrigeration energy efficiency a key strategy for improving environmental and economic performance (Ayuningtyas, Yani and Maimunah, 2020; Rosadi, Saily and Jusi, 2022; Effendi, Warlina and Nurmawati, 2024; Subal, Braunschweig and Hellweg, 2024; Kainde, Kaeng and Kandyoh, 2025; Ouaouja *et al.*, 2025).

Among available energy-saving technologies, Phase Change Materials (PCM) have emerged as an effective cold thermal energy storage solution because they absorb, store, and release latent heat during phase transitions, reducing cooling loads and compressor operating time (Liang *et al.*, 2022; Roy *et al.*, 2023; Ouaouja *et al.*, 2025). Previous studies have shown that PCM integration stabilizes storage temperatures, improves thermal performance, reduces electricity consumption, and maintains product quality without major modifications to existing refrigeration systems (Ghodrati, Zahedi and Abolfazl, 2022; Roy *et al.*, 2023; Beghetto, 2025). Despite these advantages, the overall environmental and economic benefits of PCM should be evaluated using integrated sustainability assessment approaches rather than energy-saving indicators alone (Konstantas, Stamford and Azapagic, 2020; Subal, Braunschweig and Hellweg, 2024; Ouaouja *et al.*, 2025).

Comprehensive sustainability assessment requires methods that simultaneously evaluate environmental and economic performance. Among the available approaches, Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) are widely applied because they provide complementary information for resource-efficient and sustainability-oriented decision-making (Konstantas, Stamford and Azapagic, 2020; Menna *et al.*, 2020; Subal, Braunschweig and Hellweg, 2024). LCA quantifies environmental impacts throughout a product life cycle, whereas LCC evaluates the associated life cycle costs, enabling a balanced sustainability assessment (Peña, 2020; Athirafitri, Indrasti and Ismayana, 2021; Pena, Rovira-Val and Mendoza, 2022; Mahyudin *et al.*, 2023). Their integration enables simultaneous evaluation of environmental and economic trade-offs, while incorporating eco-efficiency further supports strategies that reduce environmental burdens and maximize economic value (Konstantas, Stamford and Azapagic, 2020; Susanto *et al.*, 2022; Devi and Mirwan, 2023; Effendi, Warlina and Nurmawati, 2024; Kainde, Kaeng and Kandiyoh, 2025; Trofimenko *et al.*, 2025; Zazo, Gosselink and Kromanis, 2025).

Previous studies have applied LCA and LCC to evaluate the environmental and economic performance of food production systems, while LCA has also been used to identify environmental hotspots and carbon footprints in dairy and frozen dessert production (Konstantas, Stamford and Azapagic, 2020; Menna *et al.*, 2020; Marchi and Zanoni, 2022; Pena, Rovira-Val and Mendoza, 2022; Magdalena, 2023; Doke and Gogate, 2025; Santos and Lannes, 2025; Zazo, Gosselink and Kromanis, 2025). In addition, PCM has been shown to improve refrigeration performance by reducing electricity consumption and enhancing thermal stability in cold storage (Ghodrati, Zahedi and Abolfazl, 2022; Roy *et al.*, 2023; Ouaouja *et al.*, 2025). However, these approaches have largely been investigated separately, with limited studies integrating LCA, LCC, eco-efficiency assessment, and PCM-based energy mitigation in industrial ice cream production. Therefore, an integrated framework evaluating environmental, economic, and energy-efficiency performance is needed to support sustainability-oriented decision-making in energy-intensive food manufacturing.

Although previous studies have demonstrated the applicability of LCA, LCC, and PCM in sustainability assessment and refrigeration systems, their integration into a single framework for industrial ice cream production remains limited. Most studies have evaluated environmental impacts, economic performance, or refrigeration efficiency separately, with little attention to the combined assessment of environmental impacts, production costs, eco-efficiency, and PCM-based energy mitigation (Konstantas, Stamford and Azapagic, 2020; Menna *et al.*, 2020; Ghodrati, Zahedi and Abolfazl, 2022; Pena, Rovira-Val and Mendoza, 2022; Roy *et al.*, 2023; Ouaouja *et al.*, 2025). To address this gap, this study integrates LCA, LCC, and eco-efficiency analysis to quantitatively evaluate PCM implementation in industrial ice cream production, enabling simultaneous assessment of environmental hotspots, production costs, value added, and eco-efficiency. This integrated framework provides a quantitative basis for evaluating energy mitigation strategies and supporting sustainability-oriented decision-making in energy-intensive food manufacturing.

Accordingly, this study evaluates the environmental and economic performance of industrial strawberry loly ice cream production by integrating LCA, LCC, and eco-efficiency within a unified assessment framework. The framework identifies environmental hotspots, quantifies production costs, and evaluates the effectiveness of PCM-based energy mitigation in reducing electricity consumption while improving environmental and economic

performance. The findings provide quantitative support for sustainable energy management in the ice cream industry and other refrigeration-dependent food processing sectors.

2. MATERIALS AND METHODS

2.1 Goal and Scope Definition

This study evaluated the environmental and economic performance of industrial strawberry loly ice cream production and the sustainability improvement achieved through Phase Change Material (PCM)-based energy mitigation (Konstantas, Stamford and Azapagic, 2020; Ghodrati, Zahedi and Abolfazl, 2022; Ouaouja *et al.*, 2025). An integrated framework combining Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and eco-efficiency analysis was applied to assess environmental impacts, production costs, and overall sustainability performance. LCA identified environmental hotspots, LCC quantified production costs, and eco-efficiency evaluated the relationship between environmental performance and economic value (Huijbregts *et al.*, 2017; Konstantas, Stamford and Azapagic, 2020; Peña, 2020; Athirafitri, Indrasti and Ismayana, 2021; Effendi, Warlina and Nurmawati, 2024; Subal, Braunschweig and Hellweg, 2024; Trofimenko *et al.*, 2025).

A gate-to-gate system boundary was adopted to evaluate manufacturing activities and PCM-based energy mitigation during strawberry loly ice cream production (Athirafitri, Indrasti and Ismayana, 2021; Putri *et al.*, 2021; Widiyanto, 2022). The system comprised six production stages: mixing, homogenization, aging, freezing, packing, and cold storage. Material inputs, electricity consumption, and supporting utilities were included in both the environmental and economic assessments (Huijbregts *et al.*, 2017; Mahyudin *et al.*, 2023). The functional unit was defined as the production of 1,000 L of strawberry loly ice cream per production cycle, serving as the reference flow for all inventory, environmental, and economic analyses (Huijbregts *et al.*, 2017; Peña, 2020).

The environmental assessment was based on a life cycle inventory (LCI) including raw materials, electricity, water, packaging materials, and associated emissions (Huijbregts *et al.*, 2017; Athirafitri, Indrasti and Ismayana, 2021; Mahyudin *et al.*, 2023). The production-stage LCC included raw materials, utilities, labor, packaging, and other operational costs required to produce one functional unit (Peña, 2020; Pena, Rovira-Val and Mendoza, 2022; Kainde, Kaeng and Kandiyoh, 2025). A PCM-based mitigation scenario for the cold storage system was evaluated using the same framework to compare environmental impacts, production costs, and eco-efficiency with the baseline scenario (Ghodrati, Zahedi and Abolfazl, 2022; Roy *et al.*, 2023; Ouaouja *et al.*, 2025; Trofimenko *et al.*, 2025).

The environmental assessment of the PCM-based mitigation scenario retained the same gate-to-gate system boundary as the baseline production system. Accordingly, the PCM scenario was modeled by modifying the electricity demand of the cold storage stage based on the calculated operational energy-saving potential. The environmental burdens associated with upstream PCM production, containment materials, installation, maintenance, replacement, and end-of-life treatment were not included because the PCM strategy was evaluated as a simulation-based operational mitigation scenario rather than as a physically implemented system. Therefore, the environmental results of the PCM scenario represent the potential effect of reduced operational electricity consumption within the defined system boundary and should not be interpreted as the complete life-cycle environmental performance of PCM technology.

This study evaluated the environmental and economic performance of industrial strawberry loly ice cream production and the potential sustainability improvement associated with a proposed Phase Change Material (PCM)-based energy mitigation scenario. An integrated framework combining Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and eco-efficiency analysis was applied to assess the baseline production system and the potential effects of the modeled PCM scenario. The PCM strategy was evaluated through simulation rather than physical implementation; therefore, the resulting environmental and economic changes represent projected effects under the adopted scenario assumptions.

2.2 Life Cycle Inventory (LCI)

The Life Cycle Inventory (LCI) phase was conducted to identify and quantify all material and energy flows entering and leaving the production system as the basis for environmental impact evaluation (Huijbregts *et al.*, 2017; Athirafitri, Indrasti and Ismayana, 2021; Widiyanto, 2022). The analysis was developed using a gate-to-gate system boundary with a functional unit of 1,000 L of strawberry loly ice cream per production cycle, ensuring consistency across environmental and economic assessments (Huijbregts *et al.*, 2017; Mahyudin *et al.*, 2023). The inventory data included raw materials, electricity, water, packaging materials, and generated emissions at each production stage, forming the basis for LCA and eco-efficiency analysis (Konstantas, Stamford and Azapagic, 2020; Athirafitri, Indrasti and Ismayana, 2021; Putri *et al.*, 2021). Primary data were collected through field observations, production records, and structured interviews to reflect actual operational conditions (Athirafitri, Indrasti and Ismayana, 2021; Widiyanto, 2022; Mahyudin *et al.*, 2023), while secondary data covering background processes, material production, electricity generation, and emission factors were obtained from the Ecoinvent APOS Unit Process database in SimaPro and supporting literature (Huijbregts *et al.*, 2017; Mahyudin *et al.*, 2023).

The production system consists of six sequential stages, namely mixing, homogenization, aging, freezing, packing, and cold storage within a gate-to-gate boundary (Athirafitri, Indrasti and Ismayana, 2021; Putri *et al.*, 2021; Widiyanto, 2022). The main inputs include water, granulated sugar, liquid glucose, skim milk powder, stabilizers, flavoring agents, food additives, and PET and HDPE packaging materials as foreground processes (Huijbregts *et al.*, 2017; Mahyudin *et al.*, 2023). Electricity represents the dominant energy input, particularly during aging, freezing, and cold storage stages due to continuous refrigeration operation (Ghodrati, Zahedi and Abolfazl, 2022; Marchi and Zanoni, 2022; Roy *et al.*, 2023).

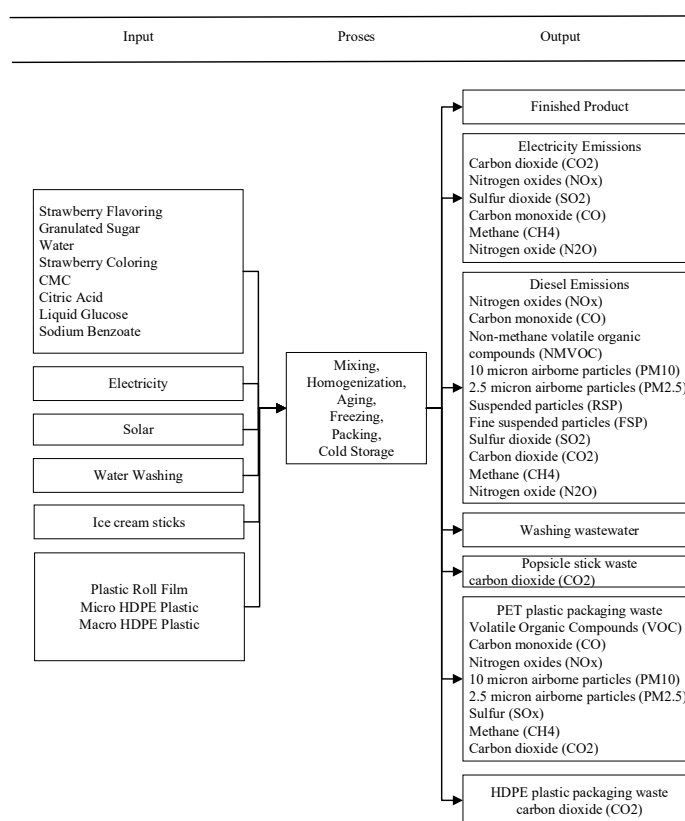


Figure 1. Life cycle inventory data for the production of 1,000 L of strawberry loly ice cream.

All inventory data were modeled in SimaPro to represent the strawberry loly ice cream production system and to support environmental impact assessment (Huijbregts *et al.*, 2017; Athirafitri, Indrasti and Ismayana, 2021). The same dataset was also used for Life Cycle Costing (LCC) and eco-efficiency analysis to ensure methodological consistency across evaluations (Konstantas, Stamford and Azapagic, 2020; Peña, 2020; Trofimenko *et al.*, 2025). The inventory details are presented in Figure 1 to enhance transparency and reproducibility of the model (Subal, Braunschweig and Hellweg, 2024). Electricity-related environmental impacts were modeled using the Indonesian electricity grid dataset from Ecoinvent APOS in SimaPro to represent upstream electricity generation processes (Huijbregts *et al.*, 2017; Mahyudin *et al.*, 2023), and electricity consumption at each stage was linked to this dataset to quantify emissions and their contribution to total environmental impacts (Huijbregts *et al.*, 2017; Ayuningtyas, Yani and Maimunah, 2020; Rosadi, Saily and Jusi, 2022).

For the PCM-based mitigation scenario, no additional PCM-related foreground inventory was introduced into the LCI model. The scenario only modified the electricity input associated with the cold storage process according to the calculated energy-saving assumption. Consequently, the LCA comparison captures the potential operational electricity benefit of the proposed PCM configuration within the existing gate-to-gate production system, while upstream and downstream environmental burdens associated with the PCM technology itself remain outside the assessment boundary.

2.3 Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) phase was conducted to translate the material and energy flows compiled during the Life Cycle Inventory (LCI) into potential environmental impacts associated with the production of strawberry loly ice cream (Huijbregts *et al.*, 2017; Athirafitri, Indrasti and Ismayana, 2021). Environmental impact assessment was performed using SimaPro version 9.6 in accordance with the principles and framework established by ISO 14040 and ISO 14044, ensuring a standardized and internationally recognized life cycle assessment procedure (Widiyanto, 2022; Mahyudin *et al.*, 2023). The ReCiPe 2016 Endpoint (H) method was selected because it integrates multiple midpoint impact categories into endpoint damage indicators, thereby providing a comprehensive and decision-oriented interpretation of the overall environmental performance of the production system (Huijbregts *et al.*, 2017; Subal, Braunschweig and Hellweg, 2024). The ReCiPe 2016 Endpoint (H) method aggregates multiple midpoint impact categories into three endpoint damage categories, namely human health, ecosystems, and resources, thereby simplifying the interpretation of environmental impacts at the decision-making level (Huijbregts *et al.*, 2017). The human health category represents the potential effects of environmental emissions on human well-being, the ecosystems category reflects damage to terrestrial and aquatic ecosystems caused by resource use and pollutant emissions, whereas the resources category quantifies the depletion of mineral and fossil resources associated with production activities (Huijbregts *et al.*, 2017; Devi and Mirwan, 2023).

The LCIA comprised four sequential analytical stages: characterization, normalization, weighting, and single score assessment, following the standardized procedures of the ReCiPe 2016 methodology (Huijbregts *et al.*, 2017). Characterization quantified the contribution of each inventory flow to the selected impact categories, while normalization evaluated the relative significance of these impacts by comparing the characterization results with reference environmental loads (Huijbregts *et al.*, 2017; Athirafitri, Indrasti and Ismayana, 2021). Weighting was subsequently applied to assign relative importance to each impact category using the ReCiPe weighting factors, and the resulting weighted impacts were aggregated through the single score approach to produce a single environmental indicator expressed in points (Pt), facilitating hotspot identification and comparative evaluation between the baseline and PCM mitigation scenarios (Huijbregts *et al.*, 2017; Konstantas, Stamford and Azapagic, 2020; Subal, Braunschweig and Hellweg, 2024).

Table 1. Environmental impact assessment method applied in this study.

Item	Description
Software	SimaPro 9.6
LCIA method	ReCiPe 2016 Endpoint (H)
Damage categories	Human health, ecosystems, resources
Indicator	Single score (Pt)

The LCIA results were subsequently used to identify the production stages that contributed most significantly to the overall environmental impacts and to evaluate the effectiveness of the Phase Change Material (PCM)-based mitigation scenario in reducing the environmental burden of the production system (Konstantas, Stamford and Azapagic, 2020; Ghodrati, Zahedi and Abolfazl, 2022; Roy *et al.*, 2023). The Hierarchist (H) cultural perspective

was adopted because it represents the default and most widely applied perspective in the ReCiPe 2016 methodology, providing balanced assumptions regarding time horizons, impact pathways, and policy choices while supporting robust comparisons across alternative production scenarios (Huijbregts *et al.*, 2017; Devi and Mirwan, 2023).

2.4 Life Cycle Costing (LCC)

Life Cycle Costing (LCC) was performed to quantify the economic performance of strawberry loly ice cream production and to complement the environmental assessment obtained through the Life Cycle Assessment (LCA), enabling a comprehensive sustainability evaluation of the production system (Peña, 2020; Pena, Rovira-Val and Mendoza, 2022; Trofimenko *et al.*, 2025). The economic assessment adopted a production-stage LCC approach using the same gate-to-gate system boundary and functional unit established for the environmental assessment to ensure methodological consistency between the environmental and economic analyses (Konstantas, Stamford and Azapagic, 2020; Menna *et al.*, 2020; Zazo, Gosselink and Kromanis, 2025). Applying identical system boundaries allowed direct integration of environmental impacts and production costs, thereby providing a reliable basis for evaluating the sustainability performance of the production system (Konstantas, Stamford and Azapagic, 2020; Subal, Braunschweig and Hellweg, 2024).

Cost data were collected directly from the manufacturing company using site-specific production records, financial documentation, and structured interviews with company personnel to ensure that the economic analysis accurately reflected the actual production conditions (Peña, 2020; Kainde, Kaeng and Kandiyoh, 2025). The production-stage LCC included all relevant manufacturing cost components, consisting of raw material costs, packaging material costs, electricity consumption, labor, water utilization, and other operational expenditures incurred throughout the production process (Pena, Rovira-Val and Mendoza, 2022; Kainde, Kaeng and Kandiyoh, 2025; Trofimenko *et al.*, 2025). The total production cost was calculated by summing all cost components associated with the defined system boundary and was subsequently expressed using the following equation (Menna *et al.*, 2020; Zazo, Gosselink and Kromanis, 2025).

$$LCC = C_{rm} + C_{op} \dots\dots\dots (1)$$

Where:

LCC= total life cycle cost (Rp);

C_{rm} = raw material cost (Rp);

C_{op} = operational cost (Rp).

Table 2. Cost components included in the life cycle costing analysis.

Cost category	Components
Raw material cost	Water, sugar, glucose, skim milk powder, additives, packaging materials

Operational cost	Electricity consumption and other production-related expenses
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The LCC results were subsequently integrated with the environmental impact assessment to evaluate the eco-efficiency performance of the strawberry loly ice cream production system within a unified sustainability assessment framework (Konstantas, Stamford and Azapagic, 2020; Effendi, Warlina and Nurmawati, 2024; Trofimenko *et al.*, 2025). In addition, the economic implications of implementing the Phase Change Material (PCM)-based mitigation scenario were assessed by comparing the production costs and economic benefits of the baseline and mitigation scenarios under identical analytical conditions (Ghodrati, Zahedi and Abolfazl, 2022; Roy *et al.*, 2023; Ouaouja *et al.*, 2025). The value added generated by the production system was determined as the economic output indicator and subsequently incorporated into the eco-efficiency analysis to evaluate the relationship between economic value creation and environmental performance (Konstantas, Stamford and Azapagic, 2020; Susanto *et al.*, 2022; Effendi, Warlina and Nurmawati, 2024).

For the PCM-based mitigation scenario, the economic assessment was limited to the change in production-stage operational costs resulting from the modeled reduction in electricity consumption. Because the present study evaluates PCM as a simulation-based mitigation scenario rather than a physically implemented system, procurement costs of PCM modules, installation costs, structural modification costs, maintenance and replacement costs, and capital amortization were not included in the calculated LCC. Therefore, the economic results for the PCM scenario represent the potential operational cost benefit associated with reduced electricity consumption and should not be interpreted as a full investment-based economic feasibility assessment of PCM deployment.

2.5 Eco-Efficiency Assessment

An eco-efficiency assessment was conducted to evaluate the sustainability performance of the strawberry loly ice cream production system by integrating environmental and economic indicators within a unified analytical framework (Konstantas, Stamford and Azapagic, 2020; Effendi, Warlina and Nurmawati, 2024). The eco-efficiency concept emphasizes the simultaneous achievement of higher economic value and lower environmental impacts, thereby promoting more sustainable production and resource utilization (Konstantas, Stamford and Azapagic, 2020; Susanto *et al.*, 2022). Accordingly, eco-efficiency provides a practical decision-support framework for identifying production improvement strategies that enhance economic performance while minimizing environmental burdens throughout the production system (Effendi, Warlina and Nurmawati, 2024; Subal, Braunschweig and Hellweg, 2024; Trofimenko *et al.*, 2025).

In this study, the economic indicator was represented by the value added (VA) generated from strawberry loly ice cream production, whereas the environmental indicator was represented by the total environmental impact expressed as a single score (Pt) derived from the ReCiPe 2016 Endpoint (H) method (Huijbregts *et al.*, 2017; Konstantas, Stamford and Azapagic, 2020). Value added was calculated as the difference between the economic value of the final product and the total production costs incurred during one production cycle, representing the net economic benefit generated by the manufacturing process (Peña, 2020; Pena, Rovira-Val

and Mendoza, 2022; Kainde, Kaeng and Kandiyo, 2025). The eco-efficiency value was subsequently determined as the ratio between the total environmental impact (single score) and the value added (VA), as presented in Equation (2), enabling quantitative evaluation of the relationship between economic performance and environmental burden (Konstantas, Stamford and Azapagic, 2020; Effendi, Warlina and Nurmawati, 2024).

$$\text{Eco-Efficiency} = \frac{\text{LCA}}{\text{VA}} \dots\dots\dots (2)$$

Where:

LCA = Life Cycle Assessment

VA = Value Added

A lower eco-efficiency value indicates a more sustainable production system because less environmental impact is generated for each unit of economic value created. Accordingly, a reduction in the eco-efficiency ratio reflects improved resource utilization and enhanced sustainability performance (Konstantas, Stamford and Azapagic, 2020; Susanto *et al.*, 2022). The eco-efficiency assessment was performed for both the baseline production system and the PCM-based mitigation scenario to quantify the extent to which the proposed energy-saving strategy improved the overall sustainability performance of the production system (Ghodrati, Zahedi and Abolfazl, 2022; Roy *et al.*, 2023; Ouajouja *et al.*, 2025). In addition to the eco-efficiency ratio, the Eco-Efficiency Index (EEI) was employed as a complementary indicator to evaluate the overall sustainability level of the production system by integrating environmental and economic performance into a single comparative measure (Konstantas, Stamford and Azapagic, 2020; Effendi, Warlina and Nurmawati, 2024). The EEI was determined by comparing the environmental and economic performances of the baseline and PCM mitigation scenarios, allowing the effectiveness of the proposed mitigation strategy to be quantitatively assessed (Konstantas, Stamford and Azapagic, 2020; Trofimenko *et al.*, 2025). An increase in the EEI value indicates an improvement in sustainability performance, demonstrating that environmental impacts were reduced while economic benefits were maintained or enhanced through the implementation of the PCM-based mitigation strategy (Susanto *et al.*, 2022; Effendi, Warlina and Nurmawati, 2024).

2.6 PCM-Based Mitigation Scenario

A Phase Change Material (PCM)-based mitigation scenario was developed to investigate the potential improvement in the environmental and economic performance of the strawberry loly ice cream production system through enhanced energy efficiency in refrigeration operations (Ghodrati, Zahedi and Abolfazl, 2022; Roy *et al.*, 2023; Ouajouja *et al.*, 2025). The mitigation strategy was formulated based on the Life Cycle Assessment results, which identified the cold storage stage as the primary environmental hotspot, contributing 58.9% of the total environmental impact due to its intensive electricity consumption (Huijbregts *et al.*, 2017; Konstantas, Stamford and Azapagic, 2020). Previous studies have demonstrated that PCM functions as a latent thermal energy storage medium capable of absorbing and releasing heat during phase transitions, thereby stabilizing storage temperatures, reducing compressor operating time, and decreasing electricity demand without compromising refrigeration performance (Ghodrati, Zahedi and Abolfazl, 2022; Roy *et al.*, 2023; Ouajouja *et al.*, 2025; Sreelekha, Landini and Roy, 2026).

The proposed mitigation scenario involved the integration of Phase Change Material (PCM) into the cold-storage system as a passive cold thermal energy storage medium (Ghodrati, Zahedi and Abolfazl, 2022; Ouaouja *et al.*, 2025). The PCM configuration was designed according to the available rack space in the existing cold storage facility (Konstantas, Stamford and Azapagic, 2020; Trofimenko *et al.*, 2025). The cold storage consisted of two racks, with six compartments per level on the first rack and seven compartments per level on the second rack. Nine PCM modules were assigned to each compartment, resulting in 108 modules for the first rack and 126 modules for the second rack, or 234 PCM modules in total. Each module had dimensions of 0.75 m × 0.50 m × 0.10 m, corresponding to a volume of 37.5 L per module and a total PCM volume of 8,775 L.

The latent thermal storage capacity of the proposed PCM configuration was calculated using the latent heat value reported by Sreelekha *et al.* (2026), namely 154 kJ/kg. The PCM mass was determined from the total PCM volume using the density assumption adopted in the calculation (Ghodrati, Zahedi and Abolfazl, 2022; Roy *et al.*, 2023; Sreelekha, Landini and Roy, 2026), and the stored thermal energy was calculated using Equation (3):

$$Q_{\text{PCM}} = m_{\text{PCM}} \times H_{\text{sf}}$$

Where:

Q_{PCM} = PCM thermal storage capacity (kJ)

m_{PCM} = total PCM mass (kg)

H_{sf} = latent heat of fusion (kJ/kg)

Based on the proposed configuration, the calculated thermal storage capacity was 1,351,350 kJ, equivalent to 375.37 kWh after conversion using 1 kWh = 3,600 kJ.

The nominal electricity-saving percentage was subsequently calculated by comparing the calculated PCM thermal storage capacity with the baseline electricity consumption of the cold-storage process, which was 1,527.8 kWh per production cycle. The calculation was expressed as:

$$S_{\text{PCM}} = (Q_{\text{PCM,kWh}} / E_{\text{CS,baseline}}) \times 100\%$$

Where:

S_{PCM} = nominal electricity-saving percentage (%)

$Q_{\text{PCM,kWh}}$ = calculated PCM thermal storage capacity (kWh)

$E_{\text{CS,baseline}}$ = baseline cold-storage electricity consumption (kWh per production cycle)

Using the calculated PCM capacity of 375.37 kWh and the baseline electricity consumption of 1,527.8 kWh, the resulting nominal saving was approximately 24.5%.

The 24.5% value was therefore used as the nominal energy-saving input in the subsequent PCM mitigation simulation. Because the PCM system was not physically installed during the study, the resulting energy reduction represents a simulation-based estimate under the configuration and assumptions adopted in this study rather than a directly measured electricity saving. The PCM calculation was conducted using the geometric configuration and baseline electricity consumption of the existing cold-storage system. Detailed transient thermal-load measurements and experimentally determined PCM phase-change behavior were not available within the scope of this study; therefore, the calculated storage capacity was used as the basis for the simulation-based mitigation scenario.

Table 3. Parameters applied in the PCM-based mitigation scenario.

Parameter	Value
Mitigation location	Cold storage
Number of PCM modules	234 modules
PCM module dimensions	0.75 × 0.50 × 0.10 m
PCM volume per module	37.5 L
Total PCM volume	8,775 L
Latent heat	154 kJ/kg
Total calculated thermal storage capacity	375.37 kWh
Baseline cold-storage electricity consumption	1,527.8 kWh/cycle
Nominal energy-saving assumption	24.5%
Assessment approach	Simulation-based scenario analysis
Evaluation indicators	Environmental impact, production cost, value added, eco-efficiency

The reduced electricity consumption obtained from the mitigation scenario was incorporated into the life cycle inventory and the environmental model developed in SimaPro to estimate the resulting changes in environmental impacts under the PCM scenario (Huijbregts *et al.*, 2017; Athirafitri, Indrasti and Ismayana, 2021). The environmental assessment of the PCM scenario was therefore limited to the operational electricity effect of the proposed mitigation. No additional inventory was assigned for PCM material production, containment or encapsulation materials, installation activities, maintenance, replacement, or disposal. These elements require specific material composition, supplier, lifetime, maintenance, and end-of-life data that were not available within the scope of the present simulation-based study. The resulting LCA values should therefore be interpreted as the potential environmental benefit associated with reduced cold-storage electricity consumption rather than the net life-cycle environmental impact of PCM deployment. The economic implications of the PCM scenario were evaluated by recalculating production-stage operational costs, Life Cycle Costing (LCC), and eco-efficiency indicators using the modeled reduction in electricity consumption. However, the recalculated LCC represents the operational cost effect of the mitigation scenario and does not include PCM procurement, installation, structural modification, maintenance, replacement, or capital amortization costs. These implementation-related costs were not estimated because the PCM configuration was evaluated as a simulation-based mitigation scenario without physical installation or investment procurement data. Accordingly, the resulting economic indicators are interpreted as potential operational savings rather than as a complete investment feasibility assessment. (Pena, Rovira-Val and Mendoza, 2022; Effendi, Warlina and Nurmawati, 2024; Trofimenko *et al.*, 2025). The effectiveness of the proposed mitigation strategy was assessed by comparing the environmental

impacts, production costs, value added, eco-efficiency ratio, and Eco-Efficiency Index (EEI) between the baseline and PCM scenarios (Konstantas, Stamford and Azapagic, 2020; Susanto *et al.*, 2022). It should be noted that the PCM scenario represents a simulation-based assessment rather than an actual implementation; therefore, the reported results indicate the potential environmental and economic benefits achievable under the technical conditions and calculated PCM performance adopted in this study (Subal, Braunschweig and Hellweg, 2024; Trofimenko *et al.*, 2025).

To examine the robustness of the PCM-based mitigation result, a sensitivity analysis was considered for the main parameter influencing the estimated electricity-saving potential, namely the PCM latent heat capacity. The sensitivity assessment was designed to evaluate how variations in the assumed latent heat value affect the calculated thermal storage capacity and the resulting electricity-saving estimate while keeping the PCM configuration and baseline cold-storage electricity consumption unchanged. Because the present study did not include experimental characterization of PCM properties, the sensitivity analysis is interpreted as a scenario-based robustness assessment rather than a statistical uncertainty estimation.

3. RESULTS, OR RESULTS AND DISCUSSION

3.1 Inventory Analysis

The life cycle inventory (LCI) analysis quantified all material and energy flows associated with the production of 1,000 L of strawberry loly ice cream within the defined gate-to-gate system boundary. The production system comprised six sequential processing stages, namely mixing, homogenization, aging, freezing, packing, and cold storage, with inventory data collected directly from the manufacturing facility through production records, field observations, and operational measurements. The compiled inventory served as the basis for constructing the life cycle model in SimaPro and for evaluating both the environmental and economic performance of the production system (Huijbregts *et al.*, 2017; Athirafitri, Indrasti and Ismayana, 2021; Widiyanto, 2022).

The production process was dominated by water, granulated sugar, and liquid glucose, which constituted the principal raw materials for strawberry loly ice cream production. Water represented the largest material input, reaching 750 L per production cycle, reflecting its essential role as the primary formulation component and its utilization in several processing operations. Packaging materials, particularly PET and HDPE, also contributed substantially to the overall material demand because they were required to maintain product quality and facilitate distribution. These inventory flows were subsequently incorporated into the life cycle model to quantify their respective contributions to the environmental impacts of the production system (Huijbregts *et al.*, 2017; Doke and Gogate, 2025; Hamdani and Harahap, 2025; Santos and Lannes, 2025).

Table 4. Life cycle inventory data for the production of 1,000 L of strawberry loly ice cream.

Process	Main Inputs	Main Outputs
Mixing	Water, sugar, glucose, additives, electricity, diesel fuel	Hot intermediate product, atmospheric emissions, wastewater
Homogenization	Electricity, water	Hot intermediate product, atmospheric emissions, wastewater
Aging	Electricity, water	Cold intermediate product, atmospheric emissions, wastewater

Freezing	Electricity, wooden sticks, water	Frozen semi-finished product, atmospheric emissions, wastewater
Packing	Electricity, PET, HDPE	Final product, atmospheric emissions
Cold storage	Electricity	Stored final product, atmospheric emissions

Electricity was identified as the dominant energy input throughout the production system, particularly in refrigeration-related operations. Among all production stages, cold storage exhibited the highest electricity consumption, reaching 1,527.8 kWh per production cycle, followed by the freezing process. The high electricity demand primarily resulted from the continuous operation of refrigeration equipment required to maintain low storage temperatures and preserve product quality throughout the storage period. Such operating conditions substantially increase compressor running time and energy consumption, making refrigeration the principal contributor to both environmental impacts and production costs. Similar observations have been reported in previous studies, which consistently identified refrigeration systems as the major energy hotspot in cold-chain and ice cream manufacturing due to their continuous cooling requirements (Ghodrati, Zahedi and Abolfazl, 2022; Marchi and Zanoni, 2022; Magdalena, 2023; Roy *et al.*, 2023; Doke and Gogate, 2025). Accordingly, the inventory analysis indicates that improving refrigeration energy efficiency represents the most promising strategy for reducing environmental burdens and operational costs, thereby providing the primary justification for evaluating the Phase Change Material (PCM)-based mitigation scenario presented in this study (Roy *et al.*, 2023; Ouaouja *et al.*, 2025; Ali, Ahmed and Ali, 2026).

3.2 Environmental Impacts of Ice Cream Production

The Life Cycle Impact Assessment (LCIA) indicated that the production of 1,000 L of strawberry loly ice cream generated a total environmental impact of 860 Pt, reflecting a substantial environmental burden associated with energy consumption, material utilization, and production activities within the defined gate-to-gate system boundary (Huijbregts *et al.*, 2017; Athirafitri, Indrasti and Ismayana, 2021). The ReCiPe 2016 Endpoint (H) assessment further revealed that the human health damage category was the predominant contributor, accounting for 823 Pt or approximately 95.7% of the total environmental impact, whereas the ecosystem and resource damage categories contributed comparatively smaller proportions (Huijbregts *et al.*, 2017). The predominance of the human health category indicates that emissions generated throughout the production process, particularly those associated with electricity generation, have a greater potential to affect human well-being than ecosystem degradation or resource depletion. This outcome is consistent with the characterization framework of the ReCiPe 2016 Endpoint method, which aggregates multiple midpoint impact categories into endpoint damages affecting human health, ecosystems, and natural resources (Huijbregts *et al.*, 2017; Widiyanto, 2022; Devi and Mirwan, 2023).

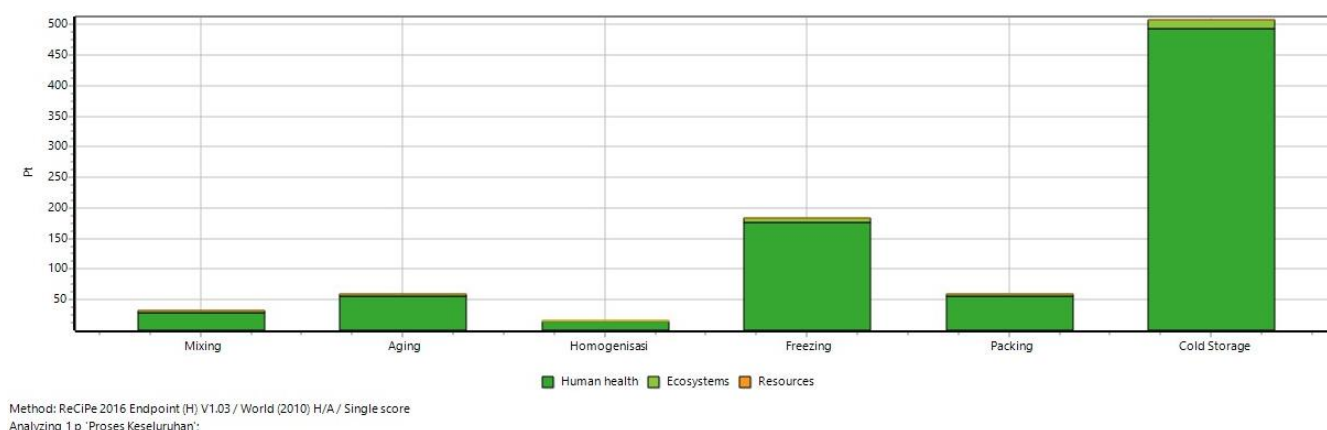


Figure 2. Environmental impacts of each production stage expressed as single score (Pt).

Figure 3 presents the environmental impacts associated with each production stage expressed as a single score (Pt). Among all production stages, cold storage was identified as the principal environmental hotspot, contributing 507 Pt or 58.9% of the total environmental impact, followed by freezing, aging, and packing processes. The dominance of the cold storage stage primarily resulted from its high electricity consumption, reaching 1,527.8 kWh per production cycle, which substantially increased indirect emissions associated with electricity generation, including carbon dioxide and other atmospheric pollutants. Continuous compressor operation required to maintain frozen storage temperatures further intensified electricity demand, thereby increasing the overall environmental burden of the production system (Ghodrati, Zahedi and Abolfazl, 2022; Marchi and Zanoni, 2022; Magdalena, 2023; Roy *et al.*, 2023).

Table 5. Environmental impacts of strawberry loly ice cream production.

Damage category	Unit	Total	Mixing	Aging	Homogenization	Freezing	Packing	Cold Storage
Total	Pt	860	32.2	58.9	16.6	184	60.2	507
Human health	Pt	823	28.5	55.3	13.9	176	55.9	493
Ecosystems	Pt	35.2	3.58	3.47	2.52	8.27	3.84	13.5
Resources	Pt	2.04	0.14	0.187	0.134	0.394	0.444	0.741

The dominance of refrigeration-related processes observed in this study is consistent with previous investigations on food processing and cold-chain systems, which have consistently identified refrigeration as the largest consumer of electricity and the principal contributor to environmental impacts because of its continuous cooling requirements (Meneghetti, 2018; Liang *et al.*, 2022; Marchi and Zanoni, 2022; Doke and Gogate, 2025; Ali, Ahmed and Ali, 2026). These findings confirm that electricity consumption represents the primary environmental driver in strawberry loly ice cream production and highlight the importance of improving refrigeration efficiency as a practical strategy for reducing environmental burdens. Consequently, identifying cold storage as the environmental hotspot provides a scientifically justified basis for evaluating Phase Change Material (PCM)-based thermal energy storage as an energy-saving mitigation strategy in the subsequent analysis (Roy *et al.*, 2023; Ouajouja *et al.*, 2025; Sreelekha, Landini and Roy, 2026).

3.3 Economic Performance

The economic performance of the strawberry loly ice cream production system was evaluated using the Life Cycle Costing (LCC) approach under the same gate-to-gate system boundary adopted for the environmental assessment, thereby ensuring consistency between the environmental and economic analyses (Menna *et al.*, 2020; Pena, Rovira-Val and Mendoza, 2022; Trofimenko *et al.*, 2025). The assessment showed that producing 1,000 L of strawberry loly ice cream required a total life cycle cost of Rp8,847,444 per production cycle. The calculated LCC comprised expenditures for raw materials, supporting materials, electricity, utilities, and direct labor, representing the principal cost components associated with the production process (Kainde, Kaeng and Kandiyoh, 2025; Zazo, Gosselink and Kromanis, 2025). Among these components, electricity represented the largest operational cost, amounting to Rp2,521,876 or approximately 29% of the total production cost, highlighting the strong dependence of the production system on electrical energy (Pena, Rovira-Val and Mendoza, 2022; Trofimenko *et al.*, 2025).

The substantial electricity expenditure was primarily associated with refrigeration-related operations, particularly freezing and cold storage, which require continuous cooling to maintain product quality and storage stability. Consequently, refrigeration systems consumed considerably more electricity than other processing stages, increasing both operational costs and environmental impacts. This finding is consistent with the environmental assessment, which identified cold storage as the principal environmental hotspot due to its intensive electricity demand (Ghodrati, Zahedi and Abolfazl, 2022; Marchi and Zanoni, 2022; Roy *et al.*, 2023; Ouaouja *et al.*, 2025). The close relationship between electricity consumption and production costs demonstrates that energy efficiency improvements have the potential to generate simultaneous environmental and economic benefits, reinforcing the importance of integrating LCA and LCC in sustainability assessments (Konstantas, Stamford and Azapagic, 2020; Trofimenko *et al.*, 2025).

Table 6. Economic performance of strawberry loly ice cream production.

Economic indicator	Value
Sales value (P)	Rp25,000,000
Life cycle cost (LCC)	Rp8,847,444
Electricity cost	Rp2,521,876
Electricity cost contribution	29%
Value added (VA)	Rp16,152,556

The production system generated a total sales value of Rp25,000,000 per production cycle for the defined functional unit. After deducting the total life cycle cost, the resulting value added (VA) reached Rp16,152,556, indicating that the production process generated substantial economic value beyond the production expenditures incurred (Menna *et al.*, 2020; Peña, 2020). The positive value added confirms the economic feasibility of the production system and demonstrates its capacity to create financial returns while supporting industrial production. In the context of sustainability assessment, value added represents an important economic indicator because it reflects the economic benefits generated relative to the resources consumed during production (Konstantas, Stamford and Azapagic, 2020; Effendi, Warlina and Nurmawati, 2024).

The results further indicate that reducing electricity consumption would provide additional economic benefits by lowering operational expenditures, particularly those associated with refrigeration. Since electricity represents the largest variable operating cost, even moderate improvements in refrigeration efficiency are expected to increase value added while simultaneously reducing environmental impacts. Therefore, integrating LCC with environmental performance indicators through an eco-efficiency framework enables a more comprehensive evaluation of production sustainability than either approach alone (Konstantas, Stamford and Azapagic, 2020; Pena, Rovira-Val and Mendoza, 2022; Effendi, Warlina and Nurmawati, 2024; Trofimenko *et al.*, 2025). Comparable findings have been reported in previous studies, which consistently demonstrated that electricity-intensive processes strongly influence both production costs and environmental burdens, emphasizing the importance of energy-efficiency strategies for improving the sustainability of food processing industries (Menna *et al.*, 2020; Marchi and Zanoni, 2022; Doke and Gogate, 2025).

3.4 Eco-Efficiency Assessment

The eco-efficiency assessment integrated the environmental and economic performances of the strawberry loly ice cream production system to evaluate its overall sustainability. The environmental performance was represented by the total environmental impact of 860 Pt obtained from the ReCiPe 2016 Endpoint (H) assessment, whereas the economic performance was represented by the value added (VA) of Rp16,152,556 generated during one production cycle. Integrating these environmental and economic indicators provides a comprehensive evaluation framework that supports sustainability-oriented decision-making by simultaneously considering environmental burdens and economic benefits rather than assessing each aspect independently (Konstantas, Stamford and Azapagic, 2020; Effendi, Warlina and Nurmawati, 2024; Trofimenko *et al.*, 2025).

Based on Equation (2), the production system achieved an eco-efficiency ratio of 0.000053 Pt/Rp, indicating that approximately 0.000053 points of environmental impact were generated for every Indonesian Rupiah of value added produced during the manufacturing process. Because the eco-efficiency ratio in this study was calculated as the ratio between environmental impact and economic value (LCA/VA), a lower eco-efficiency value reflects better sustainability performance, indicating that less environmental burden is generated to produce a given amount of economic value. Therefore, the obtained result demonstrates that although the production system is economically feasible, there remains considerable potential to further reduce environmental impacts through improvements in resource and energy efficiency (Konstantas, Stamford and Azapagic, 2020; Susanto *et al.*, 2022; Effendi, Warlina and Nurmawati, 2024).

However, the environmental assessment identified refrigeration-related processes, particularly cold storage, as the dominant contributor to the total environmental impact, while the Life Cycle Costing analysis revealed that electricity represented approximately 29% of the total production cost. The convergence of these environmental and economic hotspots indicates that electricity consumption simultaneously drives environmental burdens and operational expenditures. Consequently, improving refrigeration energy efficiency represents the most effective opportunity to reduce the eco-efficiency ratio by lowering environmental impacts while maintaining the economic value generated by the production system (Ghodrati, Zahedi and Abolfazl, 2022; Marchi and Zanoni, 2022; Pena, Rovira-Val and Mendoza, 2022; Roy *et al.*, 2023).

The eco-efficiency assessment therefore provides a quantitative basis for evaluating the proposed Phase Change Material (PCM)-based mitigation scenario. Since PCM technology is expected to reduce electricity consumption during cold storage operation, its implementation has the potential to decrease the environmental impact per unit of economic value generated, thereby improving the sustainability performance of the production system. Accordingly, eco-efficiency serves as an integrated indicator for assessing whether the proposed mitigation strategy can simultaneously reduce environmental burdens while preserving or enhancing the economic performance of strawberry loly ice cream production (Konstantas, Stamford and Azapagic, 2020; Ouauja *et al.*, 2025; Sreelekha, Landini and Roy, 2026).

Table 7. Eco-efficiency indicators of strawberry loly ice cream production.

Single Score LCA (pt)	VA (Rp)	Eco-Efficiency
860	Rp16.152.556	0,000053

Overall, the obtained eco-efficiency ratio indicates that the production system has successfully generated positive economic value; however, further improvements in sustainability remain achievable through reductions in electricity consumption and associated environmental impacts. Previous studies have consistently demonstrated that energy-efficiency measures implemented in refrigeration-based industries can substantially improve sustainability by lowering both operational costs and environmental burdens. Therefore, mitigation strategies targeting electricity-intensive processes are expected to provide the greatest contribution to improving the environmental and economic performance of ice cream production systems (Ghodrati, Zahedi and Abolfazl, 2022; Effendi, Warlina and Nurmawati, 2024; Doke and Gogate, 2025; Trofimenko *et al.*, 2025).

3.5 Environmental and Economic Improvement through PCM Scenario

A mitigation scenario based on the integration of Phase Change Material (PCM) was evaluated to investigate its potential for improving the environmental and economic sustainability of the strawberry loly ice cream production system. PCM modules were positioned beneath the cold storage racks in the developed model, where they functioned as passive cold thermal energy storage media capable of absorbing and releasing latent heat during refrigeration cycles. The proposed PCM configuration was evaluated through a simulation-based mitigation scenario to estimate its potential effect on the refrigeration performance of the cold-storage system. The configuration consisted of 234 PCM modules with a total volume of 8,775 L. Using a latent heat value of 154 kJ/kg, the calculated thermal storage capacity was 375.37 kWh. Relative to the baseline cold-storage electricity consumption of 1,527.8 kWh per production cycle, this capacity corresponded to a nominal energy-saving assumption of approximately 24.5%. The 24.5% value was subsequently applied to the cold-storage electricity inventory in the mitigation scenario. Accordingly, the resulting changes in environmental impact, production cost, value added, and eco-efficiency represent projected effects under the modeled PCM configuration and should be interpreted as simulation-based results rather than measurements obtained from physical PCM implementation (Ghodrati, Zahedi and Abolfazl, 2022; Roy *et al.*, 2023; Ouauja *et al.*, 2025; Sreelekha, Landini and Roy, 2026).

A mitigation scenario based on the proposed Phase Change Material (PCM) configuration was evaluated to investigate its potential to improve the environmental and economic sustainability of the strawberry loly ice

cream production system. In the model, PCM modules were positioned beneath the cold storage racks and represented as passive thermal energy storage media capable of absorbing and releasing latent heat during refrigeration cycles. Based on the adopted PCM parameters and the modeled configuration, the estimated thermal energy storage capacity was 375.37 kWh, corresponding to an estimated electricity-saving potential of approximately 24.5% relative to the baseline cold-storage electricity consumption of 1,527.8 kWh per production cycle. This value represents a scenario-based estimate and should not be interpreted as a directly measured electricity reduction from physical PCM installation.

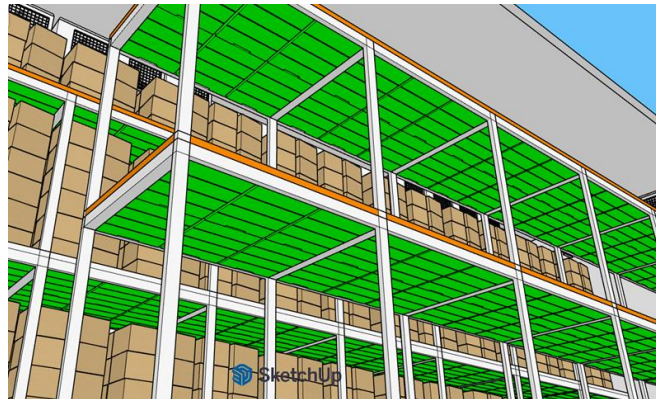


Figure 3. Schematic design of PCM installation beneath the cold storage racks.

The modeled reduction in electricity consumption resulted in a decrease in the environmental impact associated with the cold storage stage from 507 Pt to 387 Pt, corresponding to an estimated reduction of approximately 23.7%. The total environmental impact consequently decreased from 860 Pt to 740 Pt, representing a reduction of 13.95% within the defined gate-to-gate system boundary. This reduction reflects the environmental benefit associated with the modeled decrease in operational electricity consumption. However, because the PCM material and its associated upstream, installation, maintenance, replacement, and end-of-life processes were not included in the LCA inventory, the reported reduction should be interpreted as the potential operational electricity-related benefit of the PCM scenario rather than the net environmental benefit of the complete PCM life cycle (Ghodrati, Zahedi and Abolfazl, 2022; Marchi and Zanoni, 2022; Doke and Gogate, 2025).

From an economic perspective, the modeled reduction in electricity consumption resulted in a decrease in production-stage operational costs, increasing the calculated value added from Rp16,152,556 to Rp16,807,830 per production cycle. However, this comparison reflects only the operational cost effect associated with reduced electricity consumption. The PCM material cost, installation cost, structural modification, maintenance or replacement cost, and capital amortization were not included because the mitigation strategy was evaluated as a simulation-based scenario without physical implementation and investment cost data. Therefore, the increase in value added should be interpreted as a potential operational economic benefit under the modeled electricity-saving assumption rather than evidence of the overall economic feasibility or profitability of PCM investment. (Menna *et al.*, 2020; Pena, Rovira-Val and Mendoza, 2022; Trofimenko *et al.*, 2025).

The combined environmental and economic improvements also enhanced the eco-efficiency performance of the production system. Based on the adopted assessment framework (LCA/VA), the eco-efficiency ratio decreased from 0.000053 Pt/Rp under the baseline condition to approximately 0.000044 Pt/Rp after PCM implementation, representing a reduction of approximately 17%. Because lower eco-efficiency ratios indicate lower environmental impacts per unit of economic value generated, the obtained results demonstrate that PCM implementation improved the sustainability performance of the production system by simultaneously reducing environmental burdens and increasing economic value.

Table 8. Environmental and economic performance of the baseline and PCM-based mitigation scenarios.

Indicator	Baseline	PCM-based scenario
Electricity consumption (kWh)	1.527,8	1.152,4
Cold storage impact (Pt)	507	387
Total environmental impact (Pt)	860	740
Value added (Rp)	16.152.556	16.807.830
Eco-efficiency (Pt/Rp)	0,000053	0,000044
PCM implementation cost included	–	No

The sensitivity assessment provides an additional perspective on the robustness of the PCM scenario. Because the estimated electricity-saving potential is directly proportional to the assumed latent heat value, changes in PCM thermal properties can affect the magnitude of the environmental and operational cost benefits obtained from the scenario. Nevertheless, the sensitivity analysis was performed only as a scenario-based parameter variation because experimental uncertainty data for the selected PCM properties were not available within the scope of the study. Consequently, the analysis demonstrates the dependence of the results on the adopted assumptions rather than providing a probabilistic confidence interval.

Overall, the PCM-based mitigation scenario indicates potential environmental improvement through reduced refrigeration electricity consumption. The decrease in environmental impact is attributable to the modeled reduction in electricity demand within the existing production system. Because the environmental burdens associated with the PCM technology itself were outside the defined assessment boundary, the results should be considered an operational electricity-related mitigation estimate rather than a complete life-cycle comparison between PCM and the baseline system (Roy *et al.*, 2023; Ouajouja *et al.*, 2025; Ali, Ahmed and Ali, 2026; Sreelekha, Landini and Roy, 2026).

3.6 Sensitivity Analysis of the PCM Scenario

A scenario-based sensitivity analysis was conducted to examine the robustness of the estimated electricity-saving potential of the proposed PCM configuration. The latent heat value was varied around the adopted base value of 154 kJ/kg, while the PCM quantity, configuration, and baseline cold-storage electricity consumption were kept constant. The results indicate that the estimated thermal storage capacity and corresponding electricity-saving potential change proportionally with the assumed latent heat value.

Under the base-case assumption of 154 kJ/kg, the estimated thermal storage capacity was 375.37 kWh, corresponding to an electricity-saving estimate of approximately 24.5%. A 10% decrease in latent heat reduced the estimated storage capacity to 337.83 kWh and the electricity-saving estimate to approximately 22.1%,

whereas a 10% increase increased these values to 412.91 kWh and approximately 27.0%, respectively. Under the wider $\pm 20\%$ scenario range, the estimated electricity-saving potential varied from approximately 19.7% to 29.5%. These results indicate that the reported 24.5% value is sensitive to the assumed PCM latent heat and should therefore be interpreted as a scenario-based estimate rather than a fixed experimentally validated performance value.

The sensitivity results do not change the identification of cold storage as the principal environmental hotspot, but they demonstrate that the magnitude of the estimated improvement depends on the assumed PCM thermal-storage performance. Therefore, the environmental and economic improvements reported for the PCM scenario should be interpreted within the range of the underlying scenario assumptions.

4. DISCUSSION

4.1 Environmental and Economic Hotspots in Ice Cream Production

The integrated assessment performed in this study demonstrates that cold storage represents the principal hotspot in strawberry loly ice cream production from both environmental and economic perspectives, indicating that electricity consumption is the key factor linking environmental burdens and production costs. While the Life Cycle Assessment identified cold storage as the largest contributor to the overall environmental impact due to its continuous refrigeration demand, the Life Cycle Costing analysis similarly revealed that electricity constituted the largest operational cost component, confirming that refrigeration simultaneously drives environmental degradation and economic expenditure. This finding is consistent with previous studies, which identified refrigeration systems as the dominant energy consumers in cold chain and ice cream production because continuous compressor operation is required to maintain product quality and storage stability (Ghodrati, Zahedi and Abolfazl, 2022; Marchi and Zanoni, 2022; Roy *et al.*, 2023). However, unlike earlier studies that primarily evaluated environmental or energy performance independently, the present study demonstrates that integrating LCA and LCC through an eco-efficiency framework enables simultaneous identification of environmental and economic hotspots, providing a more comprehensive basis for sustainability oriented decision making. This integrated perspective suggests that prioritizing energy efficiency improvements in refrigeration systems offers the greatest opportunity to simultaneously reduce environmental impacts and operational costs, thereby establishing a scientifically justified foundation for evaluating the Phase Change Material (PCM) based mitigation strategy proposed in this study.

4.2 Sustainability Implications of Integrating LCA, LCC, and Eco-Efficiency

The findings of this study demonstrate that integrating Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and eco-efficiency provides a more comprehensive sustainability evaluation than applying each approach independently. While LCA effectively identifies environmental hotspots and LCC quantifies the associated economic performance, the eco-efficiency framework combines these two dimensions to evaluate the environmental impact generated per unit of economic value, thereby supporting more balanced sustainability oriented decision making. This integrated approach enables the identification of improvement priorities that simultaneously reduce environmental burdens and operational costs, rather than optimizing only one sustainability dimension. Previous studies have widely applied LCA and LCC separately in food manufacturing

and refrigeration systems (Konstantas, Stamford and Azapagic, 2020; Pena, Rovira-Val and Mendoza, 2022; Trofimenko *et al.*, 2025) however, relatively few have demonstrated how both assessments can be systematically integrated through an eco-efficiency indicator to support strategic decision making at the process level. The present study therefore extends existing research by providing an integrated framework capable of identifying processes that simultaneously exhibit the highest environmental impacts and economic costs, allowing industries to prioritize mitigation strategies with the greatest overall sustainability benefits. This holistic perspective is particularly relevant for refrigeration intensive food industries, where environmental and economic performances are strongly influenced by electricity consumption, making integrated sustainability assessment an effective tool for improving resource efficiency, reducing operational expenditures, and supporting long term sustainable production.

4.3 Effectiveness of PCM as an Energy-Mitigation Strategy

The PCM based mitigation scenario evaluated in this study demonstrates that thermal energy storage can effectively improve both the environmental and economic performance of refrigeration intensive food production systems. By storing excess cooling energy during compressor operation and releasing it when cooling demand increases, PCM reduces compressor running time and consequently lowers electricity consumption without affecting production capacity or product quality. The simulation results indicate that this reduction in electricity demand led to simultaneous decreases in the environmental impact of the cold storage stage and the overall production system, while also reducing operational electricity costs and increasing value added, thereby improving the eco-efficiency performance of the production process. These findings are consistent with previous studies reporting that PCM integration enhances refrigeration efficiency by stabilizing storage temperatures, reducing compressor cycling, and minimizing energy consumption in cold chain applications (Ghodrati, Zahedi and Abolfazl, 2022; Roy *et al.*, 2023; Ouaouja *et al.*, 2025; Sreelekha, Landini and Roy, 2026). However, unlike previous investigations that primarily focused on energy saving performance or thermal behavior, the present study demonstrates that the benefits of PCM extend beyond energy efficiency by quantitatively improving environmental performance, economic value, and eco-efficiency within a unified sustainability assessment framework. This integrated evaluation provides stronger evidence that PCM is not merely an energy saving technology but also a practical sustainability strategy capable of simultaneously reducing environmental burdens and operational costs, making it a promising solution for food manufacturing industries with high refrigeration demands.

4.4 Practical Implications, Limitations, and Future Research

The findings of this study provide several practical implications for sustainability management in refrigeration intensive food industries. By identifying cold storage as the primary environmental and economic hotspot, the integrated LCA–LCC–eco-efficiency framework offers a scientific basis for prioritizing energy efficiency investments where they can generate the greatest sustainability benefits. Rather than implementing broad process modifications across the entire production system, decision makers can focus on improving refrigeration performance through technologies such as Phase Change Material (PCM), which has demonstrated the potential to simultaneously reduce electricity consumption, environmental impacts, and operational costs while

enhancing eco-efficiency. Furthermore, the proposed assessment framework can serve as a decision support tool for evaluating sustainability improvement strategies in other food manufacturing sectors that rely heavily on refrigeration systems. Nevertheless, several limitations should be acknowledged. The present study adopted a gate-to-gate system boundary, thereby excluding upstream raw material production and downstream distribution and disposal stages that may also contribute to the overall environmental impacts. In addition, the PCM mitigation strategy was evaluated through simulation based on literature supported performance rather than full scale industrial implementation, meaning that operational uncertainties and long term economic feasibility were not experimentally validated. The analysis was also limited to a single ice cream product and production facility, which may restrict the generalizability of the findings to other manufacturing conditions. Therefore, future research should extend the assessment to a cradle-to-grave perspective, perform full scale industrial validation of PCM applications, incorporate uncertainty and sensitivity analyses, and evaluate different PCM materials and refrigeration configurations to identify the most effective strategies for improving sustainability in refrigeration dependent food production systems.

5. CONCLUSIONS

This study evaluated the environmental and economic sustainability of strawberry loly ice cream production through an integrated framework combining Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and eco-efficiency assessment within a gate-to-gate system boundary. The results demonstrated that electricity intensive refrigeration processes, particularly cold storage, were the principal contributors to both environmental impacts and production costs, identifying refrigeration energy consumption as the primary hotspot for sustainability improvement. The integrated assessment successfully revealed the strong relationship between environmental burdens and economic performance, providing a comprehensive basis for sustainability oriented decision making in ice cream production.

The proposed PCM-based mitigation scenario showed potential to improve the sustainability performance of the production system through a modeled reduction in refrigeration electricity consumption, resulting in lower environmental impacts and lower production-stage operational costs. However, the economic results represent operational cost savings associated with the modeled electricity reduction and do not include PCM procurement, installation, modification, maintenance, replacement, or capital amortization costs. Therefore, the findings indicate the potential operational benefit of PCM-based energy mitigation rather than demonstrating the complete investment feasibility or profitability of PCM deployment. Further research involving actual implementation and detailed investment-cost assessment is required to determine the economic feasibility of PCM under industrial operating conditions.

The main contribution of this study lies in the development of an integrated assessment framework that combines environmental, economic, and eco-efficiency analyses to quantitatively evaluate the sustainability benefits of PCM implementation in ice cream production. This framework can assist industrial practitioners in identifying sustainability hotspots, prioritizing energy efficiency measures, and supporting environmentally and economically informed decision-making.

This study was based on a simulation of PCM implementation under a gate-to-gate system boundary. Therefore, future research should validate the proposed mitigation strategy through full-scale industrial implementation, incorporate cradle-to-grave life cycle boundaries, and evaluate the long term technical and economic performance of PCM under actual operating conditions. Such investigations would provide a more comprehensive understanding of the sustainability potential of PCM technology in refrigeration based food industries.

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