International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 20s, 2025
https://theaspd.com/index.php

# Life Cycle Assessment (LCA)--A study of the Evaluating Sustainability of the Manufacture of Ice Cream Products

**Pramod S. Doke[1], Dr. Nivedita Gogate[2]**
[1]MTech Research Scholar, Department of Civil Engineering, ,Dr. Vishwanath Karad MIT World Peace University, Pune 411038, India. Email: dokeps1982@gmail.com.
[2]Associate Professor, Department of Civil engineering, Dr. Vishwanath Karad MIT World Peace University, Pune 411038, India. Email: nivedita.gogate@mitwpu.edu.in

***Abstract***
*The environmental effects of the industrial manufacture of ice cream through a Life Cycle Assessment (LCA) approach is the main focus of this study. A 200-liter batch of raw material (about 100 kg of product – ice cream) is considered as the functional unit. The LCA has a cradle-to-gate boundary. The study assesses energy and water consumption and greenhouse gas emissions (GHGs), and locates environmental hotspots during the production process, while adhering to ISO 14040 and ISO 14044 standards. To prepare a comprehensive life cycle inventory (LCI), the evaluation combines primary data from manufacturers with secondary data from well-known databases, such as Ecoinvent v3.8. The ice-cream manufacturing facility considered for the study is located in Pune, Maharashtra. With an average carbon footprint of 7.14 kg $CO_2$e per kg of ice cream, the analysis shows a total carbon footprint of 713.91 kg $CO_2$-equivalent for the studied batch of the product, which is much higher than the global average for dairy-based frozen desserts (1.5–3.0 kg $CO_2$e/kg). Due to the dairy industry's high resource and energy requirements, milk solids (43%), electricity use (9.2%), and embedded water in dairy inputs are the main causes of the increased emissions. The usage of chemical stabilizers (such as CMC Carboxy Methyl Cellulose), artificial flavorings and colorants, and paper-based packaging are other factors that contribute significantly to emissions because of their energy-intensive processing and lack of recycling or reuse plans. The environmental costs of every processing step—mixing, pasteurization, aging, freezing, hardening, and packaging that primarily relies on energy-intensive equipment are also highlighted by the LCA. Notably, because refrigeration relies on power derived from fossil fuels and hydrofluorocarbon (HFC) refrigerants, the study highlights the significance of refrigeration across the supply chain as a persistent source of carbon emissions.*
***Keywords:*** *Life Cycle Assessment (LCA), Greenhouse gas emissions (GHGs), Carbon footprint*

## INTRODUCTION

Food is essential to human existence because it is the main source of energy, sustenance, and cultural identity. However, food production, processing, distribution, and consumption all have a major role in the deterioration of the environment[1]. Agricultural practices, land use change, deforestation, animal production, transportation, refrigeration, and packaging are the main causes of the food sector's estimated 30% global contribution to GHG emissions[2]. Therefore, in the larger framework of climate change, the depletion of natural resources, and sustainability, the environmental load of food systems is a crucial concern[3]. Many sustainable approaches have been put forth and put into practice within the food industry in recognition of the pressing need to solve these problems[3]. These tactics center on cutting greenhouse gas emissions, preserving energy and water, cutting waste, improving packaging, and implementing more environmentally friendly and efficient production techniques[4]. Low-carbon and resource-efficient approaches to food production and delivery are becoming more and more important to governments, businesses, environmental organizations, and researchers[5].

### 1.1 About the Life Cycle Assessment Methodology

Life cycle assessment (LCA) is a systematic method for evaluating the environmental impact of a product, service, or process over its entire life cycle. It is a useful methodology in assessing the environmental performance, identifying impact areas and determining impact mitigation measures[6]. The assessment of life cycle impacts is crucial to lead efforts in the mitigation of negative environmental impacts[7]. Mapping the life cycle of the product / process/ building being assessed for environmental impacts is the first step to defining the system boundaries of the life cycle assessment[8].

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 20s, 2025
https://theaspd.com/index.php


**Fig 1: Stages in a product life cycle**

## About the Product

Ice cream is a distinctive product category in the larger food item landscape. Despite being frequently viewed as a "luxury" or unnecessary food item, ice cream has become a popular pleasure that is loved by people of all ages and geographical locations[9]. Urbanization, shifting consumer tastes, increased disposable incomes, and a growing desire for decadent, high-end, and inventive frozen desserts are all contributing factors to the ice cream industry's strong growth on a global scale[10]. The variety and popularity of ice cream are growing quickly, ranging from classic dairy-based varieties to low-calorie and plant-based substitutes. Take-home ice cream and wrapped or impulsive ice cream are the two primary consumption styles for ice cream. Usually served in tubs or bigger containers, take-home ice cream is kept in home freezers for later consumption. In contrast, wrapped ice creams are portioned out individually and are intended to be consumed right away. Cones, sandwiches, and ice cream bars are a few examples. These formats differ not only in packing and distribution methods but also in their environmental implications. For example, because of their shorter shelf lives and frequent shipping, impulse ice creams frequently require more robust refrigeration logistics and larger packaging-to-product ratios.

Even though ice cream is very popular, not much scientific research has been done on how it affects the environment[11]. The process of making ice cream uses a lot of resources, including electricity, water, refrigeration, and agricultural inputs, especially dairy[11]. Because of methane emissions from animals, land use for feed production, and water consumption, dairy products have one of the largest environmental footprints of any food category[12]. Furthermore, energy consumption and carbon emissions are greatly increased by the requirement to maintain cold chain logistics from manufacture to retail (and even during consumption)[13]. In 2011, the Scottish Government published one of the few studies that calculated the global warming potential (GWP) of ice cream to be 4 kg of $CO_2$-equivalents per kilogram of product[14]. This indicates that 4 kg of carbon dioxide are emitted into the atmosphere for every kilogram of ice cream that is made and eaten[15]. The ice cream manufacturer Ben & Jerry's offered a comparable estimate, stating that the GWP of their simple dairy-based ice cream was 3.36 kg $CO_2$-eq./kg[11]. When compared to other processed foods, these numbers are noteworthy, suggesting that ice cream has a large impact on carbon emissions. There are several reasons for this high GWP. Most notably, milk and cream are produced from ruminant animals (usually cows), whose digestive processes release methane, a greenhouse gas that is about 25 times more potent than $CO_2$ over a 100-year period[16]. The total environmental impact is also influenced by other ingredients including sugar, flavorings, emulsifiers, and stabilizers, particularly when they are imported from distant areas that require lengthy shipping routes. Furthermore, ice cream's freezing and storage needs pose a significant environmental risk. Throughout its supply chain, from manufacturing facilities to delivery trucks, retail freezers, and residential refrigerators, ice cream needs to be maintained at below-freezing temperatures. A large portion of the electricity needed for this ongoing refrigeration demand still originates from systems that rely on fossil fuels[16]. The product's environmental impact is further increased by the usage of refrigerants such hydrofluorocarbons (HFCs), which are strong greenhouse gases with a significant potential for global warming[17].

Another important factor is packaging. A variety of materials, including cardboard, metal foils, laminated films, and plastics, are used to package the majority of ice creams[18]. In addition to adding to solid waste, these materials are difficult to recycle, particularly when utilized in non-biodegradable or multi-layered forms. Compared to bulk tubs, single-serve ice creams usually produce more packaging waste per unit weight, which increases their environmental effect. These results make it abundantly evident that the ice cream industry's environmental performance needs more investigation and enhancement. In this sense, life cycle assessment (LCA) is a useful instrument that allows manufacturers to measure emissions and resource consumption across the whole product lifecycle, from the extraction of raw materials to the disposal of end-of-life products[19]. With the use of this information, businesses may decide whether to rethink products, switch to less harmful components (such plant-based dairy substitutes), increase energy efficiency, or invest in environmentally friendly packaging. Additionally, people are increasingly choosing more environmentally sustainable products[16]. In a market where consumers care about the environment, ice cream firms that embrace sustainability through carbon labelling, renewable energy use, recyclable packaging, and sustainable ingredient sourcing are likely to gain a competitive edge and win over new customers. In conclusion, even though ice cream is still a popular treat around the world, there are significant environmental effects associated with its manufacture and consumption that need to be taken into consideration[20]. The ice cream industry has the chance and duty to embrace more environmentally friendly methods as climate change and environmental sustainability gain more attention. The industry can significantly lower its carbon footprint while still providing consumers with happiness by concentrating on sustainable advances in ingredient sourcing, energy use, refrigeration, and packaging[21].

## 2. METHODOLOGY

According to ISO 14040 and ISO 14044 standards, the standardized Life Cycle Assessment (LCA) approach serves as the foundation for the methodological framework used in this study (ISO, 2006a; ISO, 2006b). These standards, which cover four essential stages—goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation—offer a structured framework for carrying out environmental assessments at every stage of a product's life cycle.

### 2.2 Scope and Boundaries

The scope of the study helps to define the systemic boundaries of the LCA and determines how expansive the study is. The scope and type of the study depends on the products, processes and mechanisms considered as a part of the study. LCAs are categorized as follows, and a scope best suited to the project is adopted.

- Cradle to cradle: all the phases of the lifecycle, in a circular economic model are considered in the study – starting with the extraction of raw materials, till the re-entry of waste materials arising from the process, into the supply chain.
- Cradle to grave: all the phases of the lifecycle are considered, but re-processing of waste (for example, recycling, and material re-entry in the supply chain) is not considered in this case.
- Cradle to gate: Impacts starting from raw material extraction/relevant phase in the supply chain, till the end of the manufacturing process (factory gate) are considered.
- Gate to gate: Impacts arising between the phases of raw material transportation from the source (the supplier/vendor gate) to the completion of manufacturing process (factory gate) are considered.
- Gate to grave: Impacts arising after manufacturing process till the end-of-life of materials (waste disposal beyond the boundaries of the manufacturing unit) are studied.

The objective of this study is to assess the environmental effects of industrial ice cream production and pinpoint the primary hotspots that contribute to its carbon footprint. The assessment's scope is restricted to a cradle-to-gate boundary, which encompasses all operational and upstream procedures from the procurement of raw materials to packing and cold storage before distribution. 100 kg of ice cream made in a single batch serve as the functional unit for the analysis. Since flavor differences are thought to have little effect on the environmental profile, a broad depiction of ice cream manufacture is taken into consideration.

The production facility's primary data as well as secondary data from databases and literature were gathered throughout the life cycle inventory (LCI) stage. Quantification was done on inputs like raw materials (milk, cream, sugar, and stabilizers), energy used in pasteurization, freezing, and hardening units, water use, and waste production. To enable meaningful impact comparison, all variables were normalized to the functional unit. The Global Warming Potential over a 100-year time horizon (GWP 100) technique, as outlined by the

Intergovernmental Panel on Climate Change (IPCC), was used to characterize the environmental loads throughout the life cycle impact assessment (LCIA) phase. With this method, the impact of climate change is measured in kilograms of CO2 equivalent emissions. The IPCC GWP 100 metric makes it possible to estimate greenhouse gas emissions related to each step of the ice cream production process consistently and comparably. The data were interpreted by determining which steps had the most effects on the environment and looking into ways to lessen such effects, especially in high-energy processes like freezing and hardening. The study complies with globally recognized standards for evaluating environmental sustainability thanks to the application of ISO-based LCA methodology, which is backed by the IPCC GWP 100 impact assessment.

### 2.3 Goal and Scope of the Study

The main goal of the study is to use the Life Cycle Assessment (LCA) technique to conduct a thorough assessment of the environmental impacts related to industrial ice cream production. The study specifically attempts to measure the environmental impacts associated with each stage of the production process, mainly energy use, water consumption, and greenhouse gas (GHG) emissions. Finding environmental "hotspots" in the supply chain stages or activities that account for a disproportionate amount of the overall environmental impact will be possible thanks to this study. The ultimate objective is to offer data-driven suggestions and practical insights for reducing these effects and improving the sustainability of the ice cream production process. Examining the possibility of process optimization and the application of substitute technologies or energy sources that can result in a decrease in the total carbon footprint of ice cream manufacturing is a secondary objective. This entails investigating possibilities including the incorporation of renewable energy, effective refrigeration systems, environmentally friendly packaging substitutes, and improved waste management techniques. The study defines a functional unit of "100 kg of ice cream" made in a single batch in order to guarantee uniformity and comparability of results. A precise assessment of environmental performance per unit of production is made possible by the functional unit, which acts as the reference measure to which all input and output data are standardized. In order to provide significant results that are applicable to real-world situations, this volume was chosen to represent a realistic production amount that corresponds with common batch sizes in small to medium-scale industrial settings.

Assumptions: It is assumed that the environmental impact of various ice cream flavors is uniform in order to streamline the analysis and keep the primary production processes front and center. For the purposes of this study, flavor changes are deemed insignificant, even though they might lead to minor variations in the sourcing or processing requirements of ingredients. Therefore, a representative ice cream mix formulation comprising common constituents such milk, cream, sugar, emulsifiers, stabilizers, and flavoring agents in regular amounts serves as the basis for the analysis.

Cradle-to-gate system boundaries define the study's scope, which includes all phases from the procurement of raw materials (including upstream agricultural and industrial inputs) to on-site manufacturing operations like mixing, pasteurization, homogenization, freezing, packaging, and hardening, until the final product is stored and prepared for distribution. The system boundary does not include downstream activities like consumer use, retail storage, transportation, or end-of-life disposal. This method acknowledges that post-factory phases may potentially offer chances for further research while enabling a targeted evaluation of the direct production effects that are within the manufacturer's control. The study guarantees methodological transparency and conforms to ISO 14040 and ISO 14044 standards by using this structured aim and scope description. This basis bolsters the validity of the results and makes it easier to compare them with other life cycle assessments carried out in the dairy and food industries.

### 2.4 Inventory Data

In order to guarantee accuracy and representativeness of the production processes involved, the Life Cycle Inventory (LCI) data used in this study were mainly collected from a combination of direct manufacturer inputs and thorough literature reviews.

Foreground Data: Manufacturers provided the foreground data, which includes primary data on energy consumption, emissions, and raw material use during the stages of ice cream production (Manufacturer Data, 2024 as detailed out in Table 1). The data was documented during an in-person visit to the manufacturing facility. This method reduces the uncertainty associated with generic or secondary data sources by providing precise and contextualized information that is representative of real industry processes.

Background Database: The Ecoinvent database (version 3.8), a well-known and thoroughly validated source for

life cycle assessment practitioners worldwide, provided the majority of the background LCI data used to supplement these primary data (Wernet et al., 2016). Process-based LCI datasets from Ecoinvent cover the extraction of raw materials, transportation, energy supply, and other related production chain auxiliary operations. According to ISO 14040/44 standards, this database is essential for completing data gaps for upstream and downstream processes and enabling thorough system boundary coverage (Curran, 2012).
A strong hybrid inventory that captures both site-specific operating characteristics and generic industrial supply chain impacts is made possible by the merging of Ecoinvent's background data with manufacturer-specific foreground data. For instance, regionalized Ecoinvent datasets were used to model energy inputs like electricity and thermal energy consumption in order to represent the local grid mix. This increased the environmental impact assessment's geographical relevance (Wernet et al., 2016).
Additionally, the most recent literature values were used to inventorise auxiliary materials and packaging components, which frequently provide difficulties because of their varied sources and variability. Ecoinvent's statistics on plastics, paper, and other packaging materials were also added (Sala et al., 2017). A realistic depiction of freight emissions was ensured by using transportation logistics data based on standard vehicle types and distances recorded in industry reports and Ecoinvent's transport modules (Wernet et al., 2016). This careful blending of primary and secondary data sources improves the LCI phase's dependability and transparency and lays a strong basis for later impact assessments and hotspot analyses within the supply chain for the production of ice cream.

**2.5 Raw materials and Other Relevant Data**

The raw materials considered for the LCA are based on the production of a 200-litre milk batch (approximately 100 kg of final ice cream product). Ice cream is a dairy-based frozen dessert, typically composed of a mix of milk fat, milk solids, sweeteners, stabilisers, emulsifiers, flavouring agents, and colouring additives. Additionally, utility consumption (such as electricity), packaging material, and transport logistics have been integrated into the system boundary for a comprehensive life cycle inventory.
The base ingredient is buffalo milk, comprising approximately 83% water and 17% milk solids, with milk fat being a significant fraction contributing to the creaminess and mouthfeel of the final product. The sweetener, typically sucrose (sugar), enhances palatability, while stabilisers like Carboxymethyl Cellulose (CMC) and emulsifiers such as lecithin contribute to product texture and stability during freezing. EDTA (Ethylenediaminetetraacetic acid) is added as a sequestrant to bind metal ions, thereby enhancing shelf-life and product integrity. Minute amounts of propylene glycol and food-grade colouring are used for flavouring and visual appeal.
Packaging for the final product is primarily paper-based wrappers with an average capacity of 750 ml. A material used for ice-cream packaging is 350 gsm paper, which is coated with a thin plastic film (laminated on both sides). This ensures that the paper does not get soggy and the ice cream does not leak out of the packaging. However, this material is categorised as Multi-Layered Plastic (MLP), which is often non-recyclable due to the difficulties in separating the layers of packaging with different chemical properties. When the packaging becomes waste, it is often soiled by leftover ice-cream, which makes it very difficult to segregate the materials, which is an essential step in recycling. Electricity is required for operating machinery involved in mixing, homogenizing, pasteurizing, freezing, and packaging operations, with an estimated 80 units per 200-litre batch of raw material. The homogenizer stage, which requires a high-power induction motor, consumes the highest amount of electricity in the manufacturing process. Secondly, a chiller is used for maintaining a temperature of minus 30 degrees Celsius in the freezing stage of ice-cream processing. The compressor of this freezer requires a high amount of electricity.
Transport includes inbound logistics for raw material acquisition and outbound logistics for product distribution, averaging INR 500 and INR 400 per batch respectively. Waste generated from the process amounts to approximately 5% of the batch manufactured, which is approximately equal to 10 litres of the product. Any sludge or waste ice cream, is managed by local municipal collection systems, requiring about 1 litre of diesel per batch for waste treatment. Paper and other waste is given to the mainstream municipal solid waste stream, since the quantities are relatively insignificant. There is no reuse or recycling of process ingredients or packaging materials at this stage of production.

**Table 1. Life Cycle Inventory**

| Ingredients / Inputs | Chemical Name | Quantity |
|---|---|---|
| Milk fat | Triacylglycerols (Triglycerides) | 20 Litres |
| Milk solid | Lactose (milk sugar) | 64 Litres |
| Sweetener | Sugar ($C_{12}H_{22}O_{11}$) | 32 Litres |
| Stabilisers | Carboxymethyl Cellulose | 2 Litres |
| Emulsifiers (stabiliser) | Lecithin | 2 Litres |
| Sequestrants | Ethylenediaminetetraacetic acid (EDTA) | 2 Litres |
| Water | Oxidane - 83% (Buffalo Milk) | 78 litres |
| Flavour | Propylene Glycol INS 1520 | 0.4 g |
| Food Colour | | 0.4 g |
| **Total** | | **~200 litres** |

**Table 2. Other Material Consumption over the Life Cycle**

| | | |
|---|---|---|
| **Packaging** | | |
| Packaging (size / material) | Paper / wrapper | 750 ml / Paper |
| Electricity | | |
| **Upstream Transport** | | |
| Transportation (Incoming material) | | Rs 500 (200 Litres batch) |
| **Downstream Transport** | | |
| Transportation (for distribution) | | Rs 400 (200 Litres batch) |
| **Waste Management** | | |
| Waste Transportation | Local Municipality collection | 1 Lit of Diesel |
| Reuse if any | | NA |

### 2.6 Manufacturing Process

The manufacturing process of ice cream involves a series of closely monitored stages that transform raw agricultural inputs into a finished, ready-to-distribute frozen dessert. The process follows an industrial-scale flow, integrating thermal, mechanical, and analytical operations to ensure safety, consistency, and quality of the final product. This section outlines the key stages involved in ice cream production, based on a typical commercial production line.
The process begins with the mixing of primary ingredients. Raw materials include milk, cream, milk powder, whey protein, liquid sugar, and stabilizers. These components are introduced into a large-scale mix tank in precise proportions according to the formulation. This initial blending creates a uniform mixture of fats, proteins, sugars, and emulsifiers that form the base of the ice cream.
To ensure quality and compositional consistency, samples from the mix are analysed using rapid solid and fat determination instruments, such as the CEM SMART 6 and ORACLE analysers. These devices enable non-destructive, near-infrared and microwave drying methods to rapidly quantify the solids and fat content, ensuring that the mix aligns with product specifications and regulatory standards. Once validated, the mixture undergoes pasteurization, a thermal treatment process designed to eliminate pathogenic microorganisms and improve shelf-life. Typically, the mix is heated to around 80–85°C and held for a brief duration. The pasteurized mix is then immediately cooled via a plate heat exchanger, a highly efficient unit that reduces the temperature to refrigeration levels (~4–5°C), minimizing the risk of microbial growth and preserving functional properties of the ingredients.
Following cooling, the mix enters an aging vat, where it is held under refrigeration for a period ranging from 4 to 24 hours. This aging process allows complete hydration of stabilizers, partial crystallization of fat globules, and the development of desirable rheological properties, all of which contribute to improved whipping ability and texture

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 20s, 2025
https://theaspd.com/index.php
in the final product. After aging, the mix is transferred to a freezing unit, where it undergoes either continuous or batch freezing. During this critical stage, the partially frozen mix is aerated (a process known as overrun), forming fine ice crystals and incorporating air into the structure. This step is essential for achieving the desired mouthfeel and reducing density. The mixture exits the freezer at approximately −5°C, still in a semi-solid state. The semi-frozen product is then directed to the packaging line, where it is portioned into retail containers such as paperboard tubs, plastic cups, or single-serve wrappers. This step often utilizes automated fillers and sealers to maintain sanitary conditions and ensure precise volumetric filling. Immediately after packaging, the ice cream undergoes hardening in a blast freezer or tunnel freezer, where it is rapidly cooled to storage temperatures (typically −20°C or lower). This rapid freezing finalizes the microstructure of the product, preventing large ice crystal formation and enhancing texture stability.

Once hardened, the product is moved to cold storage and distribution facilities, where it is maintained under continuous refrigeration until it reaches retailers or consumers. Throughout this process, temperature control is critical; any fluctuations can result in texture degradation or product spoilage. Throughout the production chain, intermittent quality control checks using analytical instruments such as SMART 6 and ORACLE continue to ensure consistency in solids and fat content, particularly after packaging or hardening. The entire process is energy- and resource-intensive, with notable environmental implications, especially in stages such as pasteurization, freezing, hardening, and refrigerated distribution. These stages contribute significantly to the carbon footprint of ice cream and represent potential hotspots for process optimization and sustainability improvements. This manufacturing process has been visually represented in Figure 2.

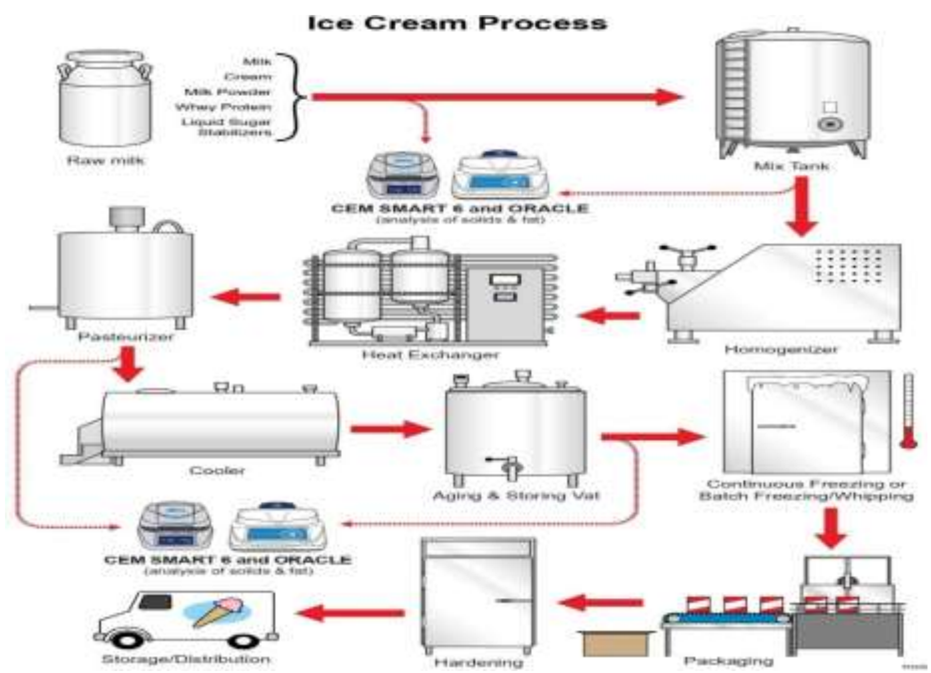


**Fig. 2. Ice cream manufacturing process**

## 3. RESULT AND ANALYSIS

### 3.1 Life Cycle Impact Assessment: Carbon Footprint Analysis

With a cradle-to-grave system boundary, the current study conducts a thorough Life Cycle Impact Assessment (LCIA) of ice cream production. Purchasing raw materials, processing ingredients, manufacturing, packing, shipping, use, and disposal are all included in this. A production batch of 200 liters of buffalo milk, which produces about 100 kg of finished ice cream, serves as the basis for the analysis. This batch size is used to standardize all emission values. In order to identify important emission hotspots and possible intervention areas to lessen the environmental impact of dairy-based frozen desserts, the goal is to evaluate greenhouse gas (GHG) emissions in the form of carbon dioxide equivalents ($CO_2e$) across each life cycle stage. According to calculations, the 100 kg batch of ice cream has a total carbon footprint of 713.91 kg $CO_2e$, or an average of 7.14 kg $CO_2e$ per kilogram of ice cream produced. The global

standard for dairy-based frozen desserts, which normally falls between 1.5 and 3.0 kg $CO_2e$ per kilogram, is far lower than this emission threshold. This disparity emphasizes the necessity of localized optimization in energy use, processing, and raw material supply. The usage of milk solids is the largest contributor to the overall carbon footprint, accounting for about 43% of the total batch emissions, or over 307.30 kg $CO_2e$. Because of the upstream environmental effects of dairy farming, milk solids require a lot of energy and resources. These include the high water demand for animal feed, nitrogen runoff from fertilizers and manure, and methane emissions from enteric fermentation. A further 44.88 kg $CO_2e$ is contributed by the utilization of milk fat. The majority of the embedded emissions in the ice cream product are caused by dairy-based ingredients combined.
The use of power is another significant hotspot. About 80 kilowatt-hours of energy are used every batch throughout the production process, which includes mix heating, pasteurization, homogenization, and shock freezing. According to India's average grid energy emission factors, this amounts to 65.60 kg $CO_2e$. About 9.2% of all emissions come from electricity use alone, underscoring the need of energy efficiency and decarbonization initiatives in manufacturing facilities. Despite being frequently disregarded, water plays a vital role in this analysis since it is a component of buffalo milk, which has an approximate 83% water content. This volume of water contributes an estimated 149.44 kg $CO_2e$ to the batch. Water-laden dairy inputs are handled, transported, and refrigerated, all of which increase the product's carbon intensity. Together, these additional inputs—stabilizers, emulsifiers, sequestrants, flavoring agents, and food coloring—contribute a lesser but still significant portion of emissions. For example, the energy-intensive chemical synthesis of carboxymethyl cellulose (CMC), which is used as a stabilizing agent, results in 34.24 kg $CO_2e$. Sequestrants like EDTA contribute 2.43 kg $CO_2e$, but emulsifiers, especially lecithin, add 3.56 kg $CO_2e$. 1.72 kg $CO_2e$ is produced by the synthetic flavoring agent propylene glycol, and an extra 0.5 kg $CO_2e$ is added by the food coloring agent. Despite their small amount, these inputs are frequently linked to manufacturing routes based on petrochemicals, which considerably increases their emission factors per unit. Another important factor that contributes 45.24 kg $CO_2e$ is packaging. In this instance, 750 ml paper wrappers make up the majority of the packaging material. Even though paper is biodegradable, the pulp production, bleaching, and printing processes nevertheless result in significant emissions. This category is a non-trivial component of the life cycle profile because of the amount of packing material utilized, which accounts for more than 6% of the overall emissions.
Both the outgoing distribution of completed ice cream and the inbound logistics for the acquisition of raw materials are considered transport-related emissions. Based on diesel-equivalent consumption and average emission factors of 3.17 kg $CO_2e$ per litre of diesel, inbound transit contributes 15.85 kg $CO_2e$, while outbound distribution adds 12.68 kg $CO_2e$. Furthermore, 3.17 kg $CO_2e$ are produced by waste collection and disposal, which is handled by municipal services and uses about 1 litre of diesel per batch. Despite being small, this number highlights how crucial it is to incorporate sustainable disposal methods and waste reduction into the overall manufacturing process. The lack of any recycling or reuse components in the system boundaries is a significant finding from the investigation. Reuse-related carbon contribution was 0 because no trash, packaging, or water reuse was found throughout the production or post-consumption stages. This suggests a chance to further lessen the environmental impact by using circular economy strategies like packaging recycling, process water reuse, or by-product valuation. In conclusion, the total carbon footprint of 713.91 kg $CO_2e$ for 100 kg of ice cream—equating to 7.14 kg $CO_2e$ per kilogram of product—is considerably higher than international best practice. The analysis highlights milk solids, electricity consumption, and embedded water in dairy inputs as the top three emission sources.

The carbon emissions from the process inputs have been tabulated in Table 3.

**Table 3. Carbon Footprint of Ingredients**

| Ingredients | Average kgCO2e / kg of product | Quantity converted to Kg | Carbon Footprint (kgCO2e) |
|---|---|---|---|
| Milk fat | 2.4 | 18.7 | 44.88 |
| Milk solid | 9.9 | 31.04 | 307.296 |
| Sweetener | 0.54 | 50.56 | 27.3024 |
| Stabilisers | 10.7 | 3.2 | 34.24 |
| Emulsifiers | 1.73 | 2.06 | 3.5638 |

| | | | |
|---|---|---|---|
| Sequestrants | 1.41 (approx) | 1.72 | 2.4252 |
| Water - Oxidane - 83% | 1.82 | 82.11 | 149.4402 |
| Flavour | 4.17 | 0.412 | 1.71804 |
| Food Colour | 1.25 | 0.4 | 0.5 |
| Packaging (size / material) | 1.56 | 29 | 45.24 |
| Electricity | 0.82 Ke eq / KwH | 80 | 65.6 |
| Transportation | 3.17 Kg eq /Lit | 5 | 15.85 |
| Transportation | 3.17 Kg eq /Lit | 4 | 12.68 |
| Waste Transportation | 3.17 Kg eq /Lit | 1 | 3.17 |
| Reuse if any | | | 0 |
| **Total** | | | **713.90564** |

**The carbon emissions from the process inputs have been visualised in Figure 3.**

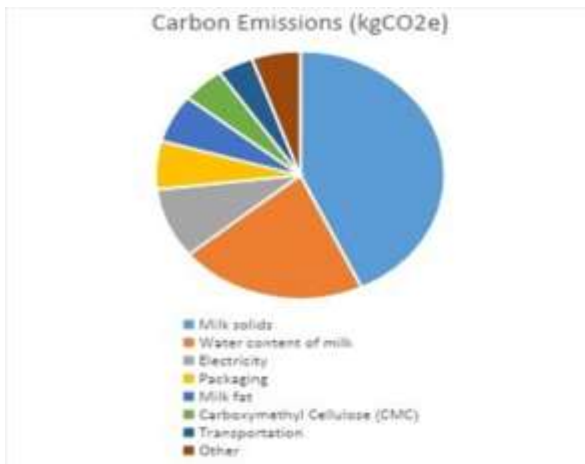


**Fig. 3. Carbon Emissions from Process Inputs**

## RECOMMENDATIONS

To reduce the environmental impacts arising from the manufacturing process, certain mitigation strategies are recommended. Milk can be sourced from low-emission farms. The implementation of sustainable farming techniques such as precision agriculture to optimise inputs, changing the nature of cattle feed to ensure better health and reduce methane emissions from their digestive processes, preferring the use of organic fertilisers over chemical inputs are some farming practices that result in low-emission farms. Such farms can be identified in the vicinity of the manufacturing facility. This also ensures that the emissions from transportation of the raw material are limited. Incorporating renewable energy in the production process may also be an efficient way to reduce the greenhouse gas emissions from electricity consumption. Since dairy farms are a good source of biological wastes, the premises may be conducive to set up a biogas plant, depending on the size of the farm. Replacing synthetic additives with natural alternatives throughout the manufacturing process may also be helpful. Optimizing packaging is another way to reduce the emissions from the product life cycle. Natural, biodegradable and recyclable materials like seaweed packaging can be explored for their efficacy. The promotion of some low-emission SKUs (stock keeping units) with an optimum product weight to packaging ratio can contribute significantly toward reducing the carbon intensity. Similarly, reusable containers in the supply chain may also be explored as a possible method of mitigating waste generation and the resulting GHG emissions from landfills.
This study thus provides a foundational basis for identifying environmental hotspots and formulating targeted interventions to align ice cream production with global sustainability targets.

## CONCLUSION

The calculated average carbon footprint of ice cream production in this study is approximately 7.14 kilograms of $CO_2$-equivalent (kg $CO_2e$) per kilogram of finished product. This value is considerably higher than the global average carbon intensity for similar dairy-based frozen desserts, which typically ranges from 1.5 to 3.0 kg $CO_2e$/kg, depending on the region, energy source, and production practices [FAO, 2010; Poore and Nemecek, 2018]. The elevated carbon footprint observed in the present analysis suggests that the current production system—particularly with respect to raw material inputs, energy consumption, and process design—is significantly more emission-intensive than global benchmarks. This high emission intensity necessitates a comprehensive hotspot analysis to identify the primary sources of greenhouse gas emissions within the life cycle. As identified in the inventory and impact assessment phases, the most emission-intensive contributors include milk solids, electricity use, and embedded water in dairy inputs, followed by packaging materials and transportation emissions. These components cumulatively account for the majority of total $CO_2e$ emissions associated with ice cream production.

In order to achieve carbon footprint levels that are in line with international sustainability standards, it is essential to explore both substitution and reduction strategies. For instance, reducing the quantity of high-impact ingredients such as milk solids, or partially substituting them with plant-based or low-carbon alternatives. Similarly, enhancing energy efficiency or transitioning to renewable energy sources such as solar or biomass can reduce electricity-related emissions. Optimizing transportation logistics, adopting low-emission vehicles, and using biodegradable and recyclable packaging materials are further avenues for improvement. Therefore, targeted interventions across the supply chain—focusing on emission hotspots and leveraging cleaner technologies—are critical for reducing the overall environmental impact of ice cream production and aligning it with global best practices for sustainable food systems.

## Statements and Declarations

### Ethical Approval

"The submitted work is original and not have been published elsewhere in any form or language (partially or in full), unless the new work concerns an expansion of previous work."

### Consent to Participate

"Informed consent was obtained from all individual participants included in the study."

### Consent to Publish

"The authors affirm that human research participants provided informed consent for publication of the research study to the journal."

### Author Contributions

"All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [Pramod S. Doke, Dr. Nivedita Gogate, and Dr. Ramesh Dod]. The first draft of the manuscript was written by [Pramod S. Doke] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript."

### Funding

"The authors declare that no funds, grants, or other support were received during the preparation of this manuscript."

### Competing Interests

"The authors have no relevant financial or non-financial interests to disclose."

### Availability of data and materials

"The authors confirm that the data supporting the findings of this study are available within the article."

### Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## REFERENCES

1. J. Fanzo et al., "Sustainable food systems and nutrition in the 21st century: a report from the 22nd annual Harvard Nutrition Obesity Symposium," Am. J. Clin. Nutr., vol. 115, no. 1, pp. 18–33, Jan. 2022, doi: 10.1093/ajcn/nqab315.
2. K. A. Brown et al., "Moving towards sustainable food systems: A review of Indian food policy budgets," Glob. Food Secur., vol. 28, p. 100462, Mar. 2021, doi: 10.1016/j.gfs.2020.100462.

3. M. V. Chiriacò, N. Galli, M. Santini, and M. C. Rulli, "Deforestation and greenhouse gas emissions could arise when replacing palm oil with other vegetable oils," Sci. Total Environ., vol. 914, p. 169486, Mar. 2024, doi: 10.1016/j.scitotenv.2023.169486.

4. C. Li et al., "Green production and green technology for sustainability: The mediating role of waste reduction and energy use," Heliyon, vol. 9, no. 12, p. e22496, Dec. 2023, doi: 10.1016/j.heliyon.2023.e22496.

5. D. Hariyani, P. Hariyani, S. Mishra, and M. K. Sharma, "A literature review on green supply chain management for sustainable sourcing and distribution," Waste Manag. Bull., vol. 2, no. 4, pp. 231–248, Dec. 2024, doi: 10.1016/j.wmb.2024.11.009.

6. E. Grubert and J. Stokes-Draut, "Mitigation Life Cycle Assessment: Best Practices from LCA of Energy and Water Infrastructure That Incurs Impacts to Mitigate Harm," Energies, vol. 13, no. 4, p. 992, Feb. 2020, doi: 10.3390/en13040992.

7. E. S. Kim, D. K. Lee, and J. Choi, "Evaluating the effectiveness of mitigation measures in environmental impact assessments: A comprehensive review of development projects in Korea," Heliyon, vol. 10, no. 11, p. e31647, Jun. 2024, doi: 10.1016/j.heliyon.2024.e31647.

8. "Managing the Life Cycle to Reduce Environmental Impacts," in Dynamics of Long-Life Assets, Cham: Springer International Publishing, 2017, pp. 93–113. doi: 10.1007/978-3-319-45438-2_6.

9. Z. Hussain, A. Albattat, F. Z. Fakir, and Z. Yi, Eds., Innovative Trends Shaping Food Marketing and Consumption. in Advances in Marketing, Customer Relationship Management, and E-Services. IGI Global, 2025. doi: 10.4018/979-8-3693-8542-5.

10. TIU University et al., "Assessing Customer Trust, Satisfaction, and Loyalty in the Malaysian Ice Cream and Milk Tea Industry," J. Community Dev. Asia, vol. 7, no. 3, pp. 355–373, Sep. 2024, doi: 10.32535/jcda.v7i3.3504.

11. A. Konstantas, L. Stamford, and A. Azapagic, "Environmental impacts of ice cream," J. Clean. Prod., vol. 209, pp. 259–272, Feb. 2019, doi: 10.1016/j.jclepro.2018.10.237.

12. J.-M. Park, J.-H. Koh, and J.-M. Kim, "Predicting Shelf-life of Ice Cream by Accelerated Conditions," Korean J. Food Sci. Anim. Resour., vol. 38, no. 6, pp. 1216–1225, Dec. 2018, doi: 10.5851/kosfa.2018.e55.

13. Harfoush, Z. Fan, L. Goddik, and K. R. Haapala, "A review of ice cream manufacturing process and system improvement strategies," Manuf. Lett., vol. 41, pp. 170–181, Oct. 2024, doi: 10.1016/j.mfglet.2024.09.021.

14. B. K. Sovacool, M. Bazilian, S. Griffiths, J. Kim, A. Foley, and D. Rooney, "Decarbonizing the food and beverages industry: A critical and systematic review of developments, sociotechnical systems and policy options," Renew. Sustain. Energy Rev., vol. 143, p. 110856, Jun. 2021, doi: 10.1016/j.rser.2021.110856.

15. M. Zehetmeier, H. Hoffmann, J. Sauer, G. Hofmann, G. Dorfner, and D. O'Brien, "A dominance analysis of greenhouse gas emissions, beef output and land use of German dairy farms," Agric. Syst., vol. 129, pp. 55–67, Jul. 2014, doi: 10.1016/j.agsy.2014.05.006.

16. M. Wróbel-Jędrzejewska and E. Polak, "Carbon Footprint Analysis of Ice Cream Production," Sustainability, vol. 15, no. 8, p. 6887, Apr. 2023, doi: 10.3390/su15086887.

17. A. Konstantas, L. Stamford, and A. Azapagic, "Environmental impacts of ice cream," J. Clean. Prod., vol. 209, pp. 259–272, Feb. 2019, doi: 10.1016/j.jclepro.2018.10.237.

18. G. Kr. Deshwal and N. R. Panjagari, "Review on metal packaging: materials, forms, food applications, safety and recyclability," J. Food Sci. Technol., vol. 57, no. 7, pp. 2377–2392, Jul. 2020, doi: 10.1007/s13197-019-04172-z.

19. D. R. Vieira, J. L. Calmon, and F. Z. Coelho, "Life cycle assessment (LCA) applied to the manufacturing of common and ecological concrete: A review," Constr. Build. Mater., vol. 124, pp. 656–666, Oct. 2016, doi: 10.1016/j.conbuildmat.2016.07.125.

20. J. Markowska, A. Tyfa, A. Drabent, and A. Stępniak, "The Physicochemical Properties and Melting Behavior of Ice Cream Fortified with Multimineral Preparation from Red Algae," Foods, vol. 12, no. 24, p. 4481, Dec. 2023, doi: 10.3390/foods12244481.

21. S. Wang and Y. Dong, "Applications of Life Cycle Assessment in the Chocolate Industry: A State-of-the-Art Analysis Based on Systematic Review," Foods, vol. 13, no. 6, p. 915, Mar. 2024, doi: 10.3390/foods13060915.