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Freezing point and footprints: a comparative life cycle assessment of standard and high-freezing-point ice cream production

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Cold-chain logistics are a key hotspot in the ice cream industry due to the need for uninterrupted sub-zero refrigeration, about −32 °C to −20 °C for plant storage and −18 °C throughout distribution and retail. This study conducts a cradle to gate comparative life cycle assessment of a standard ice cream and a high-freezing-point (HFP) reformulation mix by reducing sugar from 17% to 10% and substituting it with non-caloric soluble corn fiber. Operationally, the standard mix reached a draw temperature of −6.0 ± 0.2 °C, whereas the HFP mix drew −4.5 ± 0.1 °C, indicating less sub-zero cooling for HFP. Across all midpoint environmental impact categories considered, HFP reduced average impacts by 9–33%; notably, global warming potential (GWP) fell from 2.84 to 2.43 kg CO_2-eq. per kg (−14%), eutrophication from 0.027 to 0.022 kg N-eq. per kg (−16%), and fossil-fuel depletion from 1.919 to 1.744 MJ-surplus per kg (9.1%). Manufacturing, driven by cold storage, was the largest contributor; with warmer draw and storage temperatures, HFP reduced manufacturing's GWP share from 56% to 49%. Ingredient-stage GWP was similar across both mixes, with dairy inputs (skim milk powder, skim milk, cream) as the main upstream hotspots. Impacts were sensitive to storage time and inventories for skim milk powder, skim milk, cream, sugar, and soluble corn fiber, respectively. The impact of packaging was identical at 0.107 kg CO_2-eq. per kg. Uncertainty analysis explored robustness, where HFP results were consistently lower, with variability dominated by storage time and dairy emission factors. These findings indicate that HFP has the potential to deliver immediate, plant-side energy savings and emissions reductions, lowering overall impacts and contributing to Scope 1,2,3 emission reduction. Future work could include a cradle-to-grave assessment covering distribution, retail and end-of-life to capture downstream cold-chain nuances.

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Sustainability spotlight

This work is related to SDG 12, Responsible Consumption and Production, as it seeks to lower the environmental impact of ice cream production and distribution. This is done through the reformulation of ice cream to both contain less sugar and to have a higher freezing point, both of which contribute to a smaller environmental impact when compared to conventional ice cream production. If this new ice cream formulation were to be adopted broadly there is the potential to significant environmental savings.

1 Introduction

The food industry is the largest manufacturing sector globally,[1] generating over $9.45 trillion in annual sales, with an expected compound annual growth (CAGR) rate of 6.34% between 2025 and 2030.[2] As this sector continues to expand, it faces increasing pressure to address sustainability challenges while continuing to meet the growing demand for high-quality and diverse food products.

A key segment within this industry is the global ice cream market, a multibillion-dollar sector driven by consumer preferences for indulgent, flavorful, and refreshing taste. From street-side vendors to supermarket freezers, ice cream holds a timeless status as one of the world's most popular frozen desserts, recognized for its distinctive sensory attributes, particularly its taste, creamy texture, and smooth mouthfeel.[3] Its widespread appeal has inspired a wide array of modes of consumption; some varieties are freshly frozen and served soft in cones or cups, while others are produced, packaged, and distributed in tubs or cartons for long-term storage and retail sale.[4] Ice cream varieties also differ in composition, with

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traditional recipes high in sugar and fat now being adapted to meet the demands of health-conscious and dietary-restricted consumers.[5] In recent years, the frozen dessert market has expanded to include low-fat, low-sugar, and non-dairy ice cream alternatives, catering to health-conscious, dietary-restricted and eco-consumer audiences.[4]

Globally, in 2024, the ice cream market was valued at USD $77.8 billion and is expected to reach USD $79.4 billion in 2025. Long-term projections estimate the market will reach USD $139.7 billion by 2033, driven by a CAGR of 6.7% from 2025 to 2033.[6] In the United States (U.S), the domestic market is expected to reach USD $19.51 billion in 2025 and expand to USD $22.41 billion by 2030, reflecting a CAGR of 2.81% over the forecast period.[7] Among leading brands, Ben & Jerry's led U.S. retail sales in 2023, generating approximately USD $951 million.[8] Beyond established markets, emerging markets, especially China and India, are increasingly shaping industry growth, driven by rising disposable incomes, urbanization, and growing demand for premium and healthier frozen desserts.[9–11] These dynamics are expanding access and accelerating demand in markets that were previously underpenetrated.

However, as ice cream continues to gain global popularity, its environmental impact is drawing greater attention, particularly as sustainability and health concerns increasingly influence both consumer behaviour and industry innovation.[1] The environmental footprint of ice cream spans its entire life cycle, from the agricultural sourcing of raw materials[12] to energy-intensive manufacturing processes and the extensive cold-chain infrastructure needed for storage and distribution. Among these stages, ingredient sourcing plays a significant role in the overall environmental footprint of ice cream. Several studies have assessed the environmental impacts associated with individual ingredients.[5,9,13,14] According to García-Suárez *et al.*,[12] ingredients sourcing accounts for approximately 33% of ice cream's total carbon emissions. Among these, dairy milk is the most significant contributor, accounting for about 17% of emissions, primarily due to methane emissions from enteric fermentation in livestock and the high energy demands of dairy farming.[15] Similarly, Sakyiwaah Sekyere and Hicks[9] found even higher ingredient-related contributions, ranging between 33–70%, with dairy milk derivatives accounting for more than half of the total environmental impacts at the ingredient stage. In addition to dairy milk, other ingredients, such as sugar used as sweeteners and cocoa for flavouring, also contribute significantly to total emissions, further highlighting the importance of ingredient selection in reducing the product's environmental impact.[14,16]

Sugar, in particular, is a key component in ice cream production, typically comprising 12–16% of the product by weight.[17,18] Its inclusion is vital not only for sweetness but also for improving texture, preventing ice crystal formation, and enhancing mouthfeel. However, despite these functional roles of sugar, it presents both health and environmental challenges.[19] Excessive consumption of added sugars has been strongly linked to increased risks of obesity, type 2 diabetes, cardiovascular disease, and dental caries.[19] Environmentally, sugar production is associated with considerable ecological burdens. Most commercial sugar is derived from sugarcane and sugar beets, both of which have notable ecological impact.[20,21] Sugarcane cultivation is particularly water-intensive, requiring an estimated 1500 to 3000 litres of water per kilogram of sugar produced.[20] Moreover, the expansion of sugarcane plantations is often associated with deforestation, especially in tropical regions such as Brazil and Southeast Asia,[21] where vast areas of natural ecosystems are cleared to make way for agricultural production.

While the environmental impacts of ingredient sourcing are substantial, they represent just one part of the broader sustainability challenges associated with ice cream.[12] The production process itself, pasteurization, homogenization and freezing, adds another layer of GHG emissions due to their high energy demands.[5] Perhaps one of the most critical contributors to emissions is the cold chain needed to store and transport ice cream at sub-zero temperatures.[5,12,13] This system not only consumes large amounts of energy but also relies on refrigerants with high global warming potential (GWP), exacerbating the environmental impact of ice cream production.[22–26] A key driver of these refrigeration demands is the high sugar content in traditional ice cream, which lowers its freezing point and necessitates storage at about −32 °C to −20 °C for plant storage and −18 °C throughout distribution and retail to maintain quality and safety. Maintaining this low setpoint raises energy use across the cold chain, demonstrating how formulation, especially sugar content, drives ice cream's environmental footprint from production through distribution. To address these challenges, researchers and manufacturers are exploring the development of HFP ice cream,[17] which involves reformulating the ice cream product to reduce sugar levels or using alternative cryoprotectants that raise the freezing point.[17] Clarke (2012)[17] highlights that sugars and other solutes depress the freezing point of ice cream mixes, determining the amount of unfrozen water and the product's hardness at serving temperature. This behaviour can be explained by colligative properties, in which dissolved solutes reduce the chemical potential of water and lower the temperature at which ice crystals can form.[27–30] In simple terms, the freezing-point depression depends primarily on the number of dissolved molecules rather than their identity, meaning that higher sugar concentrations require lower temperatures to achieve the same degree of freezing. He[17] emphasizes that adjusting the type and amount of these solutes can modify the freezing behaviour, texture, and storage requirements of the final product. This understanding forms the theoretical basis for HFP ice cream, enabling storage at slightly warmer temperatures, thereby lowering cold-chain energy demands and potentially extending shelf life under less stringent refrigeration.

This study conducts a comparative Life Cycle Assessment (LCA) of standard and HFP ice cream, focusing on their environmental impacts from cradle to gate. Using standardized LCA methodology in accordance with ISO 14040/44 guidelines,[31] the analysis evaluates all 10 TRACI midpoint impact categories. The goal is to assess whether HFP ice cream offers a measurable environmental advantage over the standard mix, while also considering the trade-offs associated with formulation changes.

By quantifying the sustainability implications of freezing point modification, this study contributes to the broader discourse on low-carbon food innovation and cold chain optimization. The findings aim to support industry stakeholders, product developers, and sustainability professionals in making informed decisions about environmentally responsible product design in the frozen dessert industry.

2 Methods

This study conducted an LCA to examine the environmental impacts of ice cream production, following the guidelines established by ISO 14040 and 14044.[31] The goal and scope of the study are outlined below, followed by the inventory data and impact assessment methods used.

2.1 Goal and scope of study

The goal of the study was to compare the environmental impacts of standard and HFP ice-cream mixes across the cradle-to-gate system (raw materials and manufacturing, including plant storage) to identify hotspots and improvement opportunities, in accordance with ISO 14040/44.[31] The functional unit was defined as 1 kg of ice cream produced. The scope covers the cradle-to-gate life cycle, including ingredient production, ice cream manufacturing, packaging, hardening and plant storage, as shown in Fig. 1a and b. Distribution, retail storage, home consumption, and end-of-life waste management are not included in this analysis because the study focuses on producer-controllable savings from reformulation and processing, like manufacturing and pre-gate cold-chain efficiency, where actionable improvements are most immediate.

2.2 Inventory data

Life-cycle inventory (LCI) data were obtained from the University of Wisconsin–Madison's Babcock Dairy Plant, a university-scale commercial creamery that serves teaching and research missions while producing ice cream and other dairy products, and from the literature. Background datasets were drawn primarily from ecoinvent 3[32] and Agri-footprint[33] *via* the SimaPro software.[34] Details for each life-cycle stage are provided below.

2.2.1 Raw materials (ingredients). Ice cream samples were prepared using the ingredient formulations summarized in Table 1. The reference standard mix followed the conventional recipe, while the HFP formulation was developed by reducing the total sugar in the standard mix by 7% and replacing it with soluble corn fiber. This adjustment aimed to raise the freezing point and lower the energy demand during hardening and storage without altering the product's functional characteristics.

Table 1 summarizes the standard ice cream mix, consisting primarily of water, cream, nonfat dry milk, dry sucrose, and a stabilizer (Crest 26-2229) and HFP ice cream, where part of the sugar was replaced with soluble corn fiber to reduce sugar content while maintaining desirable texture. Both mixes included key components such as butter fat (BF%) and milk solids-not-fat (MSNF%) in varying proportions, which are essential for defining the structure and quality of the final product. Other reports indicate that standard ice cream typically contains 10–16% milk fat, 9–12% MSNF, 12–16% sucrose, 0.2–0.5% stabilizers, and emulsifiers.[18,35] Milk fat provides creaminess and flavour, MSNF contributes to body and texture, sugar enhances sweetness and controls freezing point, and stabilizers help prevent the formation of large ice crystals.[1] According to U.S. Food and Drug Administration (FDA) guidelines, ice cream must contain at least 10% milk fat, at least 20% total milk solids, and must weigh a minimum of 0.539 kg L^{-1}.[36]

2.2.2 Manufacturing. The formulation process began by mixing all dry and liquid ingredients at room temperature. The resulting mixture was initially heated to 38 °C in a processing tank and then further heated to 87 °C using a high-temperature short-time (HTST) system, followed by high-pressure homogenization. Homogenization was performed in two stages at a total pressure of 19.3 MPa, with 16.4 MPa applied in the first stage and 2.9 MPa in the second stage. This process was identical for both formulations, maintaining a consistent flow rate of 37.85 L min^{-1}. Although the batch sizes differed (1328.77 L for the standard formulation and 393.68 L for the HFP mix), all energy values were normalized to the functional unit (1 kg of product) to ensure comparability by eliminating batch-size effects. After homogenization, the mixture was held in a holding tube for 16 seconds before being cooled to 6 °C. The mix was subsequently aged at 2.2 °C for approximately 24 hours in a refrigerated tank.

Ice cream was produced using a continuous freezer operated at a dasher speed of 295 rpm, 80% overrun, a flow rate of 473 L h^{-1}, and a pump ratio of 1.20. The viscosity was set to 68%, and once the operating conditions stabilized, the ice cream was collected in either 0.473 L or 11.356 L containers. The standard formulation reached a draw temperature of -6.0 ± 0.2 °C, whereas the HFP mix reached -4.5 ± 0.1 °C. All ice cream samples were stored in a walk-in freezer maintained at −32 °C. Data for storage was logged daily (24 hours) and modelled 14 days industry average[18] of on-site storage prior to distribution to reflect producer-controllable savings. Inventory details are summarized in Table 2.

2.2.3 Refrigeration and refrigerant. Ice cream freezing starts with the continuous freezer, which uses a scraped surface heat exchanger to remove heat from the ice cream and lower the temperature. In this system, the ice cream mix is pumped into a cylinder, which is surrounded by a jacket through which refrigerant is pumped. This refrigerant keeps the inner surface of the cylinder at a temperature below the freezing point, causing the ice cream to freeze upon contact. As the mixture flows through the heat exchanger, rotating blades scrape the frozen ice cream off the inner walls, maintaining a smooth texture and preventing build-up. The semi-frozen product exits the continuous freezer with a soft-serve consistency, which makes it ideal for filling into containers in preparation for the next phase.

To monitor energy consumption and system performance during this process, the continuous freezer, operating on three-phase power, was connected to a watt transducer to record. The

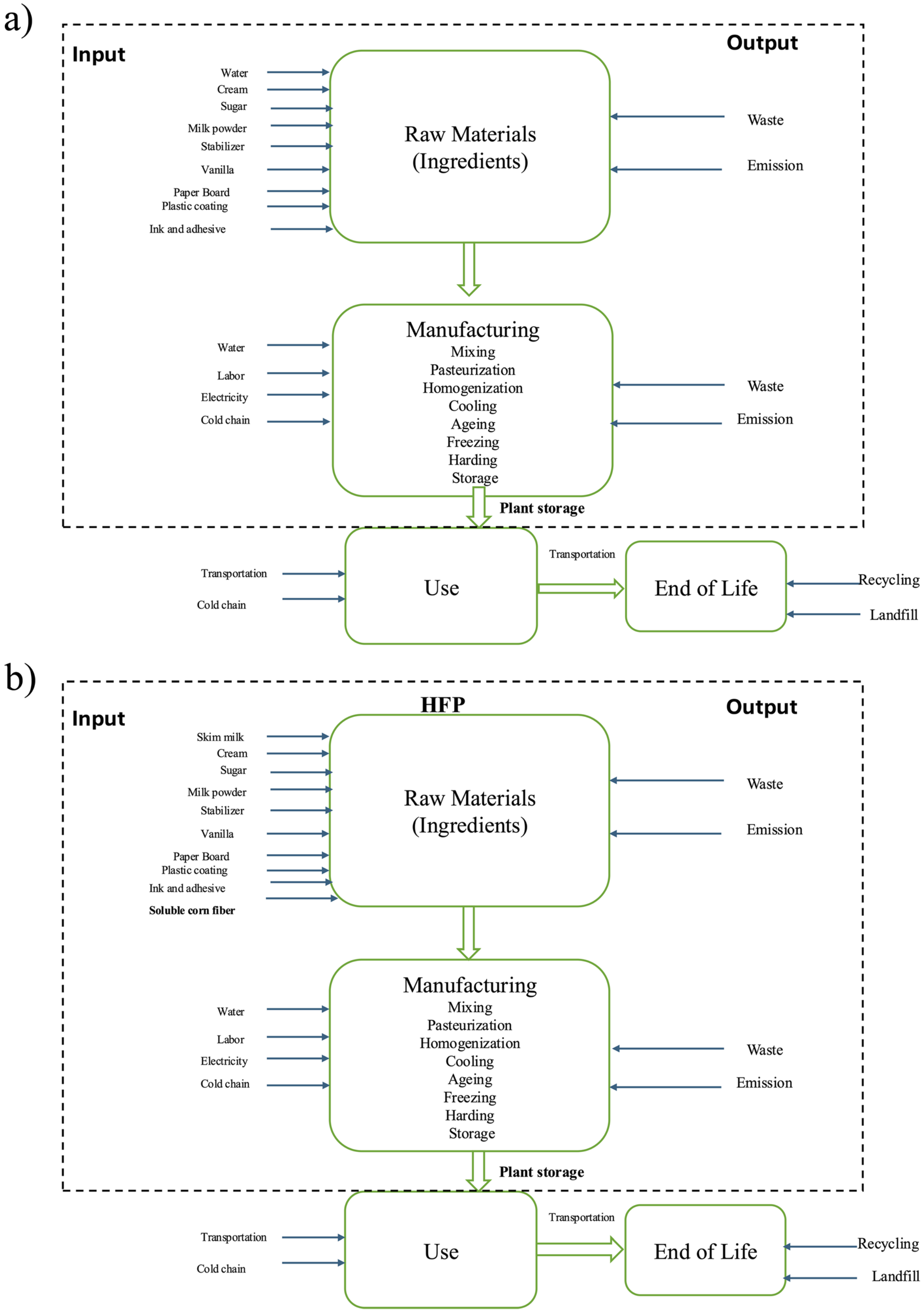

Fig. 1 Scope diagram of (a) standard ice cream mix, (b) HFP ice cream mix.

watt transducer measured the power drawn by the freezer and converted it into a proportional current signal, between 4 and 20 mA. To record this data, a 4–20 mA data logger was used. The watt transducer also outputs electrical pulses, which were measured by a pulse/state data logger. These readings were collected during both the standard and HFP ice cream runs.

Table 1 Ingredients of standard and high freezing point ice cream mix

Ingredient	BF%	MSNF%	Standard per kg	HFP per kg
Water[a]			0.344	
Cream	30.33	6.30	0.394	0.373
Milk powder		95	0.085	0.047
Sugar			0.170	0.096
Stabilizer (Crest 26-2229)			0.004	0.004
Vanilla			0.0017	0.0017
Skim milk				0.375
Soluble corn fiber				0.067

[a] The addition of water to the standard mix process was just an adjustment to achieve the same target texture or consistency, not a change to the product's function. Therefore, its inclusion does not bias comparability between the two mixes.

Following this, the ice cream is transferred to a hardening freezer, where it is held at −32 °C. This ultra-low temperature environment encourages small ice crystal growth, further solidifying the product and improving its shelf life. After approximately 24 hours, the hardened ice cream is moved to a dipping cabinet for long-term storage. The dipping cabinet operates at around −20 °C, allowing the ice cream to soften slightly so it can be served or scooped easily. Instrumentation for the hardening freezer and dipping cabinet included type E thermocouple probes connected to a temperature data logger, which recorded ice cream and air temperatures at one-minute intervals. Power consumption for these freezers was monitored using a plug-loaded data logger, which measured real-time voltage, current, and power. This setup provided a complete picture of the energy and thermal behaviour across all stages of the ice cream freezing and storage process. Refrigerant use during manufacturing was modelled using R-507A. In the freezing stage, refrigerant consumption was 17.59 mg per kg of product per day. During the hardening stage, consumption increased to 174 mg per kg of product per day, with an associated storage period of approximately one day. These values were derived from established literature data[37] to ensure consistency with industry-representative operating conditions.

2.2.4 **Packaging.** The primary packaging consists of pint containers made from paperboard with an internal polyethene (PE) coating to provide moisture and grease resistance. Each pint container weighed 14.52 g and contained approximately 10% PE by mass.[38] The lid weighed 7.34 g and is made of polypropylene (PP). Using the ice cream density of 1.114 kg L^{-1}, the packaging materials per 1 kg of ice cream are calculated as follows: 2.755 g of PE from the paperboard coating, 27.54 g of paperboard, and 13.92 g of PP from the lid. The secondary packaging, consisting of cardboard and adhesive materials used for transport and storage, weighs 219.78 g and holds 12 pint-sized containers. It is assumed that raw milk and sugar are delivered to the Babcock Dairy in bulk; therefore, their packaging impacts are excluded from this assessment. Packaging for the remaining ingredients is also not considered, as their quantities per functional unit are minimal and unlikely to contribute significantly to the overall environmental impact.

2.3 Impact assessment

The environmental impacts were estimated using the TRACI 2.1 [39] method, developed by the U.S. Environmental Protection Agency (EPA). The midpoint categories considered were Ozone Depletion Potential (ODP), Global Warming Potential (GWP, 100 years), Smog Formation Potential (SFP), Acidification Potential (AP), Eutrophication Potential (EP), Human Health Carcinogenic (HH-C), Human Health Non-carcinogenic (HH-NC), Respiratory Effects (RE, particulate matter formation), Ecotoxicity Potential (ETP), and Fossil Fuel Depletion (FFD). These categories are relevant for this study as they reflect both agricultural ingredient impacts and the energy-intensive freezing and storage processes that differ between standard and high-freezing-point ice cream. TRACI 2.1 [39] is a U.S.-centric midpoint life cycle impact assessment tool, designed to reflect regional conditions, making it appropriate for studies based on U.S. production data and energy systems.

2.4 Uncertainty analysis

The robustness of the study results was assessed using a Monte Carlo uncertainty analysis performed in SimaPro. A total of 1000 iterations were conducted to account for variability in key input parameters and to quantify the propagation of uncertainty throughout the life cycle model. Each run sampled parameter values from their respective probability distributions, reflecting

Table 2 Manufacturing process for ice cream production[a]

Process	Electricity (kWh) standard mix per kg of ice cream	Electricity (kWh) HFP per kg of ice cream
Mixing	0.00756	0.00756
Pasteurization	0.00792	0.00792
Homogenization	0.00567	0.00567
Cooling	0.0151	0.0151
Ageing	0.048	0.048
Freezing	0.00367	0.00299
Hardening	0.0155	0.0164
Storage	0.1826/day	0.1337/day

[a] Electricity consumption values were calculated based on process-specific energy use for each manufacturing stage, normalized per kilogram of ice cream mix (standard and HFP formulations). Storage energy use is expressed per day.

uncertainty in background data, inventory flows, and process emissions. The parameters most likely to influence the results, such as ingredient quantities, energy use, and refrigerant losses, were varied within their defined ranges. The outcomes were expressed as 95% confidence intervals (97.5th and 2.5th percentiles) for each impact category, allowing for statistical comparison between the standard and HFP ice cream formulations.

2.5 Sensitivity

A 25% sensitivity analysis was conducted for each individual input parameter to evaluate the influence of data variability on the overall life cycle results. This approach allowed for the identification of parameters that most significantly affected the environmental performance of both the standard and HFP ice cream formulations. By systematically varying each parameter while holding others constant, the sensitivity analysis provided insights into the relative contribution and stability of model assumptions, thereby supporting the robustness and transparency of the LCIA.

3 Results

This section presents the environmental impacts of both standard and HFP ice cream, highlighting the differences between the two. The impact categories are examined in detail. The analysis is followed by a discussion and an uncertainty analysis to assess the robustness of the results.

3.1 Environmental impact of ice cream

Fig. 2 compares the overall environmental impacts of the standard and HFP mixes in terms of GWP (A), eutrophication potential (B), and fossil fuel depletion (C). The HFP reduced all impact categories by 9–33% relative to the standard. For indicators shown with uncertainty bars, the HFP exhibited a comparatively lower mean averages than the standard mix. For example, GWP declined from 2.84 kg CO_2-eq. per kg (97.5% CI: 2.08–3.83) for the standard mix to 2.43 kg CO_2-eq. per kg (97.5% CI: 1.86–3.15) for HFP, a 14.1% reduction. The manufacturing stage was the largest contributor to GWP, accounting for 56.1% of the total for the standard mix and 48.5% for HFP, driven primarily by freezer storage.

Similarly, for eutrophication, the standard mix was 0.02668 kg N-eq. per kg (97.5% CI: 0.010–0.071), compared with 0.02223 kg N-eq. per kg for HFP (97.5% CI: 0.008–0.053), a 16.7% decrease. Likewise, fossil-fuel depletion fell from 1.919 MJ-surplus per kg (97.5% CI: 1.40–2.57) for the standard to 1.744 MJ-surplus per kg (97.5% CI: 1.36–2.20), a 9.1% reduction for the HFP. Although the HFP mix showed lower mean impacts across all indicators, the overlapping error bars indicate that the difference between the two formulations is not statistically significant. Therefore, it cannot be conclusively stated that one performs better than the other. The full set of the impact category plots is provided in the SI.

Building on Fig. 2 and 3 breaks down the total impacts by ingredient contributions of GWP (A), eutrophication potential (B), and fossil fuel depletion (C). For GWP, the ingredient stage contributed 1.134 kg CO_2-eq. per kg for the standard mix, accounting for about 40.1% of the net and 1.143 kg CO_2-eq. per kg for the HFP mix, accounting for about 47.1%, a 0.8% increase for the HFP. This difference reflects a compositional shift: compared with the standard formulation, HFP reduces skimmed-milk powder and sugar and adds skim milk and soluble corn fiber, with cream remaining similar. Although HFP uses more dairy ingredients, the offsetting of reducing the impacts of sugar leaves the ingredient-stage GWP essentially unchanged. For eutrophication, the ingredient stage contributed 0.00937 kg N-eq. per kg of the total impact for the standard

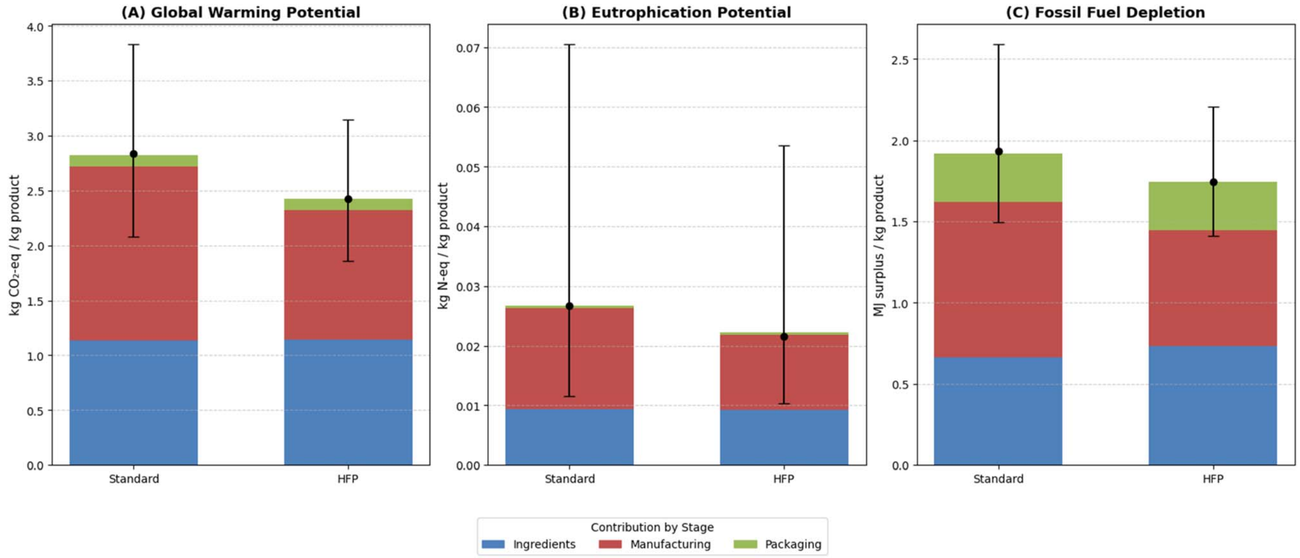

Fig. 2 Overall environmental impact of standard and HFP ice cream production, considering GW (A), eutrophication potential (B), and fossil fuel depletion (C).

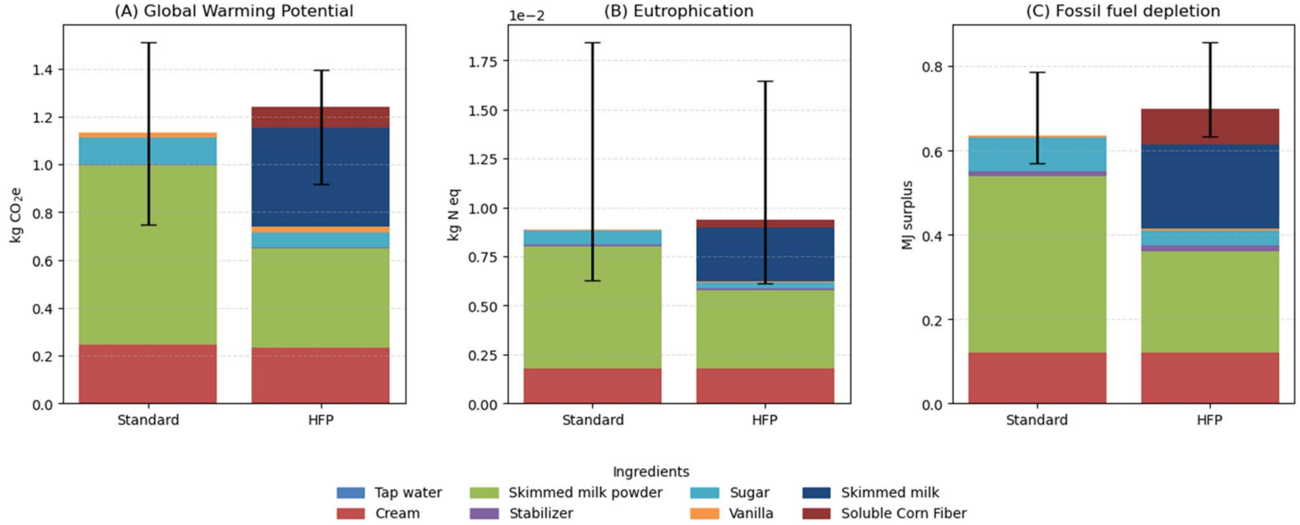

Fig. 3 Ingredient-stage contributions to the environmental impacts of standard and HFP ice cream: GWP (A), eutrophication (B), and fossil fuel depletion (C).

mix and 0.00926 kg N-eq. per kg for HFP, leading to a 1.2% reduction, as a share of the indicator, ingredients rose from 35.1% for the standard to 41.7% for the HFP. Similarly, for fossil-fuel depletion, the ingredient subtotal increased from 0.6615 to 0.7338 MJ-surplus per kg (+10.9%) for the HFP, driven by added skim milk and soluble corn fiber, outweighing prior reductions in skim-milk powder and sugar. Although the 97.5% confidence intervals show variability in the stacked totals, the pattern is clear: relative to the standard formulation, HFP reduces contributions from skim-milk powder and sugar, increases those from skim milk and soluble corn fiber, and thereby leaves ingredient-level GWP roughly unchanged, eutrophication nearly unchanged, and fossil-fuel depletion slightly higher as a share of ingredients. Hence, the overall reductions observed for HFP are driven primarily by manufacturing-stage savings and not by shifts in ingredient impacts, although HFP had a higher impact in the ingredients stage compared to the standard mix.

In Fig. 4, the GWP of the manufacturing stage contributed 1.583 kg CO_2-eq. per kg in the standard mix and 1.176 kg CO_2-eq. per kg in the HFP mix, a 25.7% decrease, representing 56.1% and 48.5% of the respective totals. Within manufacturing, storage dominates: 1.521 *vs.* 1.114 kg CO_2-eq. per kg, equating to 96.1% and 94.8% of the manufacturing burden for the standard and HFP mixes, respectively. The reduction in storage energy for HFP is mechanistically linked to the thermodynamic behaviour of the refrigeration system.[40] Ice cream formulations with higher sugar content require lower storage temperatures because dissolved sugars depress the freezing point of the mix.[17,27] By reducing sugar and increasing the freezing point, the HFP formulation allows the product to remain stable at slightly warmer temperatures. In vapor-compression

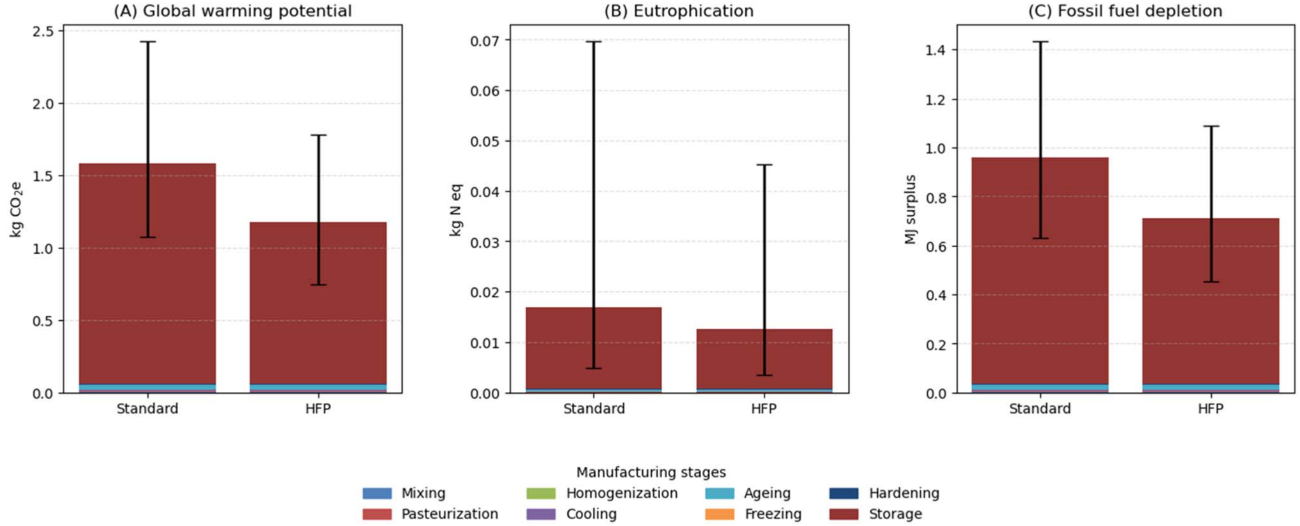

Fig. 4 Manufacturing-stage contributions to the environmental impacts of standard and HFP ice cream (excluding ingredients): GWP (A), eutrophication (B), and fossil fuel depletion (C).

refrigeration systems, warmer evaporator temperatures reduce the temperature lift between the evaporator and condenser, which improves the coefficient of performance and lowers compressor duty cycles, thereby reducing electricity demand during storage.[40]

The remaining unit operations are small, each contributing less than 2% of manufacturing GWP: ageing 1.8%, cooling 0.6%, hardening 0.6%, pasteurization 0.3%, mixing 0.3%, and homogenization 0.2% in the standard mix, with similar shares for HFP.

For eutrophication, the manufacturing subtotal declines from 0.01691 to 0.01256 kg N-eq. per kg (−25.7%), corresponding to 63.4% (standard) and 56.5% (HFP) of the total indicator. Again, storage was the key hotspot, contributing about 0.01625 for the standard and 0.01190 kg N-eq. per kg for the HFP, accounting for about 96.1% and 94.8% of manufacturing eutrophication, respectively, with all other stages individually contributing less than 2%. Likewise, for fossil fuel depletion, the manufacturing subtotal fell from 0.960 to 0.713 MJ-surplus per kg (−25.7%), representing 50.1% (standard) and 40.9% (HFP) of the totals. Storage again dominates, 0.923 and 0.676 MJ-surplus per kg, which is 96.1% and 94.8% of the manufacturing burden, while the remaining stages each contribute less than 2%. The error bars reflect the indicator-level uncertainty reported in Fig. 2, whereas the stacked bars in Fig. 4 clarify that, across indicators and formulations, Storage overwhelmingly drives manufacturing impacts, with all other unit operations contributing only marginal shares.

Beyond the three primary indicators, all other TRACI categories also decline for the HFP mix. Ozone depletion fell by 11.3% (from 1.26×10^{-7} for the standard mix to 1.12×10^{-7} kg CFC-11 eq. for the HFP mix). The manufacturing stage was the largest contributor (standard 5.87×10^{-8}; HFP 4.36×10^{-8}), with storage as the hotspot; ingredient totals are similar (6.05×10^{-8} *vs.* 6.14×10^{-8}), dominated by skimmed-milk powder (SMP) for the standard mix and skim milk for HFP mix. Smog decreases by 14.6% (from 0.1181 for the standard to 0.1008 kg O_3-eq. for the HFP); contributions are split between ingredients (standard 0.0590; HFP 0.0552) and manufacturing, where storage dominates (from 0.0502 to 0.0367). Within the ingredients stage, SMP, sugar, and cream are the principal sources. Acidification drops by 11.9% (from 0.01225 to 0.01079 kg SO_2-eq.). Here, storage again accounts for nearly all of the manufacturing burden (standard 0.00542; HFP 0.00397), while the ingredient side is driven by SMP, sugar, and cream (totals 0.00612 *vs.* 0.00611). Carcinogenics declines by 32.9% (8.22×10^{-10} to 5.52×10^{-10} CTUh per kg) and is ingredients-dominated: sugar is the major contributor (standard 6.58×10^{-10}; HFP 3.72×10^{-10}), with smaller shares from SMP; manufacturing and packaging are minor. Non-carcinogenics fell by 24.3% (8.57×10^{-9} to 6.48×10^{-9} CTUh per kg); the ingredients stage is again the largest (5.03×10^{-9} to 3.79×10^{-9}), led by sugar and SMP, while manufacturing contributes the remainder (3.28×10^{-9} for the standard and 2.44×10^{-9} for the HFP). Respiratory effects decrease by 21.0% (from 0.00918 to 0.00725 kg $PM_{2.5}$-eq.) and are manufacturing-dominated (0.00698 for the standard and 0.00519 for the HFP), almost entirely from storage (0.00671 for the standard and 0.00492 for the HFP); ingredients are smaller (0.00212 to 0.00198). Ecotoxicity drops by 22% (from 6.797 to 5.300 CTUe) and is ingredients-dominated: sugar was the largest source (standard 3.094; HFP 1.747), with additional contributions from SMP (1.167 for the standard and 0.645 for the HFP), soluble corn fiber (0.403 in HFP), and cream (from 0.386 to 0.366). Packaging remains essentially unchanged between mixes and is a minor share in all categories.

4 Discussion

Accounting for two weeks (14 days) of plant storage as an industry average, the GWP for 1 kg of ice cream was 2.84 kg CO_2-eq. per kg for the standard formulation and 2.43 kg CO_2-eq. per kg for HFP, which delivers a 14.1% reduction in the net impact. The manufacturing stage, dominated by on-site frozen storage, was the largest source of emissions, 56.1% of the total for the standard mix and 48.5% for the HFP, with the ingredients stage contributing 40.1% and 47.1%, respectively; packaging remains a small amount, about 4%, and remained identical for both mixes. Table 3 presents a comparison of reported ice cream LCA results with those obtain in this study.

Relative to literature spanning 0.3–4 kg CO_2-eq. per kg,[5,12,13,41–43] which varies by boundaries, allocation methods, and product formulation or recipe, our estimates are mid-range and notably sensitive to storage assumptions. The main novelty is the HFP-driven operational saving: manufacturing (dominated by storage) drops from 56.1% to 48.5% of total GWP, while ingredient GWP remains broadly unchanged. For instance, Garcia-Suarez *et al.*[12] found that retail refrigeration, the downstream analogue to our on-site storage, was the largest contributor of about 46% in their cradle-to-grave assessment, followed by ingredients (33%), roughly half of which were dairy. In our cradle-to-gate analysis, the cold chain still dominates, but the hotspot appears upstream at the factory because retail and household stages were out of scope. This was intentional as we targeted manufacturer-controllable savings where operating conditions can be set and verified, and where storage typically runs colder at the plant (−20 °C to −35 °C) than in retail or homes (−18 °C). Under these conditions, HFP reformulation delivers a clear, practical GWP reduction of 14.1% by lowering storage energy, while leaving ingredient-stage emissions essentially unchanged. Thus, HFP provides a direct operational lever that complements, rather than replaces, ingredient-sourcing strategies highlighted in prior work. Similarly, Konstantas *et al.*[5] reported 3.66–3.94 kg CO_2-eq. per kg cradle to grave for dairy ice cream and found that the ingredients stage contributed 42–63% of the net GWP, with dairy products being the dominant contributors. In our cradle-to-gate study, the GWP of the standard mix was 2.84 kg CO_2-eq. per kg with the ingredients stage contributing about 40% of the net GWP and 2.43 kg CO_2-eq. per kg for HFP, contributing about 47%, squarely within the Konstantas range. Consistent with their conclusion, dairy remains the principal driver within the ingredients stage, accounting for about 35.2% of total GWP in the standard and

Table 3 Comparison of reported ice-cream LCA results across studies

Study	System boundry	Product type	Functional unit	GWP (kg Co_2-eq. per kg)	Main hotspot
Wróbel-Jędrzejewska (2023)[41]	Cradle to gate	Dairy ice cream	1 kg of ice cream	0.34–0.38	Ingredients (Inulin)
Konstantas *et al.* (2006)[5]	Cradle to grave	Dairy ice cream	1 kg of ice cream	3.66–3.94	Ingredients (dairy)
Foster *et al.* (2006)[13]	Cradle to gate	Dairy ice cream	1 kg of ice cream	0.97	Ingredients
Scottish Gorvement (2011)[42]	Cradle to grave	Dairy ice cream	1 kg of ice cream	4.0	Ingredients (diary)
Garcia Suarez *et al.* (2008)[12]	Cradle to grave	Dairy ice cream	1 kg of ice cream	3.36	Cold chain/Retail refrigeration
Doke, P. S., & Gogate, N. (2025)[44]	Cradle to gate	Dairy ice cream	1 kg of ice cream	7.14	Ingredients dairy
Suksatit *et al.* (2025)[43]	Cradle to gate	Coconut ice cream	1 kg of ice cream	1.17	Coconut waste disposal
This study (HFP)	Cradle to gate	Dairy ice cream	1 kg of ice cream	2.43	Plant storage refrigeration
This study (standard)	Cradle to gate	Dairy ice cream	1 kg of ice cream	2.84	Plant storage refrigeration

39.8% in HFP, dominated by skimmed-milk powder, skim milk, and cream.

Sugar was the next ingredient-stage hotspot after dairy in the standard mix, motivating the freeze-point strategy. The freeze-point strategy works by reducing dissolved sugars, which are the main freezing-point depressants in ice-cream mix. We reduced the total sugar in the standard mix by 7%, thereby raising the mix's freezing point (*i.e.*, freezing at a warmer temperature), which in turn reduced the draw temperature and energy required for hardening and storage. To preserve bulk solids, sweetness, and texture, a portion of the removed sugar was replaced with soluble corn fiber (SCF). This substitution cuts sugar's GWP from 0.109 to 0.061 kg CO_2-eq. per kg, while SCF adds 0.086 kg CO_2-eq. per kg, leaving the ingredient-stage GWP roughly neutral. The key benefit is operational: the higher freezing point enables warmer storage, which drives the overall 14.1% GWP reduction. However, SCF slightly increases fossil-fuel depletion at the ingredient stage, while eutrophication is essentially unchanged; overall, net benefits arise because manufacturing, especially storage, drops substantially. In sum, our results reaffirm Konstantas *et al.*'s[5] emphasis on dairy dominance in the ingredient stage and show that the HFP approach provides a manufacturer-controllable lever, reducing storage emissions without materially increasing ingredient-stage GWP, albeit with a modest reallocation of impacts within the ingredient mix.

In the same vein, the Scottish Government's cradle-to-grave assessment[42] places an even greater share, about 70% of impacts in ingredients and highlights milk production and processing, enteric methane, feed and manure management, and dairy operations, as the principal sources, highlighting the complementary roles of ingredient sourcing and operational changes. In our cradle-to-gate assessment, ingredients remain important, but a larger share was assigned to manufacturing and storage because plant frozen storage was modelled explicitly. These differences reflect scope and assumption choices, including how cold-chain energy is treated, data vintage, allocation for dairy co-products, and storage times. Mechanistically, both studies point to the same levers: dairy products in the ingredient block and refrigeration across the cold chain are the hot spots in ice cream production. Our contribution is to show that a freeze-point reformulation can reduce storage energy without materially increasing ingredient-stage burdens. Collectively, improved dairy sourcing and freeze-point reformulation offer complementary, practical routes to larger reductions.

In addition, Foster *et al.*[13] reported a footprint of about 0.97 kg CO_2-eq. per kg cradle to gate, well below ours. The difference is readily explained by study design: a narrower system boundary and shorter cold-chain assumptions (*e.g.*, shorter storage), both of which lower the total. Similarly, Wróbel-Jędrzejewska[41] reported even lower values (0.34–0.38 kg CO_2-eq. per kg for cradle to gate), which are typical of very restrictive boundaries. In general, these studies show how results can shift when the cold chain is truncated or treated leniently and when allocation and data vintage differ. In contrast, our cradle-to-gate model explicitly includes plant hardening and freezer storage, producing higher, but more storage-sensitive, totals and highlighting freezing-point reformulation as a practical lever to reduce operational load.

At the other end of the range, Doke and Gogate[44] reported a substantially higher footprint of approximately 7.14 kg CO_2-eq. per kg under a cradle-to-gate boundary, far above the values obtained in the present study. This difference is likely driven by methodological choices and inventory assumptions, particularly the very high contributions assigned to milk solids, embedded water in dairy inputs, and electricity use under an Indian grid mix. Their study identifies milk solids as the dominant hotspot, followed by electricity and packaging, and also emphasizes refrigeration as a persistent source of emissions across the supply chain. In contrast, our cradle-to-gate analysis reports lower totals (2.84 kg CO_2-eq. per kg for the standard mix and 2.43 kg CO_2-eq. per kg for HFP) that are more consistent with prior ice-cream LCAs and are explicitly sensitive to plant storage assumptions. More importantly, while Doke and Gogate primarily identify hotspots within a conventional production system, our study goes further by evaluating freezing-point reformulation as a practical mitigation strategy, showing that formulation changes can reduce storage energy demand and lower overall impacts without materially increasing ingredient-stage GWP.

Suksatit *et al.*,[43] on the other hand, examined a plant-based coconut ice cream and reported a 1.17 kg CO_2-eq. per kg under a cradle-to-gate scope, with impacts concentrated in crop cultivation, processing, and waste handling rather than dairy. The footprint sits below our dairy mixes, which is consistent with the absence of raw-milk burdens and typically lower methane and feed-related emissions in plant systems. The comparison highlights scope- and recipe-dependence: ingredient hotspots shift from dairy (cream, skim milk powder and skim milk) in our mixes to agricultural inputs for coconut, while the operational cold-chain lever we highlight, raising the freezing point, remains relevant to both product types because storage energy is a shared driver. In practice, producers pursuing plant-based lines can pair ingredient choices with the same freeze-point and storage-efficiency measures to compound gains; for dairy products, ingredient sourcing (lower-emission milk powders and cream) and freeze-point reformulation act as complementary pathways.

Lastly, the packaging stage contributed only a small share of the footprint. In our cradle-to-gate results, packaging impact was the same in both mixes: 0.107 kg CO_2-eq. per kg of ice cream, but accounts for 3.8% of net GWP in the standard mix and 4.4% in the HFP mix; the differing percentages simply reflect the lower total footprint of the HFP mix. This aligns with Garcia-Suarez *et al.*[12] for Ben & Jerry's, where primary product packaging was reported at roughly 4% of the total, and rising toward about 10% when broader upstream and distribution packaging is included. In practice, packaging changes can deliver incremental gains, but the dominant levers remain refrigeration across the cold chain and dairy-driven ingredients, areas directly addressed by the HFP reformulation.

Translating these findings to a U.S. scale suggests a material, near-term win for manufacturers. The U.S. produced about 1.3 billion gallons (4.92 billion liters) of ice cream in 2023 (regular and low-fat).[45] Using the federal weight minimum of 4.5 lb per gallon (2.04 kg per gal) for finished ice cream,[36] the output is roughly 2.65 billion kg of product. Applying the measured 0.41 kg CO_2-eq. per kg reduction from adopting an HFP mix (2.84 to 2.43 kg CO_2-eq. per kg) yields an estimated 1.09 million metric tons of CO_2-eq. avoided per year if HFP were implemented broadly across U.S. production. Put differently: a modest recipe change that allows a warmer draw and storage set-point can abate 1 $MtCO_2$-eq. annually while preserving product quality, delivering immediate, plant-side reductions that are fully within manufacturers' operational control.

While changing the mix to an HFP formulation potentially offers substantial factory-level emissions reductions, the full climate benefit depends on the broader cold chain, especially distribution, grocery storage, and retail freezers. These supply chain segments are optimized for current industry standards, with set-points designed for foods requiring standard freezing temperatures. Widespread market adoption of HFP ice cream could, in principle, justify industry-wide adjustments, raising freezer set-points by several degrees, thereby cutting refrigeration energy use and associated greenhouse gas emissions at scale. However, such a shift is only practical if a critical mass of products is reformulated. Without sufficient market penetration, grocery stores and distributors would still need to cater to conventional ice cream products, limiting any system-wide temperature change and associated energy savings. For this reason, collaboration among major brands, retailers, and equipment operators would be needed to realize the full "cold chain" decarbonization potential of advances in ice cream formulation.

Beyond emissions, the same reformulation potentially unlocks energy and cost savings by reducing compressor workload and shortening hardening and storage time, benefits that flow straight to the utility bill and can be verified with metered kWh. Because the intervention is executed inside the factory fence line, it supports progress toward Scope 1and 2 (and a portion of Scope 3) targets with clear attribution for Environmental, Social, and Governance reporting (ESG). Finally, HFP is portfolio-agnostic: the freeze-point logic also stacks with plant-based ice creams, compounding gains in categories that already avoid raw-milk burdens, while dairy can pair HFP with lower-emission milk powder and cream sourcing for higher reductions. Overall, U.S. industry adoption of HFP represents a practical, scalable lever that cuts climate impact now, trims energy cost, and complements longer-horizon ingredient and farm-level strategies.

Finally, these findings should be read as plant-level, cradle-to-gate evidence of directional opportunity rather than a full life-cycle verdict. Absolute impact magnitudes may shift with alternative dairy allocations (mass *vs.* fat, protein *vs.* economic), regional grid mixes, refrigerant use, storage time beyond the factory, and set-point policies across distribution, retail, and homes. Likewise, comparative benefits of the HFP mix presume functional equivalence (texture, scoop ability, sensory acceptance) under realistic cold-chain conditions; if quality drift increases losses, net benefits could narrow or reverse. Uncertainty remains around the setpoint-energy response (kWh per kg per day) under varying loads, door openings, frosting/defrost cycles, and ambient conditions, and around upstream variability in dairy and soluble-corn-fiber supply chains. Readers should therefore treat the reported direction and order of magnitude as robust within the tested ranges, while avoiding cross-context generalization.

5 Conclusions

This cradle-to-gate LCA compared a standard ice-cream mix with a HFP reformulation designed to lower cold-chain energy. Across all ten TRACI categories, the HFP mix reduced impacts on average; three headline indicators quantify the gain: GWP fell from 2.84 to 2.43 kg CO_2-eq. per kg (−14.1%), eutrophication from 0.02668 to 0.02223 kg N-eq. per /kg (−16.7%), and fossil-fuel depletion from 1.919 to 1.744 MJ-surplus per kg (−9.1%). Manufacturing, dominated by on-site frozen storage, was the largest source and declined from 1.583 to 1.176 kg CO_2-eq. per kg (56.1% to 48.5% of total); within that, storage dropped from 1.521 to 1.114 kg CO_2-eq. per kg. Ingredients accounted for 40.1% (standard) and 47.1% (HFP) with dairy inputs (skim milk powder, skim milk, cream) as the principal drivers. The reformulation reduced the total sugar in the standard by about and replaced part of it with soluble corn fiber, leaving ingredient-stage GWP roughly unchanged while enabling the storage energy savings that drive the overall reduction. The main trade-off was a marginal increase in ingredient-stage fossil-fuel depletion; eutrophication remained essentially unchanged at the ingredient level. Packaging was minor and identical across mixes (0.107 kg CO_2-eq. per kg; 3.8%

standard, 4.4% HFP). These findings also suggest that formulation-based mitigation strategies can complement traditional ingredient sourcing approaches for reducing the environmental footprint of ice cream. While previous studies have focused primarily on lowering impacts through improved dairy sourcing or alternative ingredients, this study demonstrates that modifying formulation to alter physicochemical properties such as freezing-point behavior can reduce refrigeration energy demand without substantially increasing ingredient-stage impacts. As such, formulation design represents a practical lever that manufacturers can deploy alongside ingredient sourcing and process efficiency improvements to reduce the climate impacts of frozen foods.

Future studies should extend the system boundary from cradle-to-gate to cradle-to-grave, incorporating distribution, retail, household refrigeration, and end-of-life processes. Because the HFP formulation allows warmer storage setpoints, it could yield compounded savings throughout the cold chain, quantifying these cumulative effects would provide a more complete understanding of total life cycle benefits. Efforts to further reduce the main hotspot, storage energy, should focus on shorter storage durations, improved refrigeration efficiency, and the use of low-carbon electricity. Combining these operational strategies with the HFP mix's warmer operating temperatures could amplify emissions reductions and create lasting energy efficiencies.

Additionally, reformulation opportunities should continue to be explored. Ongoing freeze-point optimization through targeted sugar reduction and testing of alternative bulking agents can help maintain desirable texture while lowering environmental impacts. Similarly, reducing the dairy intensity of formulations, through low-impact dairy sourcing or by evaluating plant-based alternatives such as oat, soy, or almond, could further decrease greenhouse gas emissions, water use, and land demand while maintaining product performance.

Finally, it is important to ensure that sustainability improvements do not come at the cost of product quality. The HFP mix's performance at warmer storage temperatures should be tested to confirm that it maintains the same texture, overrun, melting behaviour, and sensory quality as the standard mix. These tests will help verify that the energy savings achieved through higher storage temperatures do not compromise consumer experience. By combining environmental and quality assessments, the HFP formulation can be shown to be both scientifically sound and practical for large-scale commercial use.

Author contributions

Faustina Sakyiwaah Sekyere and Andrea Hicks jointly contributed to the conception and design of the study *et al.*, of the study, while Scott A. Rankin and Douglas T. Reindl provided inventory data for the study.

Conflicts of interest

The authors declare that they have no conflicts of interest.

Data availability

All data supporting the findings of this study are included within the article.

Supplementary information (SI): detailed ingredient formulations for both standard and high-freezing-point (HFP) ice cream mixes, figures illustrating overall, ingredient-stage, and manufacturing-stage environmental impacts, and tables reporting uncertainty analysis results across all impact categories. See DOI: https://doi.org/10.1039/d5fb00951k.

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