

GATE-TO-GATE LIFE CYCLE ASSESSMENT OF SMALL-SCALE YOGURT PRODUCTION IN BOGOR, INDONESIA

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Abstract

This study presents a gate-to-gate Life Cycle Assessment (LCA) of small-scale yogurt production in Bogor, Indonesia, covering the production stage from raw material input to final packaged yogurt. The foreground system boundary excludes distribution, consumption, and end-of-life stages, while purchased raw materials (particularly raw milk) are represented using cradle-to-gate secondary datasets that inherently embed upstream agricultural burdens; this scope distinction is clarified explicitly in this revision. The assessment follows ISO 14040 and ISO 14044 standards and was conducted using openLCA software with the ReCiPe 2016 Midpoint (H) method, with a functional unit of 29.158 kg of packaged yogurt (one production batch). The Life Cycle Inventory (LCI) results show that the primary inputs include cow milk (27.184 kg), skimmed milk powder (2.000 kg), sugar (1.000 kg), microbial starter (0.030 kg), water (2.000 kg), and packaging materials (0.624 kg), with wastewater (2.150 kg) and organic residue (1.530 kg) as system outputs. The Life Cycle Impact Assessment (LCIA) results indicate that Global Warming Potential (GWP) is the most significant impact category, reaching 76.513 kg CO₂ eq per batch, equivalent to approximately 2.624 kg CO₂ eq per kg of packaged yogurt, followed by acidification (0.524 kg SO₂ eq), human toxicity (0.259 kg 1,4-DCB eq), freshwater eutrophication (0.131 kg P eq), and ozone depletion (5.51×10⁻⁴ kg CFC-11 eq). The hotspot analysis reveals that raw milk sourcing is the dominant contributor to environmental impacts across most categories, reflecting the influence of the cradle-to-gate background data embedded in the milk input. In conclusion, improving raw material sourcing, optimizing water and energy consumption, and enhancing waste management are essential strategies to improve the environmental performance of small-scale yogurt production systems.

Keywords: *Environmental impact, Life cycle assessment, openLCA, ReCiPe 2016 Midpoint, Yogurt*

Introduction

Yogurt is one of the most widely consumed dairy products due to its high nutritional value, probiotic content, and health benefits (De Souza et al., 2023). The increasing demand for yogurt has driven the expansion of both industrial and small-scale production systems, particularly in developing countries such as Indonesia. However, these production systems are

associated with environmental burdens, including high energy consumption, water usage, and waste generation. The dairy sector is recognized as a major contributor to environmental impacts, particularly greenhouse gas emissions, eutrophication, and resource depletion (FAO, n.d.; Poore and Nemecek, 2018). Therefore, it is essential to evaluate the environmental performance of dairy products to support sustainable production practices.

Life Cycle Assessment (LCA) is a widely recognized methodology used to evaluate environmental impacts associated with all stages of a product's life cycle, from raw material extraction to processing and waste management

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(Huijbregts et al., 2017). LCA enables the quantification of multiple environmental impact categories, including global warming potential, eutrophication, acidification, and resource scarcity, providing a comprehensive evaluation of environmental performance (Finnegan et al., 2017).

Recent studies have highlighted that dairy production systems contribute significantly to environmental impacts, particularly in terms of greenhouse gas emissions, resource consumption, and nutrient-related pollution (Djekic et al., 2014; González-García et al., 2013; Hayek et al., 2021; Noya et al., 2018; Wakkumbura et al., 2024). Fidan et al. (2026) compared factory-produced and homemade yogurt in Türkiye using a functional unit of 1 kg of product and showed that the choice of functional unit, together with the energy data used for pasteurization and cooling, strongly influences the magnitude and ranking of impact results between production scales. This finding is directly relevant to the present study, which uses a batch-based functional unit (29.158 kg), and is one of the reasons the per-kilogram GWP result is also reported here to allow direct comparison with Fidan et al. (2026) and other kilogram-based studies. However, most existing studies focus on large-scale industrial production, while limited attention has been given to small-scale or home-based yogurt production systems, especially in developing countries. This creates a research gap in understanding the environmental performance of localized yogurt production systems with less standardized processes.

This gap highlights the need to assess the environmental performance of localized yogurt production systems, which often operate with less standardized processes and limited technological optimization. Therefore, this study aims to evaluate the environmental impacts of small-scale yogurt production in Bogor,

Indonesia, using a gate-to-gate LCA approach to identify key hotspots and propose strategies to improve sustainability.

Research Methodology

This study applies the Life Cycle Assessment (LCA) methodology to evaluate the environmental impacts associated with packaged yogurt production (Fidan et al., 2026). The assessment follows the ISO 14040 and ISO 14044 framework (ISO, 2006). The LCA framework applied in this study is illustrated in Figure 1 and consists of four main phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. LCA is widely used to quantify environmental burdens related to food production systems by analyzing resource consumption and emissions throughout the process (Poore and Nemecek, 2018).

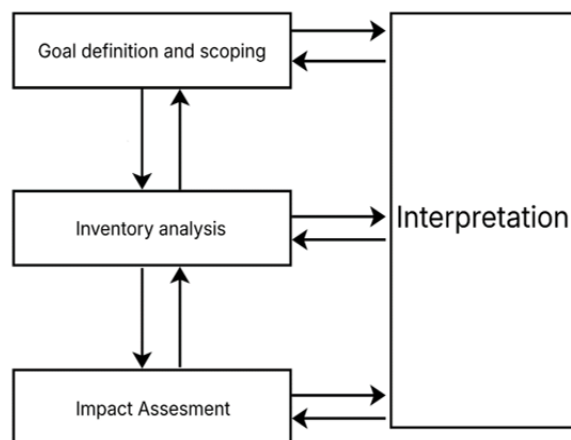


Figure 1. LCA Framework

Goal and Scope

The goal of this study is to assess the environmental impacts generated during the production of packaged yogurt and to identify key contributors within the system. A gate-to-gate approach was adopted for the foreground production system: the analysis covers only the processes carried out at the production facility itself — mixing, pasteurization, homogenization, cooling, inoculation, fermentation, cooling and maturation, and packaging — as illustrated in

Figure 2. Downstream processes such as distribution, consumption, and end-of-life waste management are excluded from the system boundary.

It is important to clarify the scope of upstream inclusion, as raised during review. While the foreground (measured) system is gate-to-gate, the purchased raw milk input is modeled using a secondary background dataset (“Cow milk, conventional, highland milk system”) obtained from the openLCA/Agribalyse database. Because background datasets of this kind are themselves cradle-to-gate — i.e., they already embed upstream agricultural processes such as feed cultivation and enteric fermentation — the impacts attributed to raw milk in the results (Figure 4 and Figure 5) reflect this embedded upstream burden rather than any additional upstream modeling performed by the authors. This is standard and accepted practice in attributional LCA, where a gate-to-gate foreground system is combined with cradle-to-gate background data for purchased inputs; it does not make the overall study a cradle-to-gate assessment of the full supply chain, but it does mean that the reported hotspot at raw milk sourcing already accounts for upstream farm-level burdens carried within that single input flow. This distinction has been made explicit here, and the revised title (“Gate-to-Gate Life Cycle Assessment...”) refers specifically to the boundary of the measured production system.

The functional unit of this study is defined as 29.158 kg of packaged yogurt, representing the total production output in one production cycle (batch). Results are additionally normalized to 1 kg of packaged yogurt in the Discussion to support comparison with kilogram-based studies such as Fidan et al. (2026).

System Boundary of Yogurt Production can be seen in Fig. 2.

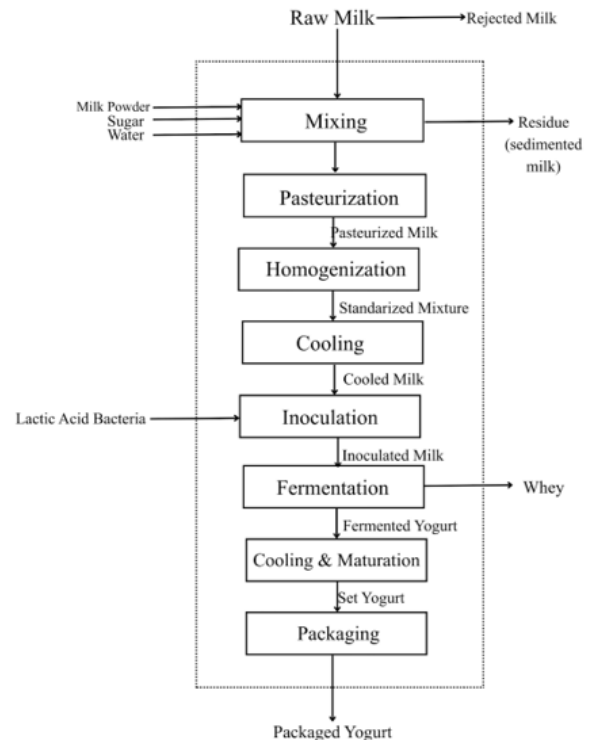


Figure 2. System Boundary of Yogurt Production

Life Cycle Inventory (LCI)

Primary data were collected through direct observation and interviews with a small-scale yogurt production unit located in Bogor, Indonesia. The data include raw material usage, water consumption, and production process parameters for one production batch. Secondary data for background processes (e.g., raw milk production, skimmed milk powder, sugar) were obtained from life cycle inventory databases such as Agribalyse, accessed through openLCA, and from relevant literature.

Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) was carried out using the ReCiPe 2016 Midpoint (H) method, selected for its hierarchist perspective balancing short-term and long-term environmental impacts, its comprehensive coverage of impact categories, and its wide application in food-related LCA studies,

allowing consistent comparison with previous research.

Five impact categories were selected for this study: Global Warming Potential (GWP), ozone depletion, human toxicity, terrestrial acidification, and freshwater eutrophication. These categories were chosen for their strong relevance to dairy production systems and their ability to capture the most significant impacts associated with yogurt production, representing three major areas of environmental concern: atmospheric impacts (GWP and ozone depletion), ecosystem quality (acidification and eutrophication), and human health (human toxicity). Regarding the eutrophication indicator specifically: ReCiPe 2016 Midpoint (H) distinguishes freshwater eutrophication (reported in kg P eq, phosphorus being the typical limiting nutrient in freshwater systems) from marine eutrophication (reported in kg N eq, nitrogen being the typical limiting nutrient in marine systems). The underlying openLCA model output for this study (Figure 4e) is expressed in kg P eq, confirming that the indicator used is Freshwater Eutrophication Potential; the unit shown in Table 2 has been corrected accordingly in this revision (previously mislabeled as kg N eq).

Interpretation

The interpretation phase was conducted by systematically analyzing the LCIA results obtained using the ReCiPe 2016 Midpoint (H) method in openLCA to identify the main contributors (hotspots) to environmental impacts within the yogurt production system. A contribution analysis quantified the percentage share of each input flow in relation to the total impact of each category, and a hotspot analysis determined which inputs (e.g., raw milk, skimmed milk powder, packaging) were primarily responsible for significant impacts in each category.

Results and Discussion

Result

Inventory Data

The total inputs consist of six key material flows: raw milk, water, skimmed milk powder, sugar, microbial starter, and packaging materials. Raw milk represents the largest input by mass (27.184 kg, 82.8% of total input), indicating its dominant contribution to the production system. In addition to the main product (29.158 kg of packaged yogurt), the system generates wastewater (2.150 kg) and organic residue (1.530 kg) as outputs, reflecting material losses during fermentation, handling, and cleaning. The complete input–output balance is summarized in Table 1.

Table 1. Input-Output Balance

No	Input	Quantity (kg)	Output	Quantity (kg)
1	Raw milk	27.184	Packaged Yogurt	29.158
2	Water	2.000	Waste Water	2.150
3	Milk powder	2.000	Organic Residue	1.530
4	Sugar	1.000		
5	Microbial starter	0.030		
6	Packaging	0.624		
	Total Input	32.838	Total Output	32.838

Life Cycle Impact Assessment Results

Table 2 presents the LCIA results across the five selected impact categories. Values are reported

using a consistent decimal-point notation and rounded to three significant figures for readability; full-precision openLCA outputs are retained in the underlying project file.

Table 2. Impact Assessment Result

No	Indicator	Description	Result	Unit
1	Global Warming	Rise in Earth's temperature due to greenhouse gases.	76.513	kg CO ₂ eq
2	Ozone Depletion	Thinning of the ozone layer that protects from UV radiation.	5.51×10 ⁻⁴	kg CFC-11 eq
3	Human Toxicity	Harmful effects of chemicals on human health.	0.259	kg 1,4-DCB
4	Acidification	Increase in acidity of soil or water, often from emissions like SO ₂ .	0.524	kg SO ₂ eq
5	Freshwater Eutrophication	Excess phosphorus in freshwater causing algae blooms and oxygen loss.	0.131	kg P eq

Flow Model

The flow model generated in openLCA (Figure 3) provides a visual representation of the yogurt production system, illustrating the relationships between inputs, processes, and outputs. The production process begins with mixing of raw materials, followed by pasteurization, homogenization, and cooling to prepare for

inoculation, during which lactic acid bacteria are added to initiate fermentation. The fermentation process converts lactose into lactic acid, forming yogurt; the product is then cooled and matured before packaging. The model graph confirms the six input flows and three output flows listed in Table 1.



Figure 3. Model Graph of Yogurt Production (openLCA)

Sankey Diagram

Figure 4 presents the Sankey diagrams generated from the openLCA model for each of the five impact categories. Each diagram depicts environmental impact flow, not material mass

flow: the thickness of each branch is proportional to the share of the total impact (in the category's respective unit — e.g., kg CO₂ eq for panel a, kg P eq for panel e) contributed by each upstream input flow, rather than to the

physical mass transferred. This distinction is noted explicitly here in response to review, as the diagrams were previously ambiguous on this point. Across all five categories, the diagrams consistently show raw milk (“Cow milk,

conventional, highland milk system”) and, to a lesser extent, skimmed milk powder as the dominant contributing input flows, which is consistent with the hotspot findings discussed below.

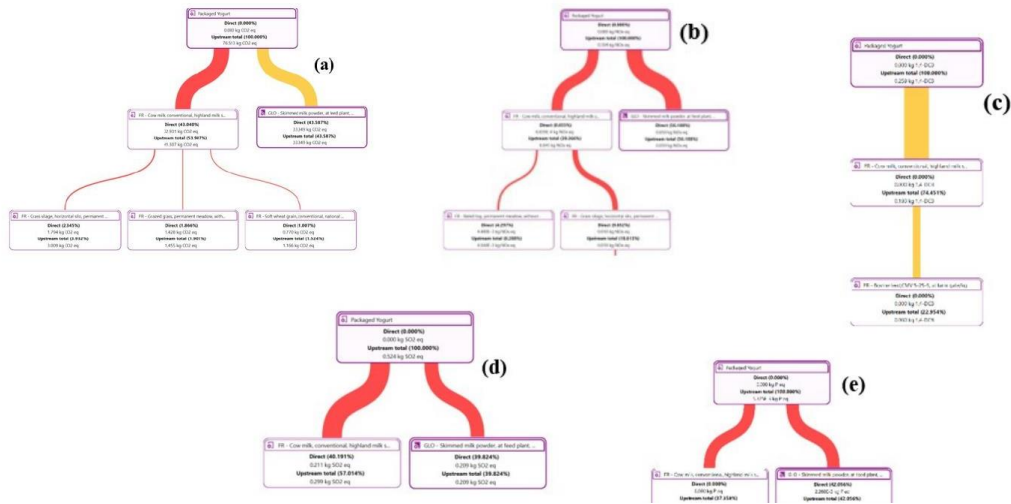


Figure 4. Sankey Diagram (Environmental Impact Flow) of (a) Global Warming, (b) Ozone Depletion, (c) Human Toxicity, (d) Acidification, (e) Freshwater Eutrophication

Contribution Analysis

Figure 5 shows the top five contributing input flows to each impact category. Raw milk is the leading contributor to Global Warming Potential, Acidification, and Freshwater

Eutrophication, while skimmed milk powder contributes most strongly to Ozone Depletion and Human Toxicity, reflecting differences in the upstream processing chains embedded in each background dataset.

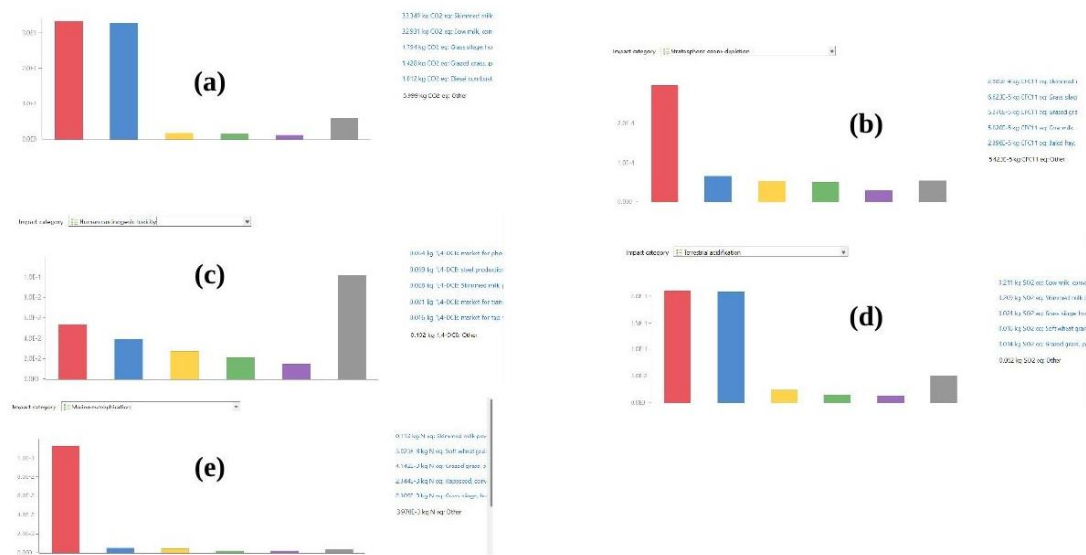


Figure 5. Top 5 Contributing Input Flows to (a) Global Warming, (b) Ozone Depletion, (c) Human Toxicity, (d) Acidification, (e) Freshwater Eutrophication

Discussion

The results of this study indicate that small-scale yogurt production contributes to several environmental impact categories, with Global Warming Potential (GWP) identified as the most significant, reaching 76.513 kg CO₂ eq per batch. Normalized to the functional unit, this corresponds to approximately 2.624 kg CO₂ eq per kg of packaged yogurt (76.513 kg CO₂ eq ÷ 29.158 kg yogurt), a figure reported here specifically to enable comparison with kilogram-based studies such as Fidan et al. (2026). This value reflects the substantial contribution of greenhouse gas emissions embedded in the raw milk background dataset, particularly from upstream processes such as enteric fermentation and feed production. Previous studies have consistently shown that dairy systems are major contributors to GWP for the same reasons (Singh et al., 2024).

In addition to climate change impacts, acidification (0.524 kg SO₂ eq) and freshwater eutrophication (0.131 kg P eq) are also significant environmental concerns in yogurt production. These impacts are primarily associated with agricultural activities, including fertilizer use and livestock waste, which release ammonia (NH₃), nitrogen oxides (NO_x), and phosphorus-containing runoff into the environment. A recent study on yogurt and fermented dairy products reported similar findings, highlighting that nutrient emissions from upstream processes play a critical role in ecosystem degradation (Pallakonda and Hariharan, n.d.).

The human toxicity impact (0.259 kg 1,4-DCB eq) observed in this study is likely related to emissions from chemical inputs used in agricultural and industrial processes, as captured by the background datasets for skimmed milk powder and raw milk. Comparable findings have been reported in recent LCA studies on dairy systems, where toxicity impacts are linked to

both agricultural inputs and processing activities (Cruz-Rivero et al., 2025; Santos et al., 2022).

For ozone depletion, the impact value of 5.51×10^{-4} kg CFC-11 eq indicates a relatively low contribution compared to other environmental categories, but remains associated with background emissions from energy production and refrigerant-related activities embedded in the skimmed milk powder dataset.

Compared to industrial-scale production, small-scale yogurt systems may exhibit lower total emissions per batch but tend to be less efficient per unit of product due to limited technology and process optimization, reinforcing the value of reporting results on a per-kilogram basis for cross-study comparison. Improving operational efficiency, adopting energy-saving technologies, and optimizing raw material sourcing are therefore essential strategies for reducing environmental impacts.

This study is limited by its gate-to-gate foreground boundary, which excludes distribution, consumption, and end-of-life stages; as clarified above, upstream agricultural burdens are nonetheless partially represented through the cradle-to-gate background dataset used for raw milk. As a result, the total impact of the full supply chain, including downstream stages, may still be underestimated. Future studies are recommended to adopt an explicit cradle-to-grave approach, with locally collected primary data for upstream dairy farming, to provide a more complete assessment of small-scale yogurt production systems in Indonesia.

Conclusions

This study evaluated the environmental impacts of small-scale yogurt production in Bogor, Indonesia, using a gate-to-gate Life Cycle Assessment with the ReCiPe 2016 Midpoint (H) method. Raw milk sourcing, via its embedded cradle-to-gate background burden, was identified as the primary contributor to

environmental impacts, followed by skimmed milk powder processing. Global Warming Potential was the most significant impact category at 76.513 kg CO₂ eq per batch ($\approx$ 2.624 kg CO₂ eq/kg yogurt), followed by acidification, human toxicity, freshwater eutrophication, and ozone depletion.

Based on these findings, improvement strategies include optimizing raw material sourcing (e.g., lower-impact milk suppliers), reducing water and energy consumption, and improving wastewater treatment. Future research is recommended to expand the system boundary toward a cradle-to-grave perspective and to incorporate more localized primary data for upstream dairy farming, improving the accuracy and representativeness of the assessment for small-scale yogurt production in developing regions.

References

- Andrieu, B., Le Boulzec, H., Delannoy, L., Verzier, F., Winter, G., Vidal, O., & Stadler, K. (2024). An open-access web application to visualise countries' and regions' carbon footprints using Sankey diagrams. *Communications Earth & Environment*, 5, 236. <https://doi.org/10.1038/s43247-024-01378-8>
- Anspach, R. L., Allen, S. R., & Lupton, R. C. (2024). Robust modeling of material flows to end-uses under uncertainty: UK wood flows and material efficiency opportunities. *Journal of Industrial Ecology*, 28, 953–965. <https://doi.org/10.1111/jiec.13511>
- Chong, C., Zhang, X., Kong, G., Ma, L., Li, Z., Ni, W., & Yu, E.-H.-C. (2021). A visualization method of the economic input–output table: Mapping monetary flows in the form of Sankey diagrams. *Sustainability*, 13, 12239. <https://doi.org/10.3390/su132112239>
- Cruz-Rivero, L., Hernández, E. A., Lince-Olguín, E., Mar-Orozco, C. E., López-García, S. A., & Cruz-Martínez, P. Y. (2025). Life cycle assessment applied to milk production and processing: An integrative systematic literature review. *Sustainability*, 17, 1615. <https://doi.org/10.3390/su17041615>
- De Souza, M., Drunkler, D. A., & Colla, E. (2023). Probiotic functional yogurt: Challenges and opportunities. *Fermentation*, 10, 6. <https://doi.org/10.3390/fermentation10010006>
- Djekic, I., Miocinovic, J., Tomasevic, I., Smigic, N., & Tomic, N. (2014). Environmental life-cycle assessment of various dairy products. *Journal of Cleaner Production*, 68, 64–72. <https://doi.org/10.1016/j.jclepro.2013.12.054>
- FAO. (n.d.). Greenhouse gas emissions from the dairy sector: A life cycle assessment. Food and Agriculture Organization of the United Nations.
- Fidan, M., Altınay, C., & Şanlı, T. (2026). Comparative life cycle assessment of factory-produced and homemade yogurt in Türkiye. *International Journal of Life Cycle Assessment*, 31, 68. <https://doi.org/10.1007/s11367-026-02636-x>
- Finnegan, W., Goggins, J., Clifford, E., & Zhan, X. (2017). Global warming potential associated with dairy products in the Republic of Ireland. *Journal of Cleaner Production*, 163, 262–273. <https://doi.org/10.1016/j.jclepro.2015.08.025>
- González-García, S., Castanheira, É. G., Dias, A. C., & Arroja, L. (2013). Environmental life cycle assessment of a dairy product: The yoghurt. *International Journal of Life Cycle Assessment*, 18, 796–811. <https://doi.org/10.1007/s11367-012-0522-8>
- Hayek, J., El Bachawati, M., & Manneh, R. (2021). Life cycle assessment and water footprint scarcity of yogurt. *Environment, Development and Sustainability*, 23, 18362–

18393. <https://doi.org/10.1007/s10668-021-01445-6>
- Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., & Van Zelm, R. (2017). ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *International Journal of Life Cycle Assessment*, 22, 138–147. <https://doi.org/10.1007/s11367-016-1246-y>
- International Organization for Standardization (ISO). (2006). ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines.
- Noya, I., González-García, S., Berzosa, J., Baucells, F., Feijoo, G., & Moreira, M. T. (2018). Environmental and water sustainability of milk production in Northeast Spain. *Science of the Total Environment*, 616–617, 1317–1329. <https://doi.org/10.1016/j.scitotenv.2017.10.186>
- Pallakonda, S., & Hariharan, D. (n.d.). Environment sustainability analysis of dahi (yogurt) production: A gate-to-gate life cycle assessment using openLCA.
- Petrík, J., Kramer, G. J., Tunn, V. S. C., & Shen, L. (2026). Carbon flow map: A substance flow analysis of carbon in the Dutch economy. *Journal of Industrial Ecology*. <https://doi.org/10.1007/s44498-026-00065-5>
- Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science*, 360, 987–992. <https://doi.org/10.1126/science.aag0216>
- Santos, L. D. L. C. D., Renato, N. D. S., Florindo, T. J., Rosa, A. P., & Borges, A. C. (2022). Life cycle assessment of dairy products: A case study of a dairy factory in Brazil. *Sustainability*, 14, 9646. <https://doi.org/10.3390/su14159646>
- Singh, A. B., Bhakar, V., Gaurav, G., Khandelwal, C., Sarkar, P., Singh, H., & Dangayach, G. S. (2024). Environmental sustainability of milk production: A comparative environmental impact analysis and sustainability evaluation. *Frontiers in Sustainability*, 5, 1352572. <https://doi.org/10.3389/frsus.2024.1352572>
- Wakkumbura, W. G. S. M. K., Rupasinghe, C. P., & Kahandage, P. D. (2024). Environmental footprints of yogurt production: A case study of a small-scale manufacturing process in Sri Lanka. *Sri Lankan Journal of Agriculture and Ecosystems*, 5, 29–46. <https://doi.org/10.4038/sljae.v5i2.129>