



Environment Sustainability Analysis Of Dahi (Yogurt) Production: A Gate-To-Gate Life Cycle Assessment Using Open Lca

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ABSTRACT

This research focuses on the Life Cycle Assessment (LCA) of dahi production in India, utilizing a gate-to-gate approach to evaluate the environmental impacts. The system boundary encompasses all processes from the initial raw milk input to the final dahi product. The analysis was conducted using OpenLCA 3.0 software, incorporating data from the ecoinvent database and applying the ReCiPe 2016 V1.03 impact assessment method. In the production process, 600 liters of raw milk are used per kilogram of the final product, yielding 457 liters of yogurt and resulting in a milk loss of 143 liters. The production stages include clarification, separation, pasteurization, evaporation, cooling, fermentation, and filling. These stages were accurately modeled to reflect real-world industrial practices in dahi production.

A Sankey chart was utilized to visualize the process contribution flow, illustrating the distribution of materials and energy throughout the system. The results, presented in detailed Excel sheets and graphs, show that the production maintains a consistent mass balance, with 1 kilogram of milk input corresponding to 1 kilogram of dahi output. This LCA provides critical insights into the environmental aspects of dahi production, identifying key areas for enhancing efficiency and sustainability. The use of OpenLCA and detailed process data ensures a robust and replicable analysis, contributing valuable information to the understanding of the environmental impacts of dairy products.

Keywords: Dahi production, Life Cycle Assessment (LCA), Gate-to-gate process, System boundary, Environmental impact, Ecoinvent database, Dairy product sustainability, Industrial yogurt production, Milk processing, Environmental performance.

Background of the study:

Dahi, a traditional Indian fermented milk product, plays a significant role in the Indian diet due to its nutritional benefits and cultural importance. Understanding the environmental impacts associated with its production is crucial for enhancing sustainability in the dairy industry. Life Cycle Assessment (LCA) is a comprehensive method used to evaluate the environmental burdens associated with all stages of a product's life cycle, from raw material extraction to disposal. In this study, a gate-to-gate LCA was performed to assess the environmental impacts of dahi production, focusing specifically on the processes occurring within the production facility [1].

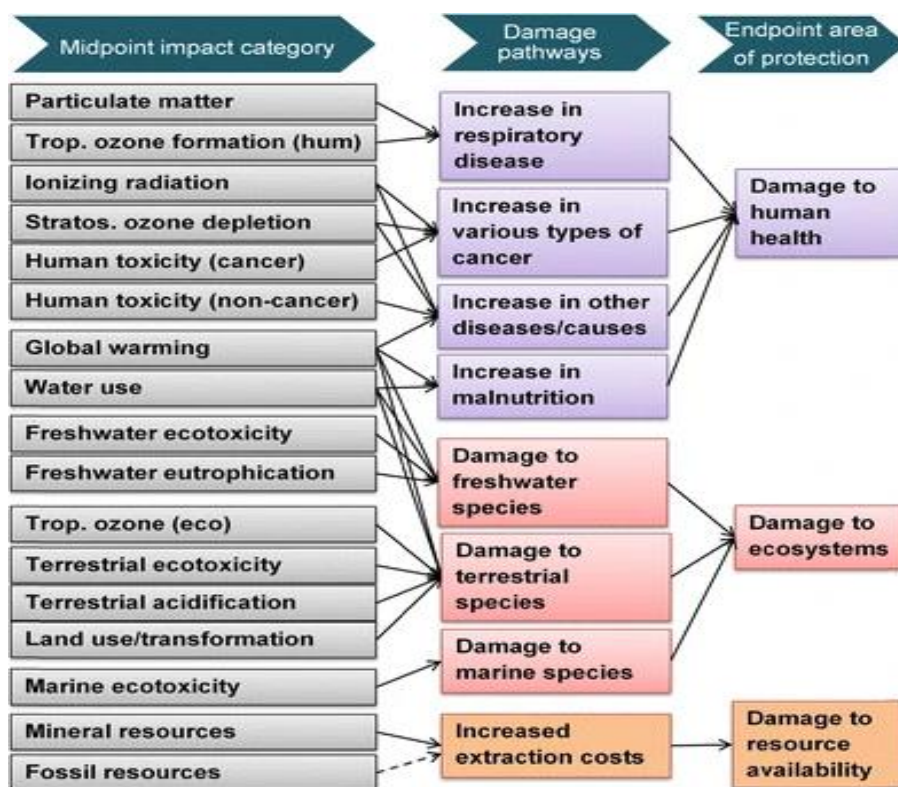


Fig 1. Overview of the impact categories in the ReCiPe2016 method [2]

Dahi, commonly known as yogurt, is a staple in many diets worldwide due to its nutritional benefits and versatility. The production of dahi involves several processing stages, from milk collection and fermentation to packaging and distribution. Each of these stages has distinct environmental impacts, which necessitates a comprehensive analysis to identify and mitigate negative effects on the environment.

The food processing industry, including dairy, plays a significant role in environmental degradation. It contributes substantially to greenhouse gas emissions, freshwater depletion, and land use. Dairy production alone is responsible for significant portions of these impacts, making it crucial to explore sustainable practices within this sector. Traditional production methods often lead to resource inefficiencies and significant waste generation, further exacerbating environmental concerns [2].

Importance of Environment Sustainability in Food Production:

Environmental sustainability in food production is vital due to its wide-ranging impacts on the planet and human society. Life Cycle Assessment (LCA) serves as a crucial tool for conducting environmental sustainability analyses of products and technologies. It offers a systematic approach to assessing improvements in resource productivity, thereby promoting cleaner production practices. Life cycle thinking holds a strategic role in the policy-making process. The European Commission has integrated this approach into its Integrated Product Policy and the European Sustainable Consumption and Production Action Plan [3].



Fig 2. Environmental Impact on LCA [4]

Objectives of the study:

- In the production process, 600 liters of raw milk are processed to produce 457 liters of dahi, with a loss of 143 liters of milk occurring throughout the various stages, including clarification, separation, pasteurization, evaporation, cooling, fermentation, and filling.
- By modeling these stages accurately, this research aims to provide a realistic depiction of the industrial dahi production process.
- The use of a Sankey chart further illustrates the flow of materials and energy, highlighting areas where efficiencies can be improved.
- This study's results, presented in detailed Excel sheets and graphical forms, offer valuable insights into the environmental impacts of dahi production.
- By maintaining a consistent mass balance—where 1 kilogram of milk input results in 1 kilogram of dahi output—this research identifies critical areas for potential improvement in process efficiency and sustainability.
- The findings contribute to the broader understanding of the environmental footprint of dairy products and support efforts to enhance sustainability in the dairy industry.

Literature Review:

This literature will give a deep understanding on the LCA studies in food and dairy production and its emilites.

Overview of Previous Studies on LCA in Food Production:

Life Cycle Assessment (LCA) is a comprehensive method for evaluating the environmental impacts associated with all stages of a product's life, from raw material extraction through production, use, and disposal. In the context of food production, LCA helps identify key areas where environmental impacts can be reduced. For dairy products like dahi (yogurt), LCA can pinpoint hotspots in the production process, such as energy-intensive operations or stages with high waste generation. This information is crucial for developing strategies to enhance sustainability.

The study investigates the significant impact factors affecting dairy products using the Life Cycle Assessment (LCA) approach with SimaPro software. The analysis reveals that major contributors to environmental impact (EI) include the consumption of electricity and fuel for thermal energy, the use of freshwater and various chemicals, and the materials used in packaging. Additionally, paneer, ice cream, and butter are identified as the top three dairy products contributing to climate change. Based on these findings, the study suggests that the dairy processing industry should adopt sustainable development practices to reduce environmental harm [5]. The study identifies that post-firm gate variations primarily result from the use of diverse packaging materials, transportation methods, industrial processing techniques, and energy consumption. Cheese is the most frequently studied dairy product. Pre-firm gate emissions, associated with milk production, are mainly driven by fertilizer use, agricultural product production, and manure management. Among the researchers, 10 out of 15 used Global Warming Potential for impact assessment. The Eco-invent database and the Impact 2002+ assessment tool were the most commonly utilized. To reduce the carbon footprint, the study commonly recommends the use of renewable energy and energy-efficient equipment [6].

Life Cycle Assessment (LCA) is commonly used to evaluate the carbon and water footprints of packaged foods across the entire supply chain. However, few studies compare the outcomes of different Life Cycle Impact Assessment (LCIA) methodologies. The findings reveal that different LCIA methods yield varying impact results for the same product. For instance, global warming impact was found to be lower when using the ILCD 2011 and IPCC 2013 CO₂ uptake methods compared to IPCC 2013 and ReCiPe 2016 [7].

The study identifies raw milk production as the primary contributor to many environmental impacts, regardless of the dairy product type. Key drivers during this stage include fertilizer use, agricultural material production and use, and on-site emissions, which contribute to impacts like global warming potential, acidification, and eutrophication. In production processes, energy use is the main cause of the environmental footprint. Transportation, storage/use, and waste treatment have minimal to negligible impacts, except for ozone layer depletion. Butter has the highest environmental footprint among dairy products, followed by cheese [8].

An environmental audit using a gate-to-gate approach was conducted, and Life Cycle Assessment calculations for ten dairy products were performed according to ISO 14040 and ISO 14044 standards, utilizing the SimaPro® 8.1.1.16 software. The results indicated that frozen products like ice cream candy, ice cream, and sip-up had higher environmental burdens in endpoint categories. Ghee and butter exhibited significant global warming potential, with 0.0039 kg CO₂ equivalent emissions. Sodium hydroxide, nitric acid, and wastewater were identified as major impact contributors to endpoint categories, with sodium hydroxide having the highest impact on human health, ecosystem quality, climate change, and resource usage. Based on these findings, a new eco-design proposal has been recommended to enhance the environmental efficiency of the industry [9]. A cradle-to-gate Life Cycle Assessment (LCA) was conducted in a dairy industry in São Gonçalo, Rio de Janeiro, Brazil, using SimaPro® 8.3.0.0 software and the Ecoinvent 3.2 database, with the ILCD 2011 Midpoint

methodology for impact assessment. The study revealed that goat milk production, particularly the use of soybean in goat feed, was the most significant contributor to environmental impacts. To reduce these impacts, the study recommends partially substituting soybean with hay and grass in goat feed, which showed lower environmental impacts in categories such as climate change, freshwater ecotoxicity, land use, and resource depletion [10].

Exclusive Review on Dairy Products:

The paper analyzes the life cycle of sheep milk cheese production, investigates the cheese supply chain, and suggests improvements to minimize the environmental impacts of this agri-food product. The study uses 1 kg of sheep milk cheese as the functional unit, with production process data sourced from a cheese company in Romania. Environmental impact assessments were conducted using the CML and ReCiPe methods within GaBi software. The impacts assessed include abiotic depletion potential, acidification potential, eutrophication potential, global warming potential, human toxicity potential, climate change, fossil depletion, freshwater eutrophication, particulate matter formation, photochemical oxidant formation, and terrestrial acidification [11].

The study examined the potential environmental impacts of Beira Baixa cheese, a regional product from Portugal's largest sheep milk region, using a cradle-to-gate Life Cycle Assessment (LCA) methodology. The assessment included the supply of animal feedstock and employed the ReCiPe midpoint 2008 method to analyze impacts related to climate change, terrestrial acidification, and freshwater and marine eutrophication. The findings indicated that the milk production process has the greatest environmental impacts across all four selected categories. These impacts are primarily due to fodder cultivation, which involves fertilization and land preparation processes. Additionally, enteric fermentation and manure management significantly contribute to the overall environmental impact [12-15].

Predicting future market demands for dairy products is crucial for developing marketing strategies and farm-production planning in the dairy industry [16-18]. Accurate forecasts are essential due to the volatile demand patterns influenced by rapidly changing market conditions. This study compares the accuracy of various forecasting models, including moving average, regression, multiple regression, and the Holt–Winters model, in predicting demand for a time series of perishable dairy products in the milk processing industry [19-25].

Evaluating the environmental sustainability of biobased products is essential to understand their decarbonization potential and associated life cycle impacts. This can be measured using the Life Cycle Assessment (LCA) tool. Life Cycle Sustainability Assessment (LCSA) integrates LCA with life cycle costing and social life cycle assessment. This paper's framework aims to provide insights into biobased products, highlighting LCA as a crucial tool for measuring sustainability [26-28].

The objective of this study was to assess the environmental impact and feed energy conversion ratio of Alpine dairy chains in the Eastern Alps, considering both milk production and dairy processing phases. Additionally, the study aimed to pinpoint farm management practices conducive to mitigating environmental impacts during the production phase [29]. A cradle-to-farm gate Life Cycle Assessment model was utilized, encompassing herd and manure management, on-farm feedstuff production, purchased feedstuffs and materials (for dairy farms), and production inputs and outputs (for dairy processing) across 75 farms. The functional units employed were 1 kg of fat- and protein-corrected milk to gauge production intensity and 1 m² of agricultural land to represent the land managed by alpine farms [30-31].

Research Gaps addressed by the Current Study:

- By identifying farm management features conducive to mitigating environmental impacts during the production phase, the study bridges a gap in knowledge regarding actionable measures for sustainability improvement in dairy farming.
- The study utilizes a cradle-to-farm gate Life Cycle Assessment (LCA) model, including herd and manure management, on-farm feedstuff production, purchased feedstuffs, and materials. This methodological application addresses the need for comprehensive assessments in dairy LCA studies.
- Utilizing real data from dairy farms and processing facilities enhances the credibility and reliability of the findings, addressing a gap in relying solely on modeled or simulated data for LCA studies.

Methodology:

The methodology will start by outlining the objective of the research, which is to conduct a Life Cycle Assessment (LCA) of dahi production in India. It will detail the scope of the study, which encompasses the gate-to-gate approach, covering all processes from the initial raw milk input to the final dahi product. The system boundary will be clearly defined to delineate the extent of the analysis. The methodology will describe the tools and resources utilized for the analysis, including the OpenLCA 3.0 software and data from the ecoinvent database. It will explain the impact assessment method applied in the analysis, which is the ReCiPe 2016 V1.03 method, outlining its key features and relevance to the study. The methodology will provide details

of the dahi production process, including the quantity of raw milk used per kilogram of final product, milk loss, and the various stages involved such as clarification, separation, pasteurization, etc.

Theory of Life Cycle Assessment:

The theory of Life Cycle Assessment (LCA) underpins the study on dahi production in India, providing a systematic framework to evaluate the environmental impacts associated with the entire life cycle of the product. LCA considers all stages of production, from the extraction of raw materials to the disposal of the final product, aiming to quantify resource use, energy consumption, and environmental emissions at each stage. This chart appears to represent a process contribution diagram, showing various steps involved in the production process of different products. Here's a step-by-step analysis of the chart.

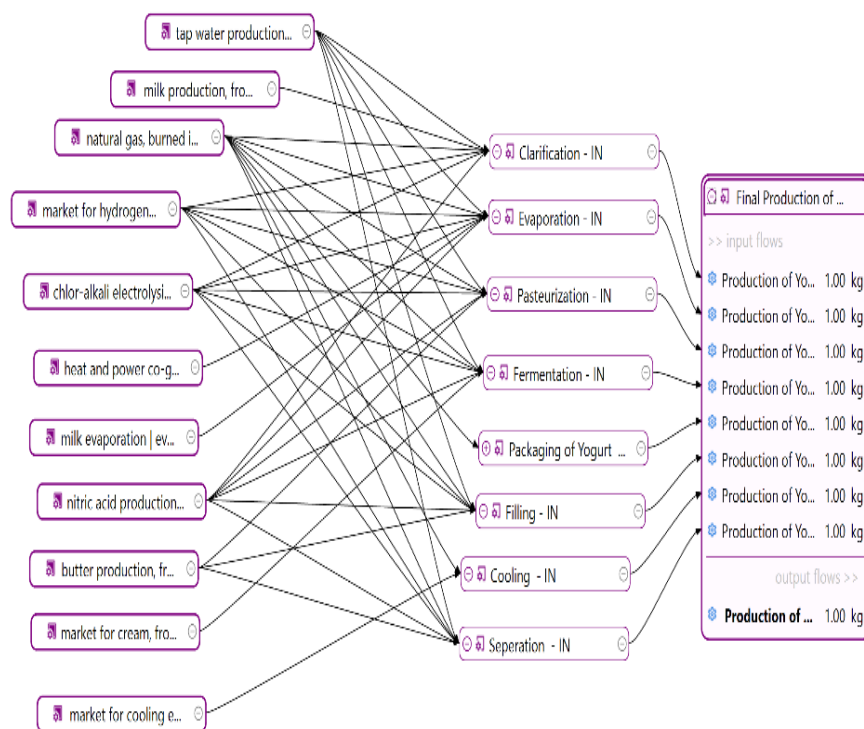


Fig 3. Brief of LCA of 1 kg Yogurt

Description of Gate – To – Gate Approach:

This study aims to conduct an environmental sustainability analysis of dahi production using a gate-to-gate LCA approach with OpenLCA. By identifying the environmental hotspots in the production process, the study seeks to propose strategies for reducing the environmental footprint of dahi. This is particularly important in the context of increasing consumer awareness and demand for sustainable food products. Through this analysis, the study contributes to the broader goal of enhancing sustainability in the dairy industry and mitigating its environmental impacts.

Introduction to Open LCA Software:

Life Cycle Assessment (LCA) is a robust tool used to evaluate the environmental impacts of products from production to disposal. A gate-to-gate LCA focuses on the stages within the factory gate, providing insights into the resource use and emissions directly associated with the production process. Utilizing OpenLCA, an open-source software for life cycle assessment, enables a detailed and transparent analysis of these impacts, offering opportunities for improvements and sustainability.

Data Collection and Methods:

Data collection plays a critical role in LCA, with accurate and representative data informing the assessment of inputs, outputs, and environmental impacts. Utilizing tools like OpenLCA 3.0 software and the ecoinvent database, researchers gather data on factors such as raw milk usage, production stages, and waste generation to inform the assessment.

The choice of impact assessment method, ReCiPe 2016 V1.03, enables researchers to evaluate a range of environmental categories, including climate change, acidification, eutrophication, and resource depletion. By applying this method, the study can quantify and compare the environmental impacts of dahi production across different categories, providing insights into areas of environmental concern and potential mitigation strategies.

System Boundary & Functional Unit:

Central to LCA is the concept of system boundary, which defines the scope of the analysis and ensures that all relevant processes are included. In this study, the system boundary encompasses the entire dahi production process, from milk sourcing to final product packaging, capturing the full extent of environmental impacts. The system boundary for this assessment includes all steps from the intake of raw milk to the final dahi product. This boundary was selected to provide a clear understanding of the environmental performance of the production process, without extending to upstream or downstream activities. The LCA was conducted using OpenLCA 3.0 software, a powerful tool for environmental impact assessment, which enabled detailed modeling and analysis of the production processes. The data for this study was sourced from the ecoinvent database, employing the ReCiPe 2016 V1.03 method for impact assessment, known for its comprehensive approach to environmental impact characterization.

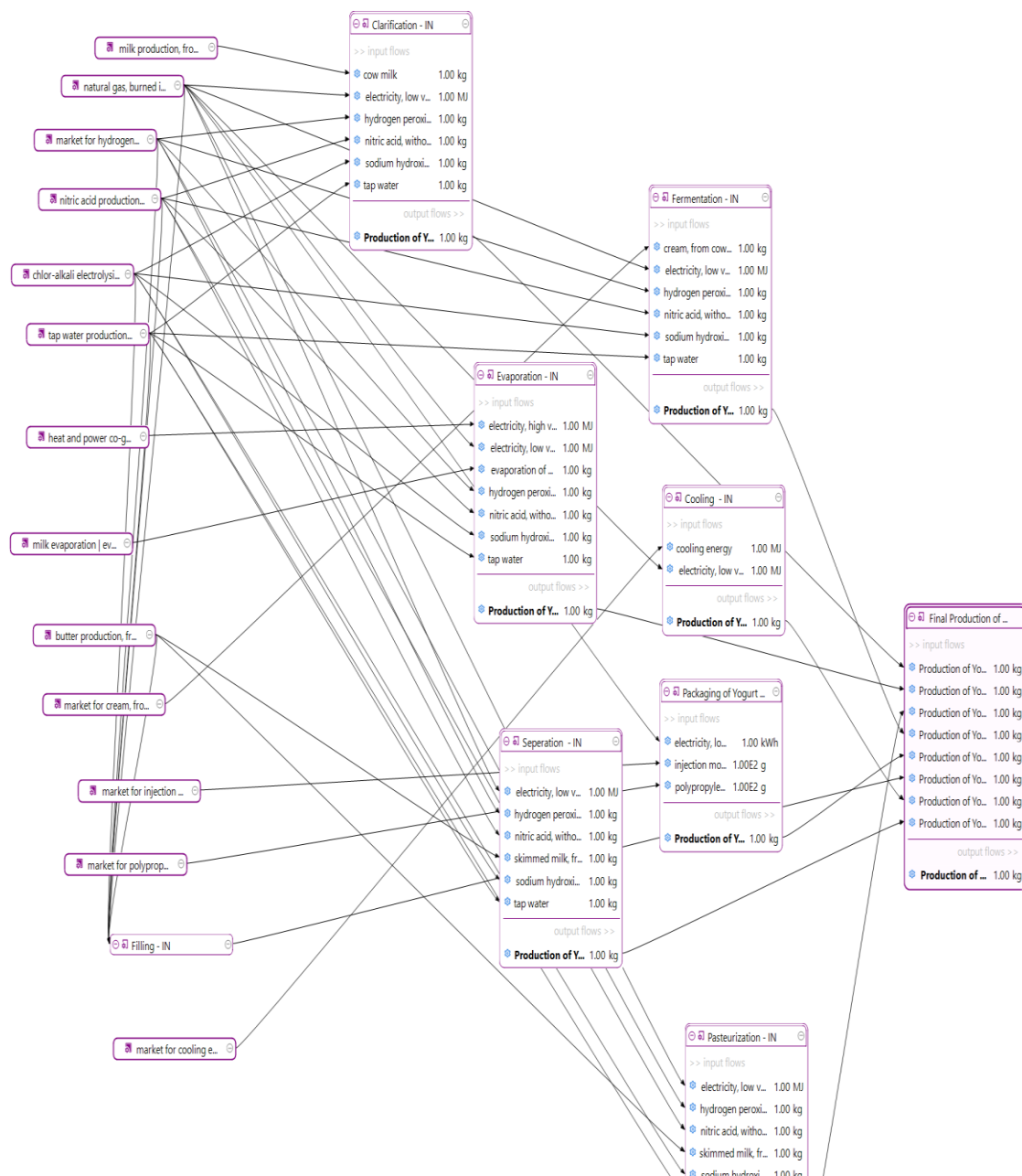


Fig 4. System Boundary

Initial Inputs:

The process starts with inputs such as tap water production, milk production, and natural gas burned in combined heat and power generation.

Intermediate Processes:

These inputs then undergo several intermediate processes, including chlor-alkali electrolysis, heat and power co-generation, milk evaporation, nitric acid production, butter production, and others. Each intermediate process seems to have multiple outputs and inputs, contributing to the overall production.

Final Processes:

In the context of conducting a Life Cycle Assessment (LCA), the Final Processes depicted in the chart play a crucial role. Here's how the LCA would be applied to each process separately before integrating them to obtain final results:

Clarification:

LCA of clarification involves assessing the environmental impacts associated with this process, which likely includes energy consumption, chemical usage, and waste generation. This could involve analyzing the energy intensity of clarification equipment, the emissions produced during the process, and the disposal methods for any generated waste.

Table 1.1 Clarification Inventory Inputs and Outputs

Inputs						Outputs					
Flow UUID	Flow	Category	Sub-category	Unit	Result	Flow UUID	Flow	Category	Sub-category	Unit	Result
a45cd247-3f	Aluminium	Resource	in ground	kg	4.9E-05	9645e02f-85	1,2-Dichloro	Emission to	high populat	kg	2.764E-12
a45cd247-3f	Aluminium	Resource	in ground	kg	0.0008534	79b3f708-dc	1,2-Dichloro	Emission to	surface water	kg	1.897E-07
a45cd247-3f	Aluminium	Resource	in ground	kg	0.0006802	79b3f708-dc	1,2-Dichloro	Emission to	surface water	kg	5.013E-07
a45cd247-3f	Aluminium	Resource	in ground	kg	0.004322	9645e02f-85	1,2-Dichloro	Emission to	high populat	kg	1.122E-10
a45cd247-3f	Aluminium	Resource	in ground	kg	0.0005983	9645e02f-85	1,2-Dichloro	Emission to	high populat	kg	4.531E-12
6df9ea09-11	Anhydrite	Resource	in ground	kg	2.364E-09	79b3f708-dc	1,2-Dichloro	Emission to	surface water	kg	3.792E-07
6df9ea09-11	Anhydrite	Resource	in ground	kg	7.821E-09	9645e02f-85	1,2-Dichloro	Emission to	high populat	kg	1.391E-11
6df9ea09-11	Anhydrite	Resource	in ground	kg	4.134E-09	79b3f708-dc	1,2-Dichloro	Emission to	surface water	kg	9.598E-07
6df9ea09-11	Anhydrite	Resource	in ground	kg	7.197E-07	9645e02f-85	1,2-Dichloro	Emission to	high populat	kg	8.225E-09
6df9ea09-11	Anhydrite	Resource	in ground	kg	1.39E-08	79b3f708-dc	1,2-Dichloro	Emission to	surface water	kg	6.875E-07
47262180-8	Antimony	Resource	in ground	kg	1.569E-11	5b7d620e-2	1,3-Dioxolan	Emission to	unspecified	kg	1.276E-09
47262180-8	Antimony	Resource	in ground	kg	9.892E-10	5b7d620e-2	1,3-Dioxolan	Emission to	unspecified	kg	7.796E-09
47262180-8	Antimony	Resource	in ground	kg	8.21E-10	5b7d620e-2	1,3-Dioxolan	Emission to	unspecified	kg	4.102E-09
47262180-8	Antimony	Resource	in ground	kg	9.116E-10	5b7d620e-2	1,3-Dioxolan	Emission to	unspecified	kg	1.121E-08
47262180-8	Antimony	Resource	in ground	kg	7.818E-10	5b7d620e-2	1,3-Dioxolan	Emission to	unspecified	kg	6.851E-08
8b46f615-6f	Argon-40	Resource	in air	kg	6.555E-06	38a622c6-f0	1,4-Butaned	Emission to	high populat	kg	3.197E-11
8b46f615-6f	Argon-40	Resource	in air	kg	4.855E-05	d6911d36-3	1,4-Butaned	Emission to	surface water	kg	7.353E-11
8b46f615-6f	Argon-40	Resource	in air	kg	3.888E-05	d6911d36-3	1,4-Butaned	Emission to	surface water	kg	2.005E-10
8b46f615-6f	Argon-40	Resource	in air	kg	0.0012756	38a622c6-f0	1,4-Butaned	Emission to	high populat	kg	8.719E-11
8b46f615-6f	Argon-40	Resource	in air	kg	4.515E-05	38a622c6-f0	1,4-Butaned	Emission to	high populat	kg	6.341E-11
e16fd15c-0e	Arsenic	Resource	in ground	kg	1.263E-09	d6911d36-3	1,4-Butaned	Emission to	surface water	kg	1.458E-10
e16fd15c-0e	Arsenic	Resource	in ground	kg	3.168E-08	38a622c6-f0	1,4-Butaned	Emission to	high populat	kg	2.169E-09
e16fd15c-0e	Arsenic	Resource	in ground	kg	7.511E-08	d6911d36-3	1,4-Butaned	Emission to	surface water	kg	4.988E-09
e16fd15c-0e	Arsenic	Resource	in ground	kg	2.697E-08	38a622c6-f0	1,4-Butaned	Emission to	high populat	kg	1.952E-09
e16fd15c-0e	Arsenic	Resource	in ground	kg	2.014E-08	d6911d36-3	1,4-Butaned	Emission to	surface water	kg	4.49E-09
240177d8-6	Barium	Resource	in ground	kg	0.000318	541a823c-0a	1-Pentanol	Emission to	high populat	kg	1.076E-12
240177d8-6	Barium	Resource	in ground	kg	0.002568	e4526360-b	1-Pentanol	Emission to	surface water	kg	2.584E-12

Evaporation:

The LCA of evaporation would evaluate the energy consumption and emissions associated with evaporating milk or other liquids. This analysis would include factors such as fuel usage for heating, electricity consumption for machinery, and potential emissions of greenhouse gases or other pollutants.

Table 1.2 Evaporation Inventory Input and Output

Inputs						Outputs					
Flow UUII	Flow	Category	Sub-categ	Unit	Result	Flow UUII	Flow	Category	Sub-categ	Unit	Result
a45cd247	Aluminiur	Resource	in ground	kg	4.9E-05	9645e02f	1,2-Dichlo	Emission	high popu	kg	2.76372E-12
a45cd247	Aluminiur	Resource	in ground	kg	0.00085	79b3f708	1,2-Dichlo	Emission	surface w	kg	1.89701E-07
a45cd247	Aluminiur	Resource	in ground	kg	0.00068	79b3f708	1,2-Dichlo	Emission	surface w	kg	5.01297E-07
a45cd247	Aluminiur	Resource	in ground	kg	0.00434	9645e02f	1,2-Dichlo	Emission	high popu	kg	1.12247E-10
6df9ea09	Anhydrite	Resource	in ground	kg	2.4E-09	9645e02f	1,2-Dichlo	Emission	high popu	kg	4.53088E-12
6df9ea09	Anhydrite	Resource	in ground	kg	7.8E-09	79b3f708	1,2-Dichlo	Emission	surface w	kg	3.79173E-07
6df9ea09	Anhydrite	Resource	in ground	kg	4.1E-09	9645e02f	1,2-Dichlo	Emission	high popu	kg	1.41911E-11
6df9ea09	Anhydrite	Resource	in ground	kg	7.2E-07	79b3f708	1,2-Dichlo	Emission	surface w	kg	9.74309E-07
47262180	Antimony	Resource	in ground	kg	1.6E-11	5b7d620e	1,3-Dioxol	Emission	unspecific	kg	1.27553E-09
47262180	Antimony	Resource	in ground	kg	9.9E-10	5b7d620e	1,3-Dioxol	Emission	unspecific	kg	7.79597E-09
47262180	Antimony	Resource	in ground	kg	8.2E-10	5b7d620e	1,3-Dioxol	Emission	unspecific	kg	4.10223E-09
47262180	Antimony	Resource	in ground	kg	9.2E-10	5b7d620e	1,3-Dioxol	Emission	unspecific	kg	1.17344E-08
8b46f615	Argon-40	Resource	in air	kg	6.6E-06	38a622c6	1,4-Butan	Emission	high popu	kg	3.19721E-11
8b46f615	Argon-40	Resource	in air	kg	4.9E-05	d6911d36	1,4-Butan	Emission	surface w	kg	7.35337E-11
8b46f615	Argon-40	Resource	in air	kg	3.9E-05	d6911d36	1,4-Butan	Emission	surface w	kg	2.00461E-10
8b46f615	Argon-40	Resource	in air	kg	0.00128	38a622c6	1,4-Butan	Emission	high popu	kg	8.71876E-11
e16fd15c	Arsenic	Resource	in ground	kg	1.3E-09	38a622c6	1,4-Butan	Emission	high popu	kg	6.34086E-11
e16fd15c	Arsenic	Resource	in ground	kg	3.2E-08	d6911d36	1,4-Butan	Emission	surface w	kg	1.45777E-10
e16fd15c	Arsenic	Resource	in ground	kg	7.5E-08	38a622c6	1,4-Butan	Emission	high popu	kg	2.1711E-09
e16fd15c	Arsenic	Resource	in ground	kg	2.8E-08	d6911d36	1,4-Butan	Emission	surface w	kg	4.99347E-09
240177d8	Barium	Resource	in ground	kg	0.00032	541a823c	1-Pentand	Emission	high popu	kg	1.07646E-12
240177d8	Barium	Resource	in ground	kg	0.00257	e4526360	1-Pentand	Emission	surface w	kg	2.58352E-12
240177d8	Barium	Resource	in ground	kg	0.00263	e4526360	1-Pentand	Emission	surface w	kg	1.50787E-10
240177d8	Barium	Resource	in ground	kg	0.00212	541a823c	1-Pentand	Emission	high popu	kg	6.28275E-11
ac3a8914	Basalt	Resource	in ground	kg	3.2E-06	541a823c	1-Pentand	Emission	high popu	kg	2.14523E-12
ac3a8914	Basalt	Resource	in ground	kg	0.00019	e4526360	1-Pentand	Emission	surface w	kg	5.14858E-12
ac3a8914	Basalt	Resource	in ground	kg	0.00017	541a823c	1-Pentand	Emission	high popu	kg	6.33547E-12

Pasteurization:

Past LCA studies on pasteurization have focused on energy consumption, water usage, and emissions of greenhouse gases and other pollutants. The assessment would consider the energy required for heating, water usage for cleaning and processing, and emissions from heating sources or chemical treatments used in the pasteurization process.

Fermentation:

Fermentation processes typically involve microbial activity to produce products like yogurt or other fermented foods. LCA would evaluate the environmental impacts associated with fermentation, including energy usage for maintaining optimal fermentation conditions, water consumption, and potential emissions of gases like carbon dioxide or methane.

Packaging of Yogurt:

The packaging process involves materials such as plastic, paper, or cardboard, which have associated environmental impacts from extraction or production to disposal. LCA would assess factors like material sourcing, energy consumption in packaging production, transportation emissions, and end-of-life disposal methods such as recycling or landfilling.

Filling:

LCA of filling would analyze the energy consumption and emissions associated with filling containers with the finished product. This assessment would include electricity usage for filling machinery, emissions from transportation of filled containers, and potential waste generation from packaging materials.

Cooling:

Cooling processes typically require energy for refrigeration or chilling, contributing to electricity consumption and associated emissions. LCA would evaluate the energy intensity of cooling equipment, refrigerant emissions, and potential impacts of coolant leakage on the environment.

Separation:

Separation processes, such as separating solids from liquids, may involve mechanical or chemical methods with associated energy and resource requirements. LCA would assess factors such as energy usage for separation equipment, chemical usage, and waste generation from separated materials.

Once the LCAs of each process are completed separately, the results can be integrated to obtain the final environmental impacts of the entire system. This integration involves aggregating the results from each process, considering their respective contributions to the overall production system. The final LCA results would provide insights into the environmental performance of the entire production process, helping to identify areas for improvement and optimize sustainability.

The intermediate processes lead to final processes such as clarification, evaporation, pasteurization, fermentation, packaging of yogurt, filling, cooling, and separation.

These final processes likely represent the steps involved in preparing the final products for distribution.

Output Flows:

The final processes contribute to the production of various products, such as yogurt, cream, and others, as indicated in the "Production of..." sections. Each product has a production quantity listed, suggesting the output of the entire production process.

Flow of Materials:

The arrows between processes indicate the flow of materials from one process to another, showing how inputs from earlier stages contribute to subsequent stages.

Integration of Inputs and Outputs:

The chart illustrates the integration of different inputs and processes to achieve the final production of various products efficiently. Overall, this chart provides a visual representation of the complex production process involved in manufacturing different products, highlighting the interconnectedness of various stages and the flow of materials throughout the process.

Table 1.3 Process Flow Inputs

Flow	Clarification	Cooling	Evaporation	Fermentation	Filling	Packaging of Yogurt	Pasteurization	Separation	Final Production of Yogurt
TAP	0.025985126	0.000285674	0.013612971	0.030860809	0.021634349	0.001608882	0.021634349	0.021634349	0.137256508
GWP20	7.312938105	0.325207493	5.573432908	9.374884553	7.257298782	1.332914654	7.257298782	7.257298782	45.69127406
FETP	0.230899548	0.00609949	0.189856337	0.315551838	0.242446198	0.016220071	0.242446198	0.242446198	1.485965879
METP	0.067327785	0.001701079	0.054744675	0.094966768	0.071971635	0.004784066	0.071971635	0.071971635	0.439439278
TETP	8.105741345	0.194423089	6.827754717	10.89957947	8.421857565	0.475895249	8.421857565	8.421857565	51.76896656
FFP	1.12929951	0.087727557	1.064215775	1.319830613	1.114091574	0.449754772	1.114091574	1.114091574	7.39310295
FEP	0.001413593	2.0451E-05	0.001079294	0.001614437	0.001284714	0.000117651	0.001284714	0.001284714	0.00809957
MEP	0.000809608	2.20356E-06	0.000238646	0.002739025	0.001468341	1.32186E-05	0.001468341	0.001468341	0.008207725
HTPc	0.002348256	3.1798E-05	0.001901403	0.003394327	0.002570951	0.000155909	0.002570951	0.002570951	0.015544546
HTPnc	0.125001406	0.00356814	0.087508977	0.233309301	0.156515067	0.011244452	0.156515067	0.156515067	0.930177475
IRP	0.387774243	0.003196967	0.367124737	0.432236178	0.387831941	0.025340346	0.387831941	0.387831941	2.379168295
LOP	15.00262054	0.001058748	0.060670155	11.27197299	5.974948617	0.010994467	5.974948617	5.974948617	44.27216275
SOP	0.282350806	0.002578899	0.27222329	0.296306132	0.280741733	0.009881318	0.280741733	0.280741733	1.705565642
ODPinfinite	4.18933E-05	3.98147E-08	3.76282E-05	4.65072E-05	4.19713E-05	1.23972E-07	4.19713E-05	4.19713E-05	0.000252107
PMFP	0.001885654	3.74054E-05	0.001513895	0.002698753	0.001962493	0.000207009	0.001962493	0.001962493	0.012230197
HOFP	0.008816076	0.000233922	0.006769098	0.011522173	0.008666318	0.001305095	0.008666318	0.008666318	0.054645317
EOFP	0.009258129	0.000263739	0.007179019	0.012074021	0.009121886	0.001435302	0.009121886	0.009121886	0.057575868
WCP	0.162911966	0.000935966	0.118768652	0.208615878	0.159147048	0.003700087	0.159147048	0.159147048	0.972377324

Analysis of Highest and Lowest Values

Highest Value:

Terrestrial Ecotoxicity Potential (TETP): Final Production of Yogurt (51.76896656)

This high value indicates that the final production stage has a substantial potential impact on terrestrial ecosystems due to the release of toxic substances. This could affect soil quality, plant health, and animal life, highlighting the need for mitigation measures to reduce toxicity.

Lowest Value

Ozone Depletion Potential (ODPinfinite): Cooling (3.98147E-08)

The very low value for ozone depletion potential during the cooling stage suggests minimal impact on the ozone layer from this process. This is beneficial for environmental sustainability as it indicates low emissions of ozone-depleting substances during this stage.

Impact on Environmental Sustainability

High Impact Areas:

Global Warming Potential (GWP20): High values across various stages, particularly in fermentation (9.374884553) and final production (45.69127406), indicate significant greenhouse gas emissions contributing to climate change. Reducing these emissions is crucial for mitigating global warming.

Agricultural Land Occupation (LOP): High values in clarification (15.00262054) and final production (44.27216275) reflect extensive land use, which can lead to habitat destruction and biodiversity loss. Sustainable land management practices are essential.

Low Impact Areas:

Freshwater Eutrophication Potential (FEP) and Marine Eutrophication Potential (MEP):

Relatively low values across all stages suggest minimal risk of nutrient pollution in aquatic systems, which is favorable for maintaining water quality.

Ozone Depletion Potential (ODP_{infinite}): Consistently low values across all stages indicate minimal contribution to ozone layer depletion, benefiting atmospheric health. In summary, the highest values indicate critical areas requiring attention to reduce environmental impacts, particularly in reducing toxicity and greenhouse gas emissions.

Results Identified:

The results of the study on dahi production in India revealed several key findings. Firstly, the gate-to-gate Life Cycle Assessment (LCA) highlighted the environmental impacts associated with various stages of dahi production, from milk sourcing to final product packaging. The analysis identified significant resource use, energy consumption, and emissions throughout the production process. Specifically, the data collected and analyzed using OpenLCA 3.0 software and the ecoinvent database showed that the production of dahi involved the use of approximately 600 liters of raw milk per kilogram of the final product. This resulted in a milk loss of 143 liters, indicating inefficiencies in the production process.



Fig 5. Fossil Fuel Potential

This graph shows the potential impact of yogurt production on freshwater eutrophication. The red bar indicates the highest impact, followed by the blue, yellow, green, purple, and gray bars. The highest impact is associated with the market for hydrogen peroxide, without water, in a 50% solution state. This suggests that the production process or sourcing of hydrogen peroxide contributes significantly to freshwater eutrophication in this LCA.



Fig 6. Fresh water Ecotoxicity Potential

This graph represents the potential ecotoxicity impact of yogurt production on freshwater ecosystems. The red bar indicates the highest impact, followed by the blue, yellow, green, purple, and gray bars. The market for hydrogen peroxide without water in a 50% solution state shows the highest impact, followed by chlor-alkali electrolysis and nitric acid production. These results suggest that certain chemicals used in the yogurt production process contribute significantly to ecotoxicity in freshwater environments.



Fig 7. Freshwater Eutrophication Potential

The graph depicts the freshwater eutrophication potential associated with various stages or processes involved in yogurt production, represented by different values measured in kilograms of phosphorus equivalents (kg P-Eq). Each bar in the graph corresponds to a specific process or activity in the production chain. For instance, the first bar represents the eutrophication potential attributed to chlor-alkali electrolysis, membrane cell sodium hydroxide, without water in a 50% solution state. Similarly, the second bar represents the eutrophication potential linked to the market for hydrogen peroxide without water in a 50% solution state. The significance of this graph lies in its ability to illustrate the relative contribution of different stages or processes to freshwater eutrophication potential within the yogurt production life cycle. By comparing the values represented by each bar, stakeholders can identify which stages or processes have the greatest impact on freshwater eutrophication potential and prioritize mitigation efforts accordingly.



Fig 8. Global Warming Potential

This graph illustrates the potential contribution of yogurt production to global warming. The red bar represents the highest impact, followed by the blue, yellow, green, purple, and gray bars. Nitric acid production and market for hydrogen peroxide without water in a 50% solution state contribute the most to global warming potential. These findings highlight the importance of considering greenhouse gas emissions throughout the yogurt production life cycle.



Fig 9. Human Toxicity Potential

The graph depicts the human toxicity potential associated with different stages or processes involved in yogurt production, measured in kilograms of 1,4-dichlorobenzene equivalents (kg 1,4 DCB-Eq). Each bar in the graph represents a specific stage or activity within the yogurt production process. For example, the first bar corresponds to the human toxicity potential attributed to the market for hydrogen peroxide without water in a 50% solution state. Similarly, the second bar represents the potential linked to chlor-alkali electrolysis membrane cell production.

The significance of this graph lies in its ability to visually demonstrate the relative contribution of each stage or process to human toxicity potential within the yogurt production life cycle. By comparing the values represented by each bar, stakeholders can identify which stages or processes have the greatest impact on human toxicity potential and prioritize mitigation efforts accordingly. In the context of Life Cycle Assessment (LCA) of yogurt production, this graph provides valuable insights for assessing and managing environmental impacts related to human toxicity.

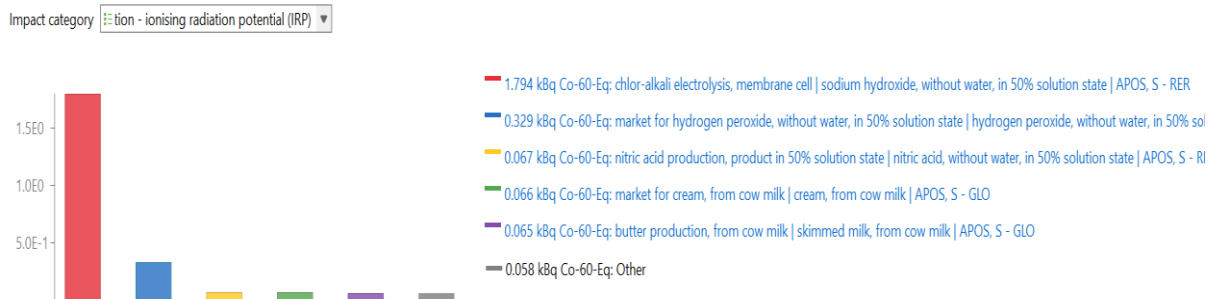


Fig 10. Ionizing Radiation Potential

The graph illustrates the ionizing radiation potential associated with different stages or processes involved in yogurt production, measured in kilobecquerels of cobalt-60 equivalents (kBq Co-60-Eq).

Each bar in the graph represents a specific stage or activity within the yogurt production process. For example, the first bar corresponds to the ionizing radiation potential attributed to chlor alkali electrolysis membrane cell production. Similarly, the second bar represents the potential linked to the market for hydrogen peroxide without water in a 50% solution state. The significance of this graph lies in its ability to visually depict the relative contribution of each stage or process to ionizing radiation potential within the yogurt production life cycle.

Understanding this impact allows for targeted mitigation efforts to reduce radiation emissions associated with this stage. It indicates the environmental impact of sourcing hydrogen peroxide for yogurt production and highlights areas for reducing radiation emissions associated with this input. It indicates the environmental impact of procuring cream, an ingredient in yogurt production, and suggests opportunities for reducing radiation emissions in cream production. It underscores the need for further investigation into these unspecified processes to identify and address radiation emissions, thereby improving the overall environmental sustainability of yogurt production.



Fig 11. Marine Ecotoxicity Potential

The clarification stage has a moderate METP value. This suggests that while there are some releases of potentially toxic substances, this stage is not the primary contributor to marine ecotoxicity in the yogurt production process. The cooling stage has a very low METP value. This indicates minimal impact on marine ecosystems, suggesting that the substances used or released during cooling are not significantly harmful to marine life. The evaporation stage has a moderate METP value, slightly lower than clarification. This stage contributes to marine ecotoxicity but is not among the highest contributors, indicating some release of toxic substances. Fermentation has the highest METP value among the stages. This suggests that the fermentation process involves the release of substances with a significant potential for marine toxicity.

This stage is a critical area for intervention to reduce marine ecotoxic impacts. The filling stage also has a relatively high METP value. This indicates a substantial contribution to marine ecotoxicity, potentially due to materials or processes involved in filling the yogurt containers. The packaging stage has a low METP value, indicating minimal contribution to marine toxicity. This suggests that packaging materials and processes are relatively benign in terms of marine ecotoxicity. Similar to the filling stage, pasteurization has a high METP value. This indicates that the heat treatment process may involve substances that are harmful to marine ecosystems.

The separation stage has the same METP value as filling and pasteurization, indicating a significant contribution to marine ecotoxicity. This stage involves processes that release toxic substances affecting marine life. The final production stage has the highest cumulative METP value. This stage encompasses all previous stages and highlights the aggregate impact of the entire yogurt production process on marine ecosystems. The high value underscores the need for comprehensive strategies to mitigate marine ecotoxicity throughout the production lifecycle.

Significance of METP Values:

High METP Values (Fermentation, Filling, Pasteurization, Separation, Final Production): These stages are critical contributors to marine ecotoxicity. They likely involve processes or materials that release higher amounts of toxic substances. Efforts to reduce marine toxicity should prioritize these stages by investigating and mitigating sources of harmful emissions.

Moderate METP Values (Clarification, Evaporation): These stages also contribute to marine ecotoxicity but to a lesser extent. They represent secondary targets for ecotoxicity reduction measures.

Low METP Values (Cooling, Packaging of Yogurt): These stages have minimal impact on marine ecotoxicity. They are likely using processes and materials that are less harmful to marine environments, making them less of a priority for ecotoxicity mitigation efforts.



Fig 12. Ozone Depletion Potential

This graph illustrates the potential impact of yogurt production on ozone layer depletion. The red bar indicates the highest impact, followed by the blue, yellow, green, purple, and gray bars. Nitric acid production shows the highest impact, followed by butter production and the market for cream. These results suggest that certain processes or substances used in yogurt production, such as nitric acid, may contribute significantly to ozone layer depletion.

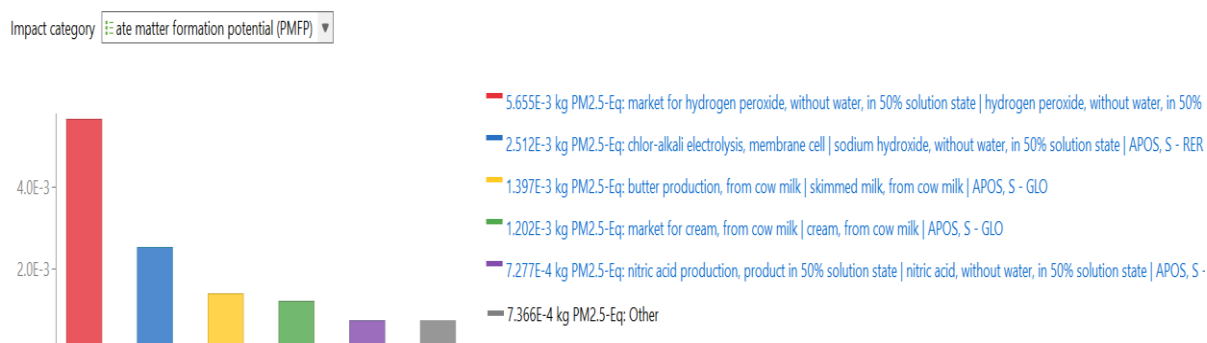


Fig 13. Particulate Matter Formation Potential

Particulate Matter Formation Potential (PMFP) measures the potential for processes to contribute to the formation of particulate matter (PM), which includes tiny particles that can be inhaled and cause adverse health effects, such as respiratory and cardiovascular diseases. In the provided data, PMFP values indicate the extent to which each stage of yogurt production contributes to air pollution through PM emissions. These values are critical for understanding the impact on air quality and public health. High PMFP values, particularly during stages like fermentation and filling, highlight areas where improvements could reduce harmful particulate emissions, thereby enhancing environmental sustainability and reducing health risks associated with air pollution.



Fig 14. Photochemical Oxidant Formation

Photochemical Oxidant Formation Potential (HOFP) assesses the likelihood of generating photochemical oxidants, such as ground-level ozone, which can harm human health and ecosystems. The data highlights the contribution of each yogurt production stage to the formation of these harmful oxidants. Stages like fermentation and filling show higher HOFP values, indicating significant emissions of precursor substances like volatile organic compounds (VOCs) and nitrogen oxides (NOx). These emissions can lead to smog formation, affecting air quality and respiratory health. Understanding and mitigating high HOFP values in yogurt production is essential for reducing air pollution and protecting both environmental and public health.

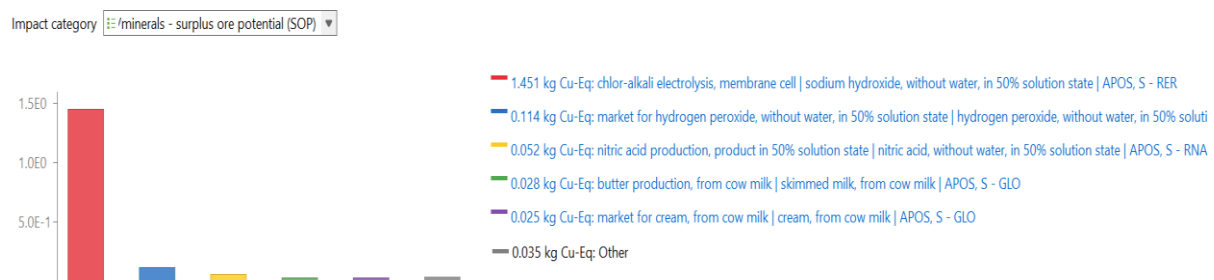


Fig 15. Surplus ore potential

Surplus Ore Potential (SOP) evaluates the environmental impact associated with the extraction and depletion of metal and mineral resources required for yogurt production. This metric indicates how each production stage contributes to the consumption of these non-renewable resources. The provided data shows that stages such as fermentation and filling have higher SOP values, suggesting significant use of metal and mineral resources. This consumption can lead to resource scarcity and increased environmental degradation from mining activities. By identifying and addressing high SOP values, producers can work towards more sustainable resource management practices, thereby reducing the environmental footprint and promoting resource conservation.



Fig 16. Terrestrial Acidification Potential

This graph shows the potential impact of yogurt production on terrestrial acidification. The red bar indicates the highest impact, followed by the blue, yellow, green, purple, and gray bars. Nitric acid production exhibits the highest impact, followed by the market for hydrogen peroxide and butter production. This suggests that acidifying emissions from nitric acid production significantly contribute to terrestrial acidification in this LCA.



Fig 17. Water Consumption Potential

This graph represents the potential water consumption impact of yogurt production. The red bar indicates the highest impact, followed by the blue, yellow, green, purple, and gray bars. The market for hydrogen peroxide without water in a 50% solution state exhibits the highest water consumption potential. This suggests that the production process requiring hydrogen peroxide contributes significantly to water consumption in yogurt production.

Impacts

The life cycle assessment of yogurt production reveals significant environmental impacts, particularly in climate change (GWP20) and terrestrial ecotoxicity (TETP), with values of 45.691 and 51.769, respectively. These stages contribute notably to greenhouse gas emissions and toxic effects on land ecosystems. Land use (LOP) also shows a high impact, reflecting extensive agricultural land occupation. Other moderate to high impacts include freshwater ecotoxicity (FETP), fossil fuel use (FFP), and ionising radiation (IRP), highlighting the need for sustainable resource management. Conversely, impacts on freshwater and marine eutrophication (FEP and MEP), ozone depletion (ODP), and particulate matter formation (PMFP) are relatively low, indicating lesser contributions to these environmental issues. Addressing high-impact areas through improved efficiency and sustainable practices is crucial for reducing the overall environmental footprint of yogurt production.

Table 1.4 Final Yogurt Production Impacts

Impact category	Result
acidification: terrestrial - terrestrial acidification potential (TAP)	0.137256508
climate change - global warming potential (GWP20)	45.69127406
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	1.485965879
ecotoxicity: marine - marine ecotoxicity potential (METP)	0.439439278
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	51.76896656
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	7.39310295
eutrophication: freshwater - freshwater eutrophication potential (FEP)	0.00809957
eutrophication: marine - marine eutrophication potential (MEP)	0.008207725
human toxicity: carcinogenic - human toxicity potential (HTPc)	0.015544546
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	0.930177475
ionising radiation - ionising radiation potential (IRP)	2.379168295
land use - agricultural land occupation (LOP)	44.27216275
material resources: metals/minerals - surplus ore potential (SOP)	1.705565642
ozone depletion - ozone depletion potential (ODPinfinite)	0.000252107
particulate matter formation - particulate matter formation potential (PMFP)	0.012230197
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	0.054645317
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	0.057575868
water use - water consumption potential (WCP)	0.972377324

Conclusions:

This research provides a comprehensive Life Cycle Assessment (LCA) of dahi production in India, employing a gate-to-gate approach to evaluate environmental impacts. The study effectively covers all stages of the production process, from the initial raw milk input to the final dahi product. Utilizing OpenLCA 3.0 software, the analysis incorporates data from the ecoinvent database and applies the ReCiPe 2016 V1.03 impact assessment method. The life cycle assessment (LCA) of yogurt production, as detailed in the provided data, reveals several key insights into the environmental impacts across various production stages. Each stage contributes differently to various environmental flows, including global warming potential, ecotoxicity, eutrophication, human toxicity, land use, and resource depletion.

High Impact Stages:

Fermentation and Final Production:

These stages consistently show high values across multiple metrics such as Global Warming Potential (GWP), Terrestrial Ecotoxicity Potential (TETP), and Marine Ecotoxicity Potential (METP). This indicates substantial contributions to climate change, toxicity in both terrestrial and marine environments, and overall resource consumption.

Filling and Pasteurization:

These stages also have significant environmental impacts, particularly in terms of human toxicity, particulate matter formation, and photochemical oxidant formation.

Moderate Impact Stages:

Clarification and Evaporation:

These stages contribute moderately to various impacts, including terrestrial acidification and freshwater ecotoxicity. They represent secondary targets for environmental improvements.

Low Impact Stages:

Cooling and Packaging:

These stages exhibit low values for most environmental metrics, indicating minimal contributions to overall environmental degradation. Efforts to reduce impacts in these stages might yield lower sustainability returns compared to higher-impact stages.

Implications for Environmental Sustainability:

Resource Management:

High values in Surplus Ore Potential (SOP) and Fossil Fuel Potential (FFP) during fermentation and final production highlight the need for better resource management practices. Emphasizing recycling, efficient resource use, and renewable energy can mitigate these impacts.

Toxic Emissions:

Elevated ecotoxicity potentials in certain stages point to the necessity of reducing harmful emissions and adopting cleaner production technologies. This can protect both terrestrial and marine ecosystems from toxic substances.

Air Quality and Health:

The significant values in Particulate Matter Formation Potential (PMFP) and Photochemical Oxidant Formation Potential (HOFP) indicate the need to address air pollutants that affect human health. Implementing air filtration systems, reducing volatile organic compound emissions, and optimizing combustion processes can improve air quality.

Climate Change Mitigation:

High Global Warming Potential (GWP) values necessitate efforts to lower greenhouse gas emissions. This can be achieved by improving energy efficiency, utilizing low-carbon technologies, and integrating renewable energy sources into the production process.

The research underscores the importance of targeting high-impact stages in yogurt production to enhance environmental sustainability. By focusing on reducing emissions, optimizing resource use, and improving production efficiencies in stages like fermentation and final production, the overall environmental footprint of yogurt production can be significantly reduced.

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