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***ORIGINAL ARTICLE***

# Environmental Footprints of Yogurt Production: A Case Study of a Small-Scale Manufacturing Process in Sri Lanka

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**Abstract**

This study investigated the life cycle environmental impacts of yogurt production from cradle to gate at the Pulathisi milk factory in Polonnaruwa, Sri Lanka. The functional unit considered was one kilogram of yogurt produced in the factory using existing technology. The defined system boundary encompassed raw milk production and transportation, machinery fabrication, standardization of milk, and standard unit operations of yogurt production. Material and energy usage data were collected through a series of observations, literature and Ecoinvent 3.7.1 databases. The ReCiPe 2008 method was employed for impact analysis, considering eighteen impact categories with SimaPro software. The inventory analysis included material consumption for machinery fabrication, energy consumption, and emissions for each unit operation in yogurt production. Results were characterized using midpoint indicators, and normalized impacts were calculated. The characterized outcomes of the yogurt production process contributed 2.48 kg$CO_2$eq to climate change, 0.0297 kg$SO_2$eq to acidification, 0.0002 kgPeq to eutrophication, and 6.9199 kg 1,4-DBeq to human toxicity. The study identified hotspots, emphasizing the significant contributions of cow milk production and electricity usage to environmental impacts. Potential mitigations, such as improved waste management in dairy farming and switching to renewable energy sources, are proposed to address these impacts. The normalized impacts provided insights for decision-makers and stakeholders to compare environmental performances and guide sustainable practices in yogurt production. The total impact was recorded as 0.014-person equivalent per year per one kilogram of yogurt.

***Keywords:*** *Cow milk, Environmental impacts, Normalized impacts, Renewable energy, Sustainable practices*

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## 1. Introduction

Agriculture has a significant role in the economies of many developing nations. The dairy industry serves as a vital component in all agricultural-based economies. The global dairy output is growing continuously as the demand for dairy products continues to rise considerably due to population expansion and livelihood changes. The increased demand for high-quality nutrients in developing nations primarily fuels the surge in milk production (Houssard et al. 2021).

The surge in consumer demand for milk has led to an increased focus on processing raw milk to produce a variety of milk-based products. This includes well-known dairy items such as liquid milk, cheese, yogurt, butter, and a range of desserts. The procedures and technologies used in milk processing are adaptable, with variations based on both regional preferences and the intended end product. The complete process involves steps such as milk collection, testing, cream separation, standardization, pasteurization, homogenization, chilling, fermentation, addition of additives, packaging, storage, and distribution (CRB 2023). Each stage contributes to the transformation of raw milk into a broad assortment of edible dairy delights. Nevertheless, the production and processing of milk demand a substantial energy input across all three stages: agriculture, dairy farming, and industrial operations (Mojarab Soufiyan and Aghbashlo 2017). Globally, the dairy sector ranks fifth in terms of most energy-intensive industries, following oil, chemical, pulp and paper mill, and iron and steel manufacturing sectors (Munir, Yu, and Young 2014).

With the increasing production and processing of milk, there is a growing pressure on the environment, especially on freshwater and air (WWF 2024). Dairy farming has environmental implications, with dairy cows and their manure are sources of greenhouse gas emissions that contribute to climate change (Santos et al. 2022). In addition, inapproriate management of manure and fertilizers poses a hazard to local water resources (Bijay-Singh and Craswell 2021). The sustainability of dairy farming practices and feed production results in the loss of ecologically important landscapes, including prairies, wetlands, and forests. Addressing these environmental challenges is critical for promoting a more sustainable and environmentally conscious dairy industry, and it necessitates a collaborative effort involving farmers, the dairy industry, and other stakeholders to prioritize environmental conservation. The integration of life cycle assessment (LCA) emerges as a valuable tool for comprehensively evaluating the environmental impact of dairy farming practices, promoting sustainability, and identifying avenues for improvement ( Rousset et al. 2011; Kwofie and Ngadi 2011)] .

In Sri Lanka, in year 2022, the overall milk production reached 506.5 million liters, with cow milk accounting for 419.2 million liters, while the remaining share was buffalo milk (DCS 2024). In 2019, Sri Lanka exported approximately 1366 metric tons of milk and milk products, while importing 98,837 metric tons of similar goods, resulting in an expenditure of nearly 282 million US dollars (Damunupola et al. 2022). Yogurt emerging as a highly favored dairy product in the country, constituting over 80% of the total dairy market (Jahan et al. 2021). Therefore, the goal of this case study was to explore the environmental footprints associated with yogurt production in Sri Lanka, which delves into the various ecological aspects and impacts of the Sri Lankan yogurt manufacturing processes. Through assessing and understanding the environmental implications of yogurt production, the sustainability considerations, and potential areas for improvement within this specific industry in Sri Lanka can be identified.

## 2. Materials and Methods

### The goal and scope definition

The life cycle environmental impacts of yogurt production from cradle to gate in Pulathisi milk factory, Polonnaruwa, Sri Lanka was investigated. The functional unit was considered as 1 kg of yogurt produced in the factory using existing technology, considering raw milk production and transportation, fabrication of machinery, standardization of milk, milk heating, homogenization, pasteurization, cooling, filling, incubation, refrigeration, and storing. Fig. 1 shows the system boundaries considered in this study.

### Data sources and analyzing

Material and energy consumption data for yogurt production were obtained through experiments conducted at the Pulathisi Milk Factory in Polonnaruwa, Sri Lanka, comprising five process cycles during typical factory operations. Required secondary data were collected from literature and Ecoinvent 3.7.1 databases. ReCiPe 2008 (Hierarchist perspective (H), version 1.12) with midpoint indicators and world normalization factors was usedfor the impact analysis. The ReCiPe method provides three perspectives on the assessment of environmental impacts, such as egalitarian (E), hierarchist (H), and individualist (I). The individualist perspective focusses on short-term interest, well-established impact types, and an optimistic view of human adaptability to technology. The egalitarian perspective adopts an overly cautious approach, considering the longest timeframe and potential impact types that are not yet fully understood, howevershow some early indications. The hierarchist perspective, on the other hand, aligns with commonly observed policy principles regarding timing and other concerns (SimaPro 2022).
Midpoint indicators, also known as impact categories, were used in LCA studies to quantify the potential environmental impacts associated with a specific product or process. Midpoint indicators aim to simplify the complex and diverse set of environmental impacts across different life cycle stages into a smaller set of measurable and comparative indicators. These represent the midpoint between inventory analysis, which quantifies the inputs and outputs, and the endpoint analysis, which assesses the potential impacts on human health, ecosystems, and resources. The midpoint results were used in this study, as the results from the midpoint level are relatively robust (Prasara-A2009).

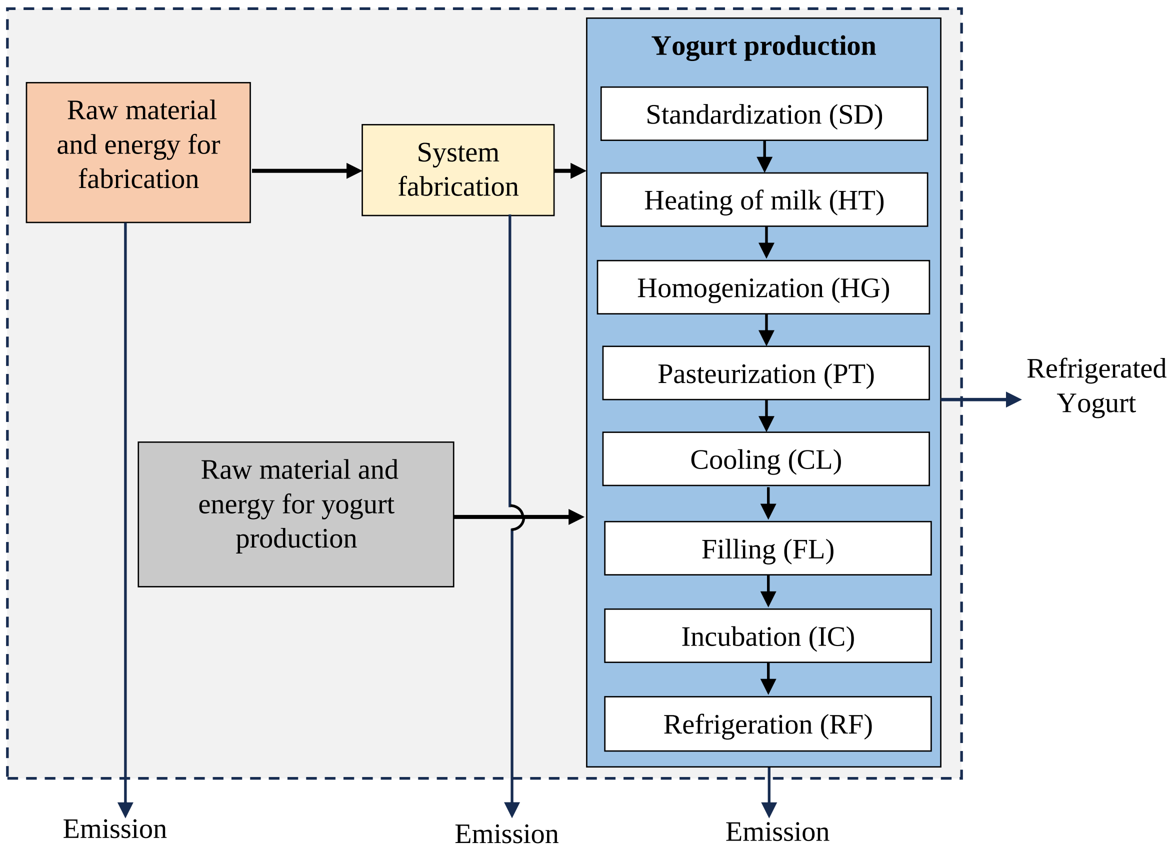


**Figure 1.** System boundary for yogurt production

Eighteen impact categories such as climate change (CC), ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), human toxicity (HT), photochemical oxidant formation (PO), particulate matter formation (PM), terrestrial ecotoxicity (TE), freshwater ecotoxicity (Fec), marine ecotoxicity (Mec), ionizing radiation (IR), agricultural land occupation (ALO), urban land occupation (ULO), natural land transformation (NLT), water depletion (WD), metal depletion (MD), and fossil depletion (FD) are available in the ReCiPe method, and all these impact categories were considered in this study (Kahandage et al. 2023). The LCA was conducted with SimaPro software (Version 8.4.0.0).

**Inventory analysis**

According to Figure 1, the contribution of the fabrication of machinery and infrastructure was considered for each yogurt production process. The study focused on the available machinery and equipment, including cream separators, heating boilers, homogenizers, pasteurizers, cooling tanks, filling machines, incubators, and cooling rooms at the Pulathisi milk factory in Polonnaruwa, Sri Lanka. The goal was to investigate the materials used to manufacture all these components. Table 1 provides a summary of the materials used in the fabrication process for each unit operation in yogurt production.

The total output (TO) machines were determined using following equation (1),

$$TO = OH \times WC \times LT \qquad (1)$$

where:

OH - annual operating hours (h), WC - working capacity (kgh-1), and LT - Lifetime (y).

Table 2 summarizes the material and energy expenses along with emissions for each unit operation in the yogurt production process.

**Table 1:** Materials used for the fabrication of each process

| Material (kg) | Processes | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **SD** | **HT** | **HG** | **PT** | **CL** | **FL** | **IC** | **RF** |
| Stainless | 75 | 195 | 600 | 195 | 1060 | 400 | - | - |
| Steel | 40 | 20 | - | 20 | 150 | 50 | 40 | - |
| Synthetic | 0.2 | - | - | - | - | - | - | - |
| Copper | 10 | 20 | 25 | 23 | 100 | 20 | 0.5 | 20 |
| Cast iron | 20 | 47 | 85 | 47 | 170 | 40 | - | 30 |
| Aluminum | - | 10 | 10 | 10 | 50 | 10 | - | - |
| Nickel | - | - | - | - | 50 | - | - | 30 |
| Ceramic | - | - | - | - | - | 10 | 0.6 | - |
| Plastics | - | - | - | - | - | - | - | 40 |

For brevity: SD – Standardization, HT- Heating of milk, HG- Homogenization, PT- Pasteurization, CL- Cooling, FL- Filling, IC- Incubation, RF- Refrigeration

**Table 2:** Inventory data to produce 1 kg of yogurt

| Input | Unit | Processes | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | SD | HT | HG | PT | CL | FL | IC | RF |
| **Energy** | | | | | | | | | |
| Electricity | kWh | 0.05 | 0.06 | 0.02 | 0.03 | 0.41 | 0.32 | 0.38 | 0.25 |
| Diesel | L | - | 0.0603 | - | - | - | - | - | - |
| **Material** | | | | | | | | | |
| Raw milk | kg | 1.036 | - | - | - | - | - | - | - |
| Starter culture | kg | - | - | - | - | - | 0.028 | - | - |
| Vanilla | kg | - | - | - | - | - | 0.011 | - | - |
| Sugar | kg | - | 0.143 | - | - | - | - | - | - |
| Milk powder | kg | - | 0.11 | - | - | - | - | - | - |
| Polypropylene | kg | - | - | - | - | - | 0.052 | - | - |
| Aluminum foil | kg | - | - | - | - | - | 0.013 | - | - |
| Transportation | T.km | 51.25 | - | - | - | - | - | - | - |
| **Emission** | | | | | | | | | |
| $CO_2$ | kg | Ei | 0.2032 | Ei | Ei | Ei | Ei | Ei | Ei |
| $CH_4$ | kg | Ei | 0.000008 | Ei | Ei | Ei | Ei | Ei | Ei |
| $N_2O$ | kg | Ei | 0.000001 | Ei | Ei | Ei | Ei | Ei | Ei |

For brevity: SD – Standardization, HT- Heating of milk, HG- Homogenization, PT- Pasteurization, CL- Cooling, FL- Filling, IC- Incubation, RF- Refrigeration, Ei- From Ecoinvent database in SimaPro software

## 3. Results and Discussion

### Characterized midpoint environmental impact results

Characterized results reflect the outcomes derived from the evaluation of the environmental impacts of the full process of the entire life cycle under several impact categories, which represent distinct environmental indicators. For each impact category, the findings quantify the magnitude and significance of environmental impact by assigning numerical values. These values are derived based on the environmental relevance of the inputs and outputs of the studied system, such as resource consumption, emissions, and waste generation. Table 3 outlines the characterized midpoint environmental impact assessment findings for multiple impact categories associated with the production of 1 kg yogurt, utilizing different units for each category. The results assisted assessing and comparing the environmental footprint associated with yogurt production across different impact categories (Table 3).

The global warming potential, which is measured by kg $CO_2$ eq, is the defining factor of climate change (SimaPro 2022); and it has been recorded that 2.48 kg $CO_2$ eq for 1 kg of yogurt production. According to findings, the production of 1 kg of yogurt at a dairy processing facility in Spain releases 1.94 kg $CO_2$ eq (Vasilaki et al. 2016). A study in Serbia has demonstrated that the climate change index for the production of 1 kg of yogurt is 1.672 kg $CO_2$ eq (Djekic et al. 2019). Differences in yogurt production processes contribute to distinct climate change values in economic and regional perspectives.

The characterized results provide a comprehensive understanding of the potential environmental burdens and benefits associated with a particular system or activity. On order to identify the hotspots in the life cycle where interventions can be made to reduce environmental impacts, an analysis of the contribution from each process and input was be carried out. Therefore, Fig. 2 provides a comprehensive breakdown of characterized results according to the contribution of different processes and inputs.

**Table 3:** Characterized midpoint results of production of 1 kg of yogurt

| Impact category | Abbreviation | Unit | Total |
|---|---|---|---|
| Climate change | CC | kg $CO_2$ eq | 2.4817 |
| Ozone depletion | OD | kg CFC-11 eq | 0.000000336 |
| Terrestrial acidification | TA | kg $SO_2$ eq | 0.0297 |
| Freshwater eutrophication | FE | kg P eq | 0.0002 |
| Marine eutrophication | ME | kg N eq | 0.0049 |
| Human toxicity | HT | kg 1,4-DB eq | 6.9199 |
| Photochemical oxidant formation | PO | kg NMVOC | 0.0104 |
| Particulate matter formation | PM | kg $PM_{10}$ eq | 0.0066 |
| Terrestrial ecotoxicity | TE | kg 1,4-DB eq | 0.0037 |
| Freshwater ecotoxicity | Fec | kg 1,4-DB eq | 0.0022 |
| Marine ecotoxicity | Mec | kg 1,4-DB eq | 2.4023 |
| Ionizing radiation | IR | kBq $U_{235}$ eq | 0.0999 |
| Agricultural land occupation | ALO | $m^2a$ | 1.4360 |
| Urban land occupation | ULO | $m^2a$ | 0.0319 |
| Natural land transformation | NLT | $m^2$ | 0.0011 |
| Water depletion | WD | $m^3$ | 0.0248 |
| Metal depletion | MD | kg Fe eq | 0.0923 |
| Fossil depletion | FD | kg oil eq | 0.6858 |

CC- Climate change, OD- Ozone depletion, TA- Terrestrial acidification, FE- Freshwater eutrophication, ME- Marine eutrophication, HT- Human toxicity, PO- Photochemical oxidant formation, PM- Particulate matter formation, TE- Terrestrial ecotoxicity, Fec - Freshwater ecotoxicity, Mec- Marine ecotoxicity, IR- Ionizing radiation, ALO- Agricultural land occupation, ULO- Urban land occupation, NLT- Natural land transformation, WD- Water depletion, MD- Metal depletion, FD- Fossil depletion, and Fab.- Fabrication process

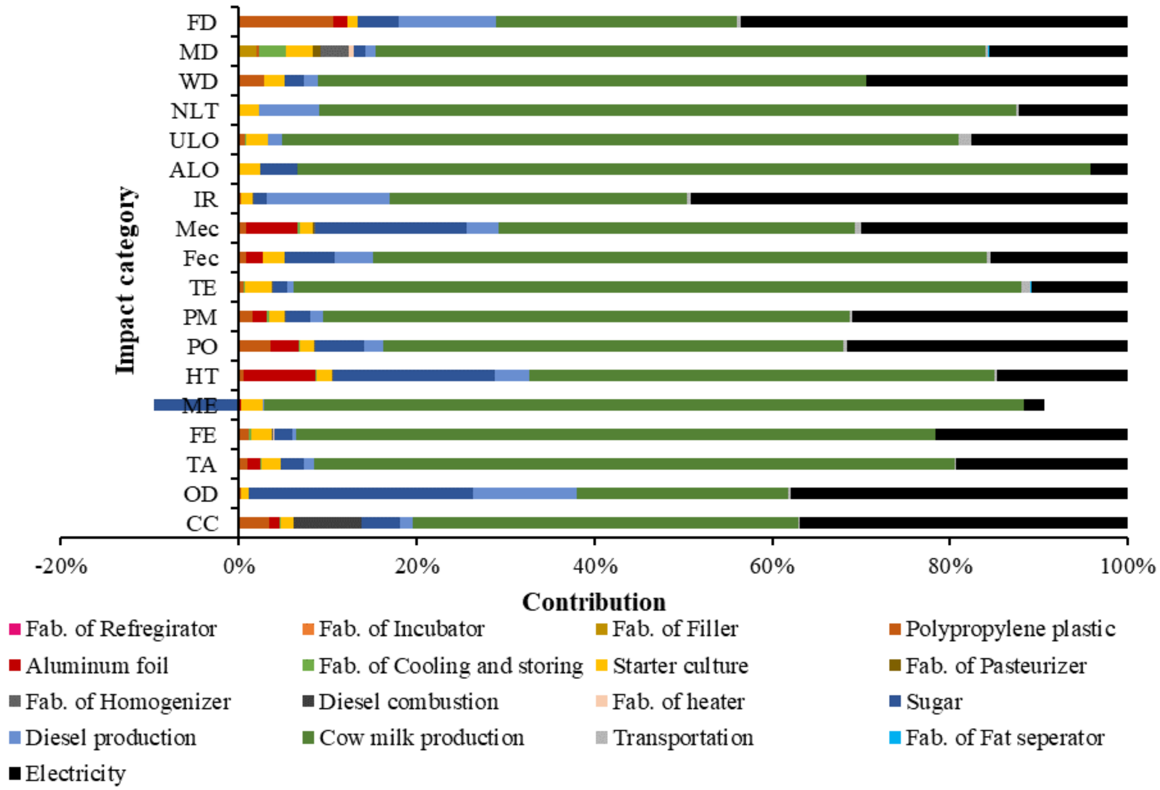


**Figure 2.** Contribution of each component for the characterized results of production of 1kg yogurt (CC- Climate change, OD- Ozone depletion, TA- Terrestrial acidification, FE- Freshwater eutrophication, ME- Marine eutrophication, HT- Human toxicity, PO- Photochemical oxidant formation, PM- Particulate matter formation, TE- Terrestrial ecotoxicity, Fec - Freshwater ecotoxicity, Mec- Marine ecotoxicity, IR- Ionizing radiation, ALO- Agricultural land occupation, ULO- Urban land occupation, NLT- Natural land transformation, WD- Water depletion, MD- Metal depletion, FD- Fossil depletion, and Fab.- Fabrication process).

All midpoint indicators were highly affected by cow milk production process and use of electricity. Cow milk production contributed less than 50% to the impact categories of CC, OD, Mec, IR, and FD, while in contrary, the use of electricity contributes more than 30% to the impact categories of CC, OD, PO, PM, Mec, IR, and FD (Fig. 2).

, The global warming index (2.48 kg $CO_2$ eq) was contributed by 43.30% from cow milk production, 36.85% from electricity, 9.08% from diesel production and combustion, 4.32% from sugar production, 4.60% from packaging, 1.42% from starter culture, 0.26% from transportation, and 0.17% from the fabrication of machinery (Fig. 2). The production process of cow milk and the use of electricity collectively account for over 80% of the climate change index connected with the production of 1 kg of yogurt.

The kg $SO_2$ eq characterizes terrestrial acidification. While acidification potential (AP) is typically characterized by sulfur dioxide ($SO_2$) equivalence, substances including sulfur dioxide ($SO_2$), nitrogen dioxide ($N_2O$), nitrogen monoxide (NO), nitrogen oxides (NOx), and various other compounds have the potential to contribute to acid rain (Kim and Chae 2016). The acidification index to produce 1 kg yogurt was0.0297 kg$SO_2$eq. The cow milk production process considerably influences terrestrial acidification, contributing 72%, while electricity usage adds 19% to this environmental impact.

Eutrophication, alternatively termed nutrification, encompasses the consequences of high quantities of macronutrients in the environment resulting from the release of chemicals into the air, water, and soil (SimaProDatabaseManual 2021). Freshwater eutrophication index for producing 1 kg of yogurt was 0.0002 kgPeq, and was contributed by cow milk production process (71%) and electricity (23%). Sulfur oxides (SOx), nitrogen oxides (NOx), carbon monoxide (CO), and particulate matter ($PM_{10}$) have been recognized as substances toxic to human health (Li and Qian 2012). The human toxicity index to produce 1 kg of yogurt was 6.9199 kg 1,4-DBeq.

The cow milk production process consists of several unit operations such as growing fodder for feeding, making houses, using electricity for lighting and other welfare facilities, milking, and waste disposal, which can contribute to the pollution of the environment significantly (Berton et al. 2021). In the dairy industry, a considerable share of the environmental impacts are attributed to farm operations ( Fantin et al. 2012; Barros et al. 2022). Cattel farming generate substantial volumes of methane, which has a higher global warming potential than carbon dioxide, through their digestion process (EPA 2024) . The collection and storage of cow manure releases ammonia, hydrocarbons, and other volatile organic compounds into the air. These compounds contribute to air pollution, causing respiratory difficulties and other health issues for both humans and animals. The untreated or inadequately treated waste from dairy farms, which includes manure and urine, often travels to nearby water bodies like rivers and lakes (Nimisha 2021). This can affect eutrophication, causing oxygen levels to deplete in aquatic ecosystems and harming aquatic life. Moreover, large lands are required for grazing and growing fodder for cows that leads to deforestation, conversion of natural habitats into agricultural land, and soil erosion. Land degradation can result in decreased biodiversity and the loss of ecosystem services. Growing fodder for cows requires fertilizers, pesticides, and water, which can contribute to environmental pollution and degradation. An important factor to consider was the high amount of energy and resource consumption. Implementing appropriate waste management systems, optimizing feed efficiency, and reducing greenhouse gas emissions through improved cow diets are some of the sustainable and responsible practices that can be adopted in the dairy industry to mitigate these environmental issues.

In many countries, electricity generation at the national level is achieved through a combination of renewable power, thermal power from fossil fuels, and nuclear power. The use of carbon-based fuels like coal and diesel for electricity generation significantly contributes to carbon dioxide emission, resulting in global warming. Furthermore, these fuels emit sulfur and nitrogen oxides, which contribute to the occurrence of acid rain and pose health hazards to humans. Therefore, pollution can be substantially avoided by investing in renewable energy sources to power dairy farms.

The emissions from the process of sugar production have a significant impact on OD, HT, and Mec, while some of the other impact categories were marginally affected as well. The sugar production process can have several negative environmental impacts, leading to pollution. Sugar production requires a large amount of water, particularly for irrigation and cleaning purposes, as well as a high level of fertilizers and pesticides (Chami, Daccache, and El Moujabber 2020). Numerous research studies have indicated that water samples from sugarcane regions exhibited concentrations of pesticides and herbicides, notably "Ametrin," "Diuron," "Triazine," and "Hexazinone," all of which are extensively employed molecules in sugarcane cultivation ; (Shaw, Brodie, and Mueller 2012; Davis et al. 2013). Moreover, during sugar milling, a substantial levelof energy consumption and large volumes of wastewater production are present. Surprisingly, the effect of the fabrication processes of machinery and other facilities to produce 1 kg of yogurt was not significant at all, as the lifetime and the total output during the lifetime of all the machinery are very high.

**Normalized environmental impacts**

The normalized results indicate the environmental impact of a product or process relative to a reference value to simplify comparison across different products or processes. The reference value could be the average performance of all products or processes within a certain industry or it could be a specific target value set by regulations or agreements. The environmental performance data acquired from the LCA is divided by the reference value, yielding a dimensionless ratio (as described in the SimaProDatabaseManual 2021), typically presented as a percentage, which signifies the comparative superiority or inferiority of the product or process in relation to the reference value. Normalized results offer a means for decision-makers, policymakers, and stakeholders to compare different impact categories and identify particularly risky sectors to implement more sustainable options. The normalized impacts of the production of 1 kg of yogurt are illustrated in Fig. 3.

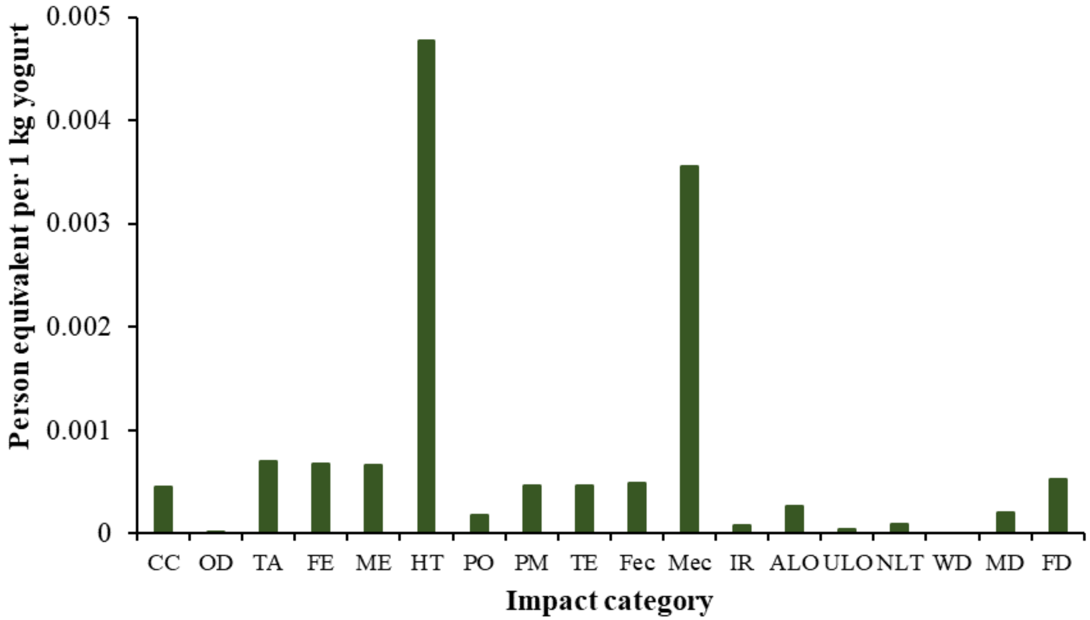


**Figure 3.** Normalized results of production of 1kg yogurt (CC- Climate change, OD- Ozone depletion, TA- Terrestrial acidification, FE- Freshwater eutrophication, ME- Marine eutrophication, HT- Human toxicity, PO- Photochemical oxidant formation, PM- Particulate matter formation, TE- Terrestrial ecotoxicity, Fec - Freshwater ecotoxicity, Mec- Marine ecotoxicity, IR- Ionizing radiation, ALO- Agricultural land occupation, ULO- Urban land occupation, NLT- Natural land transformation, WD- Water depletion, MD- Metal depletion, and FD- Fossil depletion).

The impact on human health, expressed in terms of toxicity (HT), is notable at 0.0048-person equivalent per 1 kg of yogurt, suggesting possible deleterious consequences on human well-being. The impact of ecotoxic substances on marine ecosystems (Mec) was significant at 0.0036-person equivalent per 1 kg of yogurt, indicating potential harm to marine organisms. The total impact on the environment due to the production of 1 kg of yogurt is 0.014-person equivalent.

## 4. Conclusions

In conclusion, this case study specifically focused on the environmental footprints associated with yogurt production in Sri Lanka. By delving into the intricacies of the production process at the Pulathisi milk factory, the study sheds light on numerous ecological elements and repercussions. The findings revealed significant contributions to climate change (2.48 kg $CO_2$ eq), terrestrial acidification (0.0297 kg $SO_2$ eq), freshwater eutrophication (0.0002 kg P eq), and human toxicity (6.9199 kg 1,4-DB eq).

Notably, this study identified key contributing environmental impacts, such as cow milk production and electricity use. The insights provided by the life cycle assessment pinpointed areas where interventions can be strategically implemented to lower environmental footprints. Key recommendations include implementing sustainable practices in dairy farming, optimizing feed efficiency, improving waste management, and transitioning to renewable energy sources for electricity generation.

As the dairy industry grapples with its environmental implications, it becomes imperative to balance the growing demand for dairy products with responsible and sustainable practices. The case study serves as a valuable resource for stakeholders, enabling a deeper understanding of the environmental challenges posed by yogurt production in Sri Lanka and paving the path for informed decision-making towards a more environmentally conscious dairy industry.

**Conflicts of Interest:** The authors declare that there are no conflicts of interest regarding the publication of this paper.

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