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An analysis of Brazilian raw cow milk production systems and environmental product declarations of whole milk

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ABSTRACT

The aim of this study is twofold: (i) to provide an LCA of raw cow milk production systems from the two most representative states (Paraná and Minas Gerais) for milk production in Brazil considering four impact categories according to product category rules of raw milk; and (ii) to analyze the environmental performance of milk produced in Brazil (at the farm-gate) with that of milk produced in other parts of the world (at the farm-gate) based on valid EPDs of processed whole milk and LCA studies of milk in the existing literature. For building life cycle inventories, agricultural processes and activities associated with milk production were mapped out. Three milk production systems in Brazil were assessed, one confined, and two semi-confined, in two different regions, within Minas Gerais and Paraná states. The functional unit used in this study was 1 kg of fat and protein corrected milk. Moreover, an analysis of the environmental performance of milk produced in Brazil with that of milk produced in other parts of the world based on valid EPDs of processed milk was made. LCA results and the results obtained from the valid EPDs used different life cycle impact assessment methods (IPCC 2013; CML, ReCiPE) and impact categories (climate change, acidification potential, eutrophication, formation potential of tropospheric ozone). The raw milk (cradle-to-farm-gate) produced in Brazil (in different states and based on different systems - confined or semi-confined) has lower environmental impacts when associated with those (cradle-to-farm-gate) of published EPDs. The study also briefly compared the results of Brazilian milk production systems with cradle-to-farm-gate LCAs of raw milk found in the literature, and discussed a few strategies for the Brazilian market of milk and dairy products. MPS in Brazil can serve as a benchmark for MPS in other countries, and EPDs can add transparency to business-to-business and business-to-consumer relations.

1. Introduction

Global livestock is responsible for 7.1 gigatonnes of CO_2-eq per year, representing 14.5% of all anthropogenic greenhouse gas (GHG) emissions (FAO, 2020). Although milk is one of the most widely produced and valuable agricultural commodities worldwide (Üçtuğ, 2019), the production of milk causes environmental impacts, such as nutrient enrichment of surface water and emissions of GHGs (Thomassen et al., 2008), on top of using a significant amount of water for processing and cleaning (Yan and Holden, 2019). While the dairy sector contributes to

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the fight against hunger, by trying to provide food security, and improving the nutritional value of diets in a sustainable manner (IDF - International Dairy Federation, 2020), the sector also has an important role to play to significantly reduce GHG emissions (such as methane), and other severe impacts to the quality of air, water, and soil.

The increase in milk production is significantly driven by the greater demand for high-quality nutrients in developing countries (Houssard et al., 2021). In India, the largest milk producer in the world, the production of milk increased by 4.2% in 2019, compared to the previous year, thus amounting to 192 Mt of milk (OCDE-FAO, 2020). Moreover, the worldwide production of milk (being 81% cow milk, 15% buffalo milk, and a total of 4% for goat, sheep and camel milks combined) grew by 1.6% in the same time window to about 838 Mt in 2018 (OCDE-FAO, 2020). Furthermore, the global milk production has increased more than 59% over the last three decades, for which more than 150 million milk farmers around the world have been engaged in the sector (FAO, 2019).

Agriculture and food production are of great importance for human subsistence, and reducing the emissions caused by these activities is a key concern currently and in the future (Flysjö et al., 2012; Chojnacka et al., 2021). Indoor feeding and high protein diets have increased, while grazing has decreased (Brizga et al., 2021) due to technological advances in the last few years. As modern dairy farming is associated with major sustainability challenges (Arvidsson et al., 2020), which relate to the reduction of environmental impacts on soil, water, and air, robust tools need to be used to assess such impacts.

Among the many methodologies to assess the environmental performance of milk production, life cycle assessment (LCA) is a robust option. LCA evaluates in a holistic way the environmental consequences of a product system or activity, by quantifying the energy, materials, and wastes (Baldini et al., 2018) within a system. LCA has been the most complete tool for environmental assessment (Salvador et al., 2021), been a multi-criteria method and helps to identify direct and indirect environmental impacts associated with goods, processes, and services (Righi et al., 2018), with the goal of determining the full range of environmental damage (Carvalho et al., 2021), and propose improvement actions in all of the life cycle phases that account for the highest shares of impacts in the environmental profile (França et al., 2021; Rebolledo-Leiva et al., 2021).

1.1. LCA of milk production in the literature

LCAs of milk production can be found in the literature. An overview of the research on LCA of milk in the existing literature is shown in Table 1, highlighting the research gap they intended to cover and the goal of each study. Although Italy appears to be one of the main countries that has a history of measuring the environmental impacts of milk through LCA (Bacenetti et al., 2016), actors in other locations in the world have also done so, like those developed for milk production in Brazil. Some of these studies are of Carvalho et al. (2021), which chose Northeast Brazil for assessing the environmental performance of cow milk produced, and Léis et al. (2015) that chose the southern region of Brazil to evaluate the carbon footprint of milk production. Both works evaluate milk production in three dairy production systems: confined, semi-confined feedlot, and pasture systems. The actors concluded the carbon footprint of the farm products is directly related to enteric methane emissions and they emphasize that improving productivity per milk cow and the composition of feed are the main strategies to improve the environmental performance of milk production. In addition, Soares et al. (2018) developed the LCA of buffalo milk production aimed to find ways to reduce the environmental impacts, and evaluated the intensification of the milk buffalo production and types of handling system, organic and nonorganic system. Soares et al. (2018) concluded that in order to have an increase in milk productivity combined with a lesser impact on the environment, the improvement of the food provided to the buffaloes must be taken into account, taking into account the forms of cultivation of the food provided to the animals. Santos Júnior et al. (2017) carried out an LCA of cheese production with many suggestions and indications about which inputs involved in the production process are the main responsible for environmental damage in manufacturing.

The study of Cortés et al. (2021) used LCA + data envelopment analysis (DEA) for a group of 96 dairy farms to evaluate the eco-efficiency of the dairy sector in a region of Spain. Mazzetto et al. (2020), analyzed 552 farms to evaluate multiple environmental burdens of dairy production, expanding the boundaries of LCA to account for coupled dairy-beef production systems in Costa Rica. Drews et al. (2020), used LCA to assess the environmental impacts of Northern German farms throughout the period 2004–2013, and as the result, the growth in productivity accompanied a decrease in environmental impacts, and the choice of feed had a major influence in mitigating potential environmental impacts. Soteriades et al. (2020), in turn, combined LCA with DEA to develop an eco-efficiency indicator for each of 738 UK dairy farms by measuring the balance of environmental trade-offs between milk and beef production. The authors Naranjo et al. (2020) covered a cradle-to-farm-gate agricultural LCA for dairy production and evaluated changes in GHG emissions, and water and land use in California, USA, in 1964 and 2014. The influence of milking techniques, and the number of cows (Supartono et al., 2019), as well as the intensification of systems (e.g. confined or extensive) (Ledgard et al., 2019) on the environmental impacts of milk production have also been investigated.

In general, for milk production, previous studies have shown that the greater portion of impacts are at the farm (Fantin et al., 2012). However, in order to build an LCA study, it is necessary that life cycle inventories (LCI) be available. An LCI comprises data collection and calculation procedures to quantify the inputs and outputs of a product system (ISO - International Organization for Standardization, 2006a), and allows the quantification of resource flows and emissions for each phase of the life cycle of the system under study. One of the first studies published in the realm of LCI applied to the dairy industry seems to be the one of Eide and Ohlsson (1998), who evaluated two different inventories (simplified and detailed) in two dairies. Later on, Cederberg and Flysjö (2004) collected data from 23 dairy farms in Sweden accounting for the use of diesel, electricity, pesticides, and plastic. Moreover, Anestis et al. (2015) presented a cradle-to-farm-gate LCI for milk production in Greece using as reference flow 1 kg of fat and protein corrected milk (FPCM), and the results revealed that the enteric fermentation of cattle, the excretion and storage of manure, and slurry spreading in ryegrass fields were the most important contributing processes at the farm level to the total methane, nitrous oxide, and ammonia emissions in this partial life-cycle of cow-milk.

1.2. Research gap, scope and aim

The need and lack of specific LCIs for within the farm gates have been discussed in the literature (Gilardino et al., 2020; Branco-Vieira et al., 2020; Blaauw and Maina, 2021). For the compilation of the LCI, data on the relevant system inputs and outputs should be collected and calculated using real process data to obtain more reliable results (Branco-Vieira et al., 2020). The need to develop country- and region-specific inventories is demonstrated through data validation and sensitivity analyses, to highlight key factors affecting estimates and support conclusions and recommendations (Blaauw and Maina, 2021).

On those notes, life cycle assessment (LCA) (ISO - International Organization for Standardization, 2006a; 2006b) adjoined with life-cycle-based declarations and labels might be an alternative for fomenting more sustainable production and consumption and also enhancing competitiveness in the dairy sector (Fantin et al., 2012). Type III labels, which are environmental product declarations (EPD®), standardized by ISO 14025 (ISO - International Organization for Standardization, 2006b) potentially enable comparability of LCA studies due to the establishment of product category rules (PCR). PCRs provide guidance and standardize how an LCA should be conducted and how its

Table 1
Existing research on life cycle assessment of milk.

Reference	Title	Goal of the study	Stated research gap
Anestis et al. (2015)	Life cycle inventory analysis for the milk produced in a Greek commercial dairy farm – The link to Precision Livestock Farming	Presenting a 'cradle-to-farm-gate' Life Cycle Inventory (LCI) for the milk production from a commercial dairy cattle producing farm in Greece and to discuss its possible link to Precision Livestock Farming (PLF) approach	No published LCA studies for livestock products in Greece have been found in the international scientific literature
Bacenetti et al. (2016)	Anaerobic digestion and milking frequency as mitigation strategies of the environmental burden in the milk production system	Assessing, through a cradle to farm gate LCA, different mitigation strategies of the potential environmental impacts of milk production at farm level	–
Carvalho et al. (2021)	Environmental life cycle assessment of cow milk in a conventional semi-intensive Brazilian production system	Assessing the environmental performance of cow milk produced in a conventional semi-intensive system using a cradle-to-farm gate attributional LCA	LCA studies of milk in different regions can provide an overview of the environmental impacts in the activity across the country. Due to Brazil's geographical dimensions, results may vary not merely because of regional features but also because of the handling and management practices used
Cederberg and Flysjö (2004)	Life Cycle Inventory of 23 Dairy Farms in South-Western Sweden	Gaining increased knowledge of the environmental impact of milk production and of the variations between farms regarding resource use and emissions	–
Cortés et al. (2021)	Pursuing the route to eco-efficiency in dairy production: The case of Galician area	Integrating LCA and Data Envelopment Analysis (DEA) in the calculation of environmental indicators associated with milk production for a large group of farms, nearly 100 decision-making units	It is highly relevant to propose improvement actions based on a detailed eco-efficiency analysis of different facilities so that roadmaps for more sustainable processes are considered. The joint use of LCA and DEA appears to be an appropriate methodology to assess the eco-efficiency of multiple units, providing targets and benchmarks for inefficient ones
Drews et al. (2020)	A life cycle assessment study of dairy farms in northern Germany: The influence of performance parameters on environmental efficiency	investigating the influence of performance parameters on the level of important environmental impacts (global warming potential (GWP), freshwater eutrophication (FE), terrestrial acidification (TA) and agricultural land occupation (ALO)) associated with milk production	–
Eide and Ohlsson (1998)	A Comparison of Two Different Approaches to Inventory Analysis of Dairies	Evaluating and comparing two different methods to carry out a life cycle inventory where all the steps of the life cycle of milk are assumed to be identical except for the dairy processing	–
Fantin et al. (2012)	Life cycle assessment of Italian high quality milk production. A comparison with an EPD study	Identifying critical aspect affecting the comparability of EPDs in the food sector	The results of this analysis were used to participate in the open consultation of the PCR revised version and to highlight the importance of including more detailed instructions
Ledgard et al. (2019)	Nitrogen and carbon footprints of dairy farm systems in China and New Zealand, as influenced by productivity, feed sources and mitigations	Comparing contrasting dairy farming systems in China and NZ, varying in farming intensity and amount and types of brought-in feeds used, for the N and C footprints of milk and to evaluate mitigation options to decrease these footprints	There have been no detailed LCA-based studies on the N footprint of dairy production, although various LCA studies have accounted for some environmental impacts associated with N emissions
Léis et al. (2015)	Carbon footprint of milk production in Brazil: a comparative case study	Assessing the carbon footprint per 1 kg of energy-corrected milk at the farm gate for different dairy production systems in the southern region of Brazil	At the time of this research, no environmental information using LCA was available regarding Brazilian milk production
Mazzetto et al. (2020)	Comparing the environmental efficiency of milk and beef production through life cycle assessment of interconnected cattle systems	Evaluating multiple environmental burdens of dairy production, expanding the boundaries of LCA to account for coupled dairy-beef production systems and consequences for pure-beef farms	Milk and beef production are inherently interconnected, and a narrow focus on milk production neglects wider synergies and trade-offs across cattle systems, outside dairy farm boundaries
Naranjo et al. (2020)	Greenhouse gas, water, and land footprint per unit of production of the California dairy industry over 50 years	Conducting a cradle-to-farm gate environmental impact analysis and resource inventory of the California dairy production system to estimate the change in greenhouse gas emissions and water and land use over the 50-yr period between 1964 and 2014	California has unique attributes in its milk production system that have not been analyzed previously, and several advancements in the methodology of calculating emissions have been published since the latest studies were conducted
Santos Júnior et al. (2017)	Life cycle assessment of cheese production process in a small-sized dairy industry in Brazil	Suggesting improvements for minimizing environmental impacts in the manufacture of cheese in Brazil	Due to Brazil's geographical dimensions, environmental impacts of cheese production may vary not merely because of regional features but also by characteristics employed in the manufacture and production practices used
Soares et al. (2018)	Effect of handling and feeding strategies in the environmental performance of buffalo milk in Northeastern Brazil	Assessing the effect of intensification of feeding strategies on the environmental impacts of different animal-handling scenarios of buffalo milk production	Brazilian studies are needed to assess whether local intensification strategies contribute to improved environmental performances of livestock systems
Soteriades et al. (2020)	Maintaining production while reducing local and global environmental emissions in dairy farming	Developing an indicator of eco-efficiency for each of 738 UK dairy farms (3624 data points in 15 years) that aggregates multiple burdens and expresses them per unit of milk and dairy-beef produced	In LCA studies of dairy farming systems, dairy-beef production is often ignored or 'allocated off', which may give a distorted view of production efficiencies
Supartono et al. (2019)	Implementation of life cycle assessment on production of Fresh Pasteurized Milk	Calculating and evaluating energy use and environmental impacts of pasteurized fresh milk and packed in a plastic cup	–

results should be reported. A PCR is tailored to a product or product family, and provides recommendations on, e.g., the use of system boundaries, functional unit, and impact categories, on top of establishing data quality requirements.

Some published LCA studies for milk production in Brazil have been found in the literature. All published studies aimed at a comparative assessment between livestock management and milk production systems in specific farms and regions. However, no studies have been found in the international scientific literature aiming to assess the life cycle impacts of the two most representative states for milk production in Brazil. Moreover, no EPDs of milk or dairy products produced in Brazil have been found in the International EPD System (2021) as of May 2021. Therefore, the aim of this study is twofold: (i) to provide an LCA of raw cow milk production systems from the two most representative states (Paraná and Minas Gerais) for milk production in Brazil considering four impact categories according to product category rules of raw milk; and (ii) to analyze the environmental performance of milk produced in Brazil (at the farm-gate) with that of milk produced in other parts of the world (at the farm-gate) based on valid EPDs of processed whole milk and LCA studies of milk in the existing literature.

In that sense, what characterizes the novelty of this study is the unveiling of the impacts of MPSs in the two states who are the largest producers of milk in the country, as no other LCA study of milk production in Brazil has tackled either of these states. Therefore, in view of the broad scenario of milk production and consumption, the environmental impacts generated in the entire milk production process, performing contemporary investigation of the performance of milk produced in Brazil is necessary, mainly in order to allow effective interpretations and achieve current and complete results for LCA studies involving Brazilian dairy farming. The use of regional data can contribute to increasing the robustness of the study and reduce uncertainties due to system variability (Mutel et al., 2019), for the territorial extension of Brazil and the social and geographical diversities show the need to build regionalized inventories (Ruviaro et al., 2012). The primary data used to build the life cycle inventories of milk production used in this study are part of a project to encourage the creation of a national life cycle database, promoted by the Ministry of Science and Technology (MCTI) of Brazil and the Brazilian National Council for Scientific and Technological Development (CNPq), call CNPq/MCTIC nº 40/2018 – Incentive to build life cycle inventories of milk production in Brazil.

This study can provide policy makers, farmers, academicians and stakeholders with information for planning and developing strategies for reducing the environmental impacts associated with milk production. This research is directed to LCA researchers and practitioners, and it intends on helping pave the way for future LCA studies of raw milk production and milk products. It can also assist in the development of new LCA-related studies of dairy products, such as processed milk, cheese, yogurt, and butter.

The manuscript is structured as follows. This section presented the contextualization and the aim of this paper. Section 2 describes the research design used to conduct the study. The findings on the LCI, LCA, and registered EPDs of milk are presented in section 3. Section 4 draws on a discussion of the results including further developments in terms of the Brazilian market for milk and dairy products. The last section presents a few final considerations, as well as topics for further research.

2. Methods

The methods used to conduct this research comprised a few phases. Therefore, this section is divided into subsections to address the methodological procedures of this research. Section 2.1 shows the definition of the case study. Section 2.2 presents the LCA for the milk production. Section 2.3 describes the verification of the environmental performance of milk produced in Brazil with that of milk produced in other parts of the world based on valid EPDs of processed milk.

2.1. Definition of the case study

Brazil is the third largest milk producer in the world, only behind India and the USA (FAOSTAT, 2020), and in 2017, the country registered 1.176 million milk producing establishments, with the vast majority of producers being of small-scale, of which 93% produce up to 200 L per day (Martins et al., 2020). In Brazil, milk production systems are defined by the degree of intensification and productivity level, where the basic difference is the way feed is made available to animals. In the country, food is considered one of the main basic products of the economy and agriculture. For the same type of system different forms of management are found, dairy cattle breeds with different characteristics and productivity, which are influenced by the type and availability of food, local climate, technological level, manure management and others.

Three types of milk production systems in the country are described, namely confined, semi-confined, and extensive (Assis et al., 2005). This study focused on the most representative systems in terms of volume of milk produced. The extensive production system (with feeding based on pasture) has low representativeness in volume considering the total milk produced in the country, wide heterogeneity, and a tendency of properties transitioning out of this system due to its low productivity (Martins et al., 2020), and therefore, no system of the sort is reported in this study. Other production systems, such as organic, represent niche markets and have no representation in production volume. The three systems reported here (1 confined and 2 semi-confined) differ in terms of food availability and quality, animal genetics, technology used, type of manure management, differences between states, culture, and climate. The confined milk production system is characterized by the confinement of animals, which are fed directly into the feed troughs. In the semi-confined milk production system, the animals are reared on pasture and receive supplementation in the feed trough. The way of obtaining food and the management of waste is what distinguishes the environmental impacts caused by these systems.

The difference between a system and a region shows the need to characterize representative regional production systems. In this sense, the importance of milk in the Brazilian economy is highlighted, as well as the perspective of assessing the potential impacts arising from this production. In order to obtain homogeneity of information, the most representative mesoregions of the 2 largest producing states (Minas Gerais - MG and Paraná - PR) were considered, in terms of milk production volume and type of production system. The state of Minas Gerais (8939 million liters in 2018) is the largest milk producer in the country, and the state of Paraná (4375 million liters in 2018) is the second largest (Zoccal, 2019).

The specific characteristics for the two mesoregions are presented hereafter.

2.1.1. Mesoregion of Zona da mata (Minas Gerais state)

The state of Minas Gerais (southeast region of Brazil) is the largest milk producer in the country (26.6% of the total national production), and the mesoregion of Zona da Mata has one of the highest production rates of milk by area in the state (Zoccal, 2019). Fig. 1 shows the geographic location of the mesoregion and the quantity of milk produced (in million liters per year).

Four rural properties, representative of the semi-confined system in the mesoregion, were selected (see LCI 1 in Fig. 3). The Girolando breed is the most representative breed in the mesoregion, and dominant in 50% of the Brazilian dairy herd (Martins et al., 2020).

The semi-confined system is the most expressive in the state of Minas Gerais (Vilela et al., 2017). In this type of system, animals spend part of the day in the pasture, which reduces the concentration of waste to be treated, since natural decomposition occurs, and in the remainder of the day animals are confined. For those wastes deposited in the corrals, there is a daily dispersion management, defined as the daily application of manure in areas of agricultural crops or in pastures. The type of milking adopted in the mesoregion is mostly mechanical, with manual and automatic cleaning. Animal reproduction occurs by artificial insemination. This system, semi-confined system - Mesoregion of Zona da Mata (Minas Gerais state), is hereinafter referred to as MPS 1.

2.1.2. Mesoregion of Central-east (paraná state)

In the state of Paraná (southern region of Brazil), the Central-East mesoregion embeds the majority of the milk produced in the Campos Gerais region, which received the title of "national milk capital" by a Federal Law (Lana et al., 2019). Fig. 2 shows the geographic location of the mesoregion and the quantity of milk produced (in million liters per year).

According to the availability and accessibility of the data, eight milk producing rural properties were selected for data collection. Four rural properties ran a confined system, and four a semi-confined system. Rural properties running a confined system have more than 200 animals in lactation (each of the four properties belonged to one of the following production ranges: between 30 and 40 thousand L/day; between 20 and 30 thousand L/day; between 10 and 20 thousand L/day; up to 10 thousand L/day). Although the confined system corresponds to a minority of rural properties, the properties usually present larger production volumes, as this system represents a worldwide trend of intensifying production, and the contribution for having a national, regionalized, inventory is relevant.

Rural properties running a semi-confined system have between 50 and 150 animals in lactation, producing between 1 thousand and 5 thousand L/day. The rural properties of the semi-confined system (see LCI 2 in Fig. 3) or MPS 2 (semi-confined system - Mesoregion of Central-East (Paraná state)) and confined (see LCI 3 in Fig. 3) or MPS 3 (confined system - Mesoregion of Central-East (Paraná state)) systems use open lagoon systems to treat manure and subsequently apply it to the crops, thereby partially replacing inorganic fertilization. The semi-confined system generates less waste to be treated, since the animals spend part of the day in the pasture. The scraping of manure in the corral is carried out with the use of agricultural equipment (tractor). The land is managed by the farmers themselves. All farms in this mesoregion are part of an agro-industrial cooperative.

2.2. Building an LCA of milk production

2.2.1. Goal and scope

Initially, this study follow the methodological framework of ISO 14040 (ISO - International Organization for Standardization, 2006a) in some aspects, such as intended application, reasons for carrying out the study, intended audience, functional unit, system boundary, impact categories selected, impact assessment, data requirements, limitations, initial data quality requirements, and others which are presented below.

The scope and the intended application of this study considers a 'cradle-to-gate' approach. The initial phase of an LCA, the LCI, comprises the identification of input flows of materials, energy, water, and output flows of co-products, waste, and emissions. This phase is often regarded as the most time-consuming and critical in the context of an LCA (Branco-Vieira et al., 2020). Therefore, the inventory provides as a result the flows of raw materials, water and energy consumption, and emissions. Generally, the main reason for carrying out the study is to develop representative LCIs, in order to allow effective interpretations and achieve actualized and complete results for LCA studies involving the Brazilian dairy farming. The intended audience is for policy makers, farmers, academicians and stakeholders.

The functional unit represents the reference unit used to quantify the environmental impacts of the system's output. The functional unit used in this study was 1 kg of fat and protein corrected milk (FPCM), as recommended by IDF - International Dairy Federation (2015), based on the year 2019. Most studies found in the literature also used 1 kg of FPCM, as recommended by IDF - International Dairy Federation (2015), which corresponds to an improvement in productive efficiency (Drews et al., 2020).

Fig. 3 presents the boundaries of the milk production system separating primary and secondary data. Upstream processes are represented by general inputs, inputs for pasture and feed production - crops (secondary data). Core processes comprehends all at-the-farm activities, thus comprising all three LCIs of milk production from (primary data). As outputs there is milk, animals for slaughtering, and waste, as well as

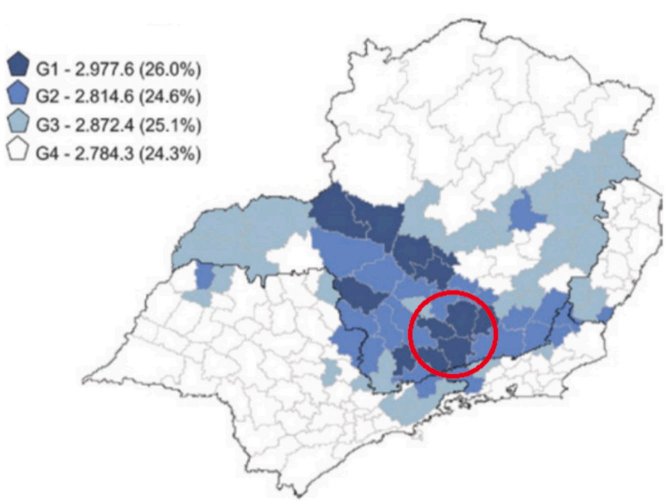

Fig. 1. Geographical location of Zona da Mata mesoregion (within the red circle).
Source: Adapted from Zoccal (2019).Legend: G1 - Group1 (groups of micro regions responsible for 26% of the milk production in southeast Brazil); G2 - Group 2 (micro regions responsible for 24.6% of the milk production in southeast Brazil); G3 - Group 3 (micro regions responsible for 25.1% of the milk production in southeast Brazil); G4 - Group 4 (micro regions responsible for 24.3% of the milk production in southeast Brazil).

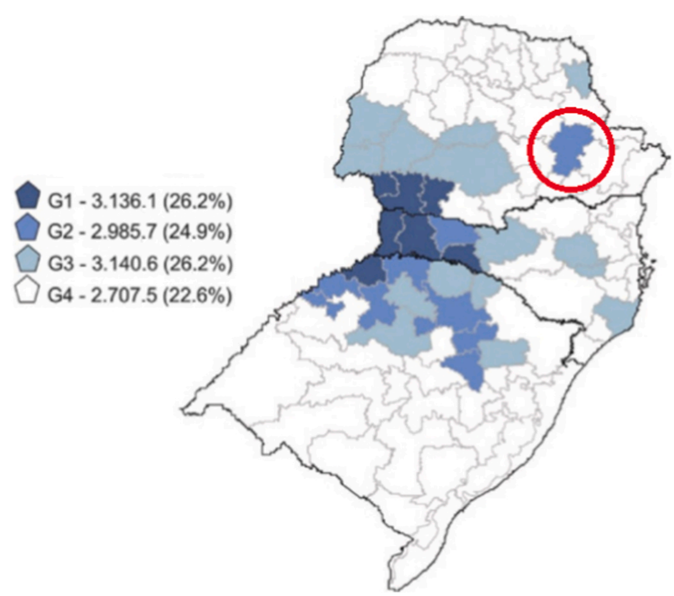

Fig. 2. Geographical location of Central-eastern Mesoregion of Paraná (within the red circle).
Source: Adapted from Zoccal (2019).Legend: G1 - Group1 (groups of micro regions responsible for 26.2% of the milk production in southern Brazil); G2 - Group 2 (micro regions responsible for 24.9% of the milk production in southern Brazil); G3 - Group 3 (micro regions responsible for 26.2% of the milk production in southern Brazil); G4 - Group 4 (micro regions responsible for 22.6% of the milk production in southern Brazil).

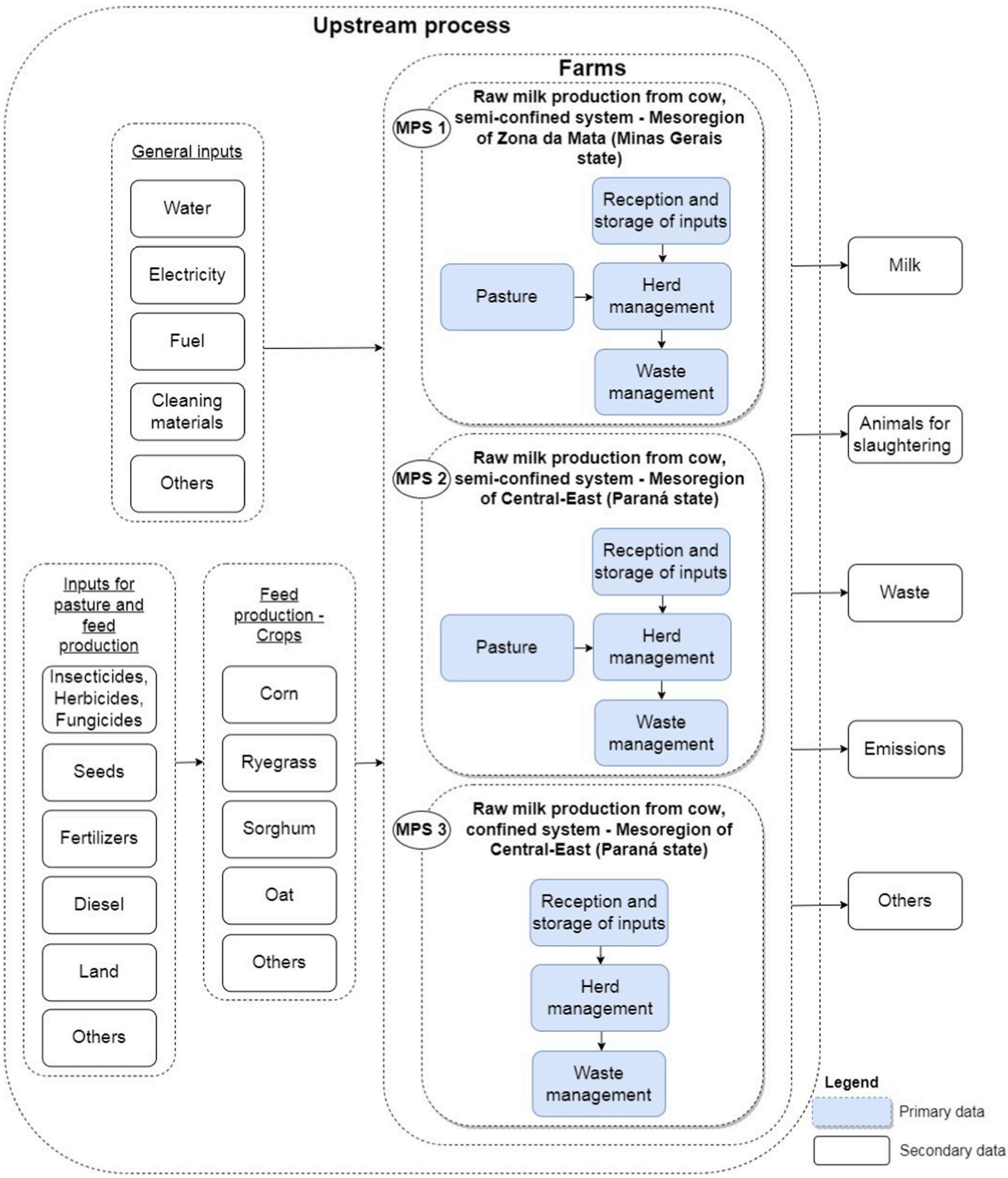

Fig. 3. Boundaries of the milk production systems.

emissions (secondary data).

Buildings, infrastructure, equipment and transportation were not considered within the limits of the system, but were included in some processes from the Ecoinvent database, which were used as selected generic data. The production of medicine, the industrial phase (processing of the milk - core), the use phase, and the final destination of the packaging were also not included.

2.2.2. *Inventory analysis*

An inventory is presented by collecting data from all (or most of) the material and energy flows related to a system. The outcome is a set of input and output flows to be used in an LCA study and to be used in the calculation of potential environmental impacts. The objective is to collect data from primary sources, i. e., collect data on the field seeking to obtain accurate and quality information. The inventory analysis is often the most time-consuming part of an LCA (Bjørn et al., 2018), therefore, efforts must be devoted to it.

A guide for building LCIs in Brazil was developed in 2016 by experts in the field, and aims to provide guidelines for submitting LCIs to the Brazilian National Database of Life Cycle Inventories (SICV) (Rodrigues et al., 2016). Building an inventory demands a high amount of quantitative data, coming from several elementary processes (Mazzetto et al., 2020; Baldini et al., 2017). In this sense, for data collection, a structured questionnaire was created. The questionnaire was previously tested through interviews with specialists in the area to certify the consistency of the questions and the compliance with the data quality criteria. The questionnaire can be found in the Supplementary Material A, and the life cycle inventories data can be found in the Supplementary Material B.

Most of the data provided in the inventories is primary, collected in the field, through on-site interviews with farm owners and managers and expert technical consultants from the agro-industrial cooperative (see Table 2). When it was not possible to obtain primary data, secondary data was obtained and calculated based on scientific literature and methodologies.

The input data established represents operational characteristics of the farm for the production of milk under Brazilian conditions, such as resource utilization, forage planting, transportation, use of diesel, source and quantity of water and electricity, necessary inputs in all stages of cattle management, milking, cooling, types of technologies used, number of animals, quantity of milk produced, type and quantity of feed, destination of animals, cleaning, destination of wastes and others.

The output data were the quantity of milk, emissions related to the various stages of production, such as those due to the management of animal waste, use of fuels such as diesel on the farm, use of fertilizers, and others. All data refer to the year 2019. Table 2 presents the characteristics of the MPS for the three LCIs, and Table 3 presents the characteristics of the flows used from the Ecoinvent v3.7 database for modeling the MPS.

In terms of cut-off, as indicated by ISO - International Organization for Standardization (2006c), inputs related to drugs and insemination were not accounted for, as they represent much less than 1% in terms of mass of the system inputs (see Carvalho et al., 2021), and result in non-significant impacts (Ross et al., 2014). Direct CO_2 emissions from land use change have not been accounted for, assuming that no land transformation has been involved in the past 20 years (standard time), according to the IPCC - Intergovernmental Panel on Climate Change (2019) to consider emissions by anthropogenic action. Transportation data has not been included. No data on heavy metal inputs and emissions from sources other than natural deposition and fertilizers (organic and mineral) were accounted for. In addition, the farm's infrastructure and the manufacture of tractors were not considered.

In terms of emissions, IPCC - Intergovernmental Panel on Climate Change (2019) was used to calculate GHG emissions, such as enteric gasses emitted by animals and (as recommended by Baldini et al., 2017) GHG emitted due to waste management. Ammonia (NH_3), nitrous oxide (as N_2O) and methane (CH_4) are recognized as direct or indirect GHG associated with global warming and climate change (Zhang et al., 2021).

High-quality data is essential for a study to be reliable and transparent (Cortés et al., 2021). According to ISO (2006a, b), the uncertainty analysis is a procedure performed to quantify the uncertainty introduced in the data of an LCI, due to the cumulative effects of the imprecision of the models, uncertainty of the inputs and variability of the data. The standard describes the importance of performing this procedure, as it is a way of attesting the reliability of the results. This study used Data Quality Indicators as the applicable ISO (2006a, b) guidelines. For that, a data quality matrix was used and applied to all data in this study. The Pedigree quality matrix (Weidema and Wesnaes, 1996; Ciroth et al., 2016) provides a score to each item in the inventory ranging from 1 to 5 (1 means greater quality, and 5 means lower quality), across five different criteria (reliability, completeness, temporal correlation, geographical correlation, and further technological correlation). After indicating the matrix score for each of the LCI flows, it was possible to calculate the degree of uncertainty, for a 95% confidence interval, using the lognormal distribution, directly on the OpenLCA software v1.10.3.

After completion, the three inventories were sent for external review, where 5 specialists critically provided feedback on the inventories. After such review, the inventories were submitted to the SICV/Brazil. The external review was carried out by five professionals trained in both LCA and milk production who do not belong to the team who conducted this study and the reviewers did not report any known conflict of interest related to reviewing those inventories.

2.2.3. *Impact assessment*

The life cycle impact assessment (LCIA) was conducted using the OpenLCA software. O software é gratuíto e de base aberta, o que viabiliza a replicabilidade do estudo According to the PCR for raw milk (Product Category Classification: UN CPC 022), the following impact categories were used to assess the environmental impacts of the production of milk at the farm:

- Global warming potential (GWP);
- Acidification potential (AP);
- Eutrophication potential (EP);
- Formation potential of tropospheric ozone (POCP).

A few other impact categories are suggested by the referred PCR. However, they were not included in this study as results for such categories were not found across all EPDs be used in the verification (see section 2.3), therefore, those categories were not accounted for in this study.

Table 2
Main characteristics of dairy farms (three inventories).

Characteristics	MPS 1	MPS 2	MPS 3
Number of rural properties surveyed (representative of the entire region	4	4	4
Average land occupied by the milk production system (acres)	90	54	20
Animal genetics	Girolando	Dutch black and white	Dutch black and white
Average number of animals in lactation (animals/year)	70–150	70–150	>200
Average milk production per animal (L/animal/day	18	28	38
Average feed consumption - *lactation cows* (kg dry matter/animal/day)	1800	3180	17400
Average feed consumption - *dry cows* (kg/animal/day)	3.40	3.22	3.26
Average feed consumption - *pre-calving heifers* (kg/animal/day)	3.84	3.53	3.61
Average daily feed consumption - *heifers older than 1 year* (kg/animal/day)	1544	9369	35526
Average daily feed consumption - *heifers (*3-month *to 1-year old)* (kg/animal/day)	24.5	22	136
Average daily feed consumption - *heifers (younger than* 3-months *old)* (kg/animal/day)	18	20.12	23.9

Source: In-person interviews with farmers and technicians.

Table 3
Providers of input flows from the Ecoinvent database.

Inputs to the system	Flow from database (Ecoinvent 3.7)
Diesel	Cutoff-U-BR
Cleaning products	Cutoff-U-GLO
Electricity	Cutoff-U-BR
Tifton seedlings	Cutoff-U-GLO
Hay	Cutoff-U-GLO
Inorganic fertilizer as N	Cutoff-U-BR
Inorganic fertilizer as P_2O	Cutoff-U-BR
Inorganic fertilizer as K_2O	Cutoff-U-BR
Urea (animal feed)	Cutoff-U-BR
Mineral supplement	Cutoff-U-GLO
Pesticide	Cutoff-U-GLO
Protein concentrate	Cutoff-U-GLO
Ryegrass pre-dried	Cutoff-U-GLO
Oat pre-dried	Cutoff-U-GLO
Cotton kernel	Cutoff-U-GLO
Grass silage	Cutoff-U-RoW
Corn silage	Cutoff-U-BR
Sodium hypochlorite	Cutoff-U-RoW
Maize meal	Cutoff-U-BR
Soybean meal	Cutoff-U-BR
Soybean husk	Cutoff-U-GLO

2.2.4. Interpretation

Given the characteristics of the system under study, it is possible to quantify the difference of the environmental impacts of the three inventories presented. The outcome of the LCA is presented in section 3.

2.3. Verification with EPDs of processed milk

The verification of the environmental performance of milk produced in Brazil with that of milk produced in other parts of the world based on valid EPDs of processed milk were done.

A search was conducted on the International EPD System (2021) to identify valid EPDs of processed whole milk. Three documents (or EPDs) fit those criteria. Table 4 presents the characteristics of those three EPDs. The EPDs followed the requirements stated in the PCR for raw milk (RAW MILK PRODUCT CATEGORY CLASSIFICATION: UN CPC 022) for modeling the life cycle from cradle-to-farm-gate. The content of the referred PCR has now been included in a joint PCR for DAIRY PRODUCTS (PRODUCT CATEGORY CLASSIFICATION: UN CPC 0221, 2211, 2212, 2221, 2223, 2224, 2225) (International EPD System, 2022). The same requirements stated in the referred PCR were followed in this study to model the cradle-to-farm-gate, to build the life cycle inventories and to conduct the life cycle impact assessment.

3. Analysis of the environmental performance of milk produced in Brazil and in other parts of the world

3.1. Life cycle impact assessment of milk production

The LCA results and the results obtained from the valid EPDs are presented in Fig. 4 and Table 5, respectively. All of them are presented for 1 L of milk, and used different LCIA methods (such as IPCC 2013; CML, ReCiPE) and impact categories (climate change, acidification potential, eutrophication, formation potential of tropospheric ozone.

The results presented in Fig. 4 and Table 5 show that the confined system in PR (MPS 3) presented lower GHG emissions per kg FPCM of milk, with a figure of 1.14 kg CO_2-eq, while the semi-confined system in PR (MPS 2) and MG (MPS 1) emitted 44% and 61% more GHGs, respectively. In all three production systems, enteric and fossil CH_4 emissions were responsible for the highest contribution to GHG impacts, being 45% for MPS 1, 63% for MPS 2, and 40% for MPS 3. Similar results were found by Léis et al. (2015) when assessing the carbon footprint of milk production systems in Brazil, in which the total CH_4 emission was 55% for confined and 51% for semi-confined systems. Other authors have found similar results for methane emission results as well (see, e.g., Reisinger et al., 2017; Baldini et al., 2018; Ledgard et al., 2019).

In semi-confined systems, inorganic fertilization of pasture is responsible for more than 50% of impacts for acidification, both for MPS 1 and MPS2, and corn and forage crops contributed 26% in MPS 1 and 13% in MPS 2. In the confined system (MPS 3), food production was the main responsible for the impacts in the acidification category, contributing to 36% of the total impacts in said category. LCA results carried out in Italy have indicated that feed production is the biggest contributor to acidification potential in studies comparing the environmental impact of different milk production systems (Bava et al., 2014; Baldini et al., 2018; Berton et al., 2021).

Eutrophication potential is also mainly caused by the inorganic fertilization of the pasture, representing 43% and 35% of the impacts of this category within the system, for MPS1 and MPS 2, respectively. The use of inorganic fertilizers for feed production was responsible for the highest contribution for eutrophication potential in MPS 3, accounting for 52% of the total impacts in the category. Similar results were found by Baldini et al. (2017) and Baldini et al. (2018) in LCA studies of milk production in Italy. Payen and Ledgard (2017) also reported the impact of fertilizer use, mainly N and P in the eutrophication category by analyzing milk production in New Zealand.

In the production systems studied, the main contributors for the potential for tropospheric ozone formation were the methane emissions and emissions from deforestation. In MPS 1 the highlighting contributor was the methane emissions, responsible for 68% of emissions in this category. González-García et al. (2013) and Soltanali et al. (2015) found similar results with a greater contribution (40%) of methane emissions from manure management and enteric fermentation for this category. In MPS 3, transport was the main contributor to impacts in this category, accounting for 25% of total impacts. A few studies show differences in the results for this category as they consider different system boundaries (Chobtang et al., 2017). Baldini et al. (2018) found a greater contribution of emissions in the feed production stage for this category, while for Bieńkowski et al. (2021) and Baldini et al. (2018) feed import was the most relevant contributor in Poland and Italy, respectively, showing that for milk production systems that rely on brought-in feed, transportation contributes significantly for tropospheric ozone formation.

The common impact categories across the three EPDs were climate change, acidification, eutrophication, and photochemical oxidation. Those are the ones recommended for use in EPDs (International EPD System, 2021) and are the categories that have the greatest relevance for assessing the environmental impacts of milk production (Seó et al., 2017; Bieńkowski et al., 2021). The recommended methods for each were: IPCC 2013 for climate change, CML for acidification and eutrophication, and ReCiPE for photochemical oxidation. IPCC 2013 has the main methods for measuring GHG of milk production, and in the results of total GHG, it does not consider the removal of emissions occurring at any stage (O'Brien et al., 2012). CML uses a midpoint approach for environmental impact categories and is the most used method in LCA because it includes the mandatory impact assessment categories (Piekarski et al., 2012). ReCiPE is a method that combines Eco-Indicator 99 and CML to produce a methodology with different levels of aggregation in the analyzed flows (Goedkoop et al., 2009).

3.2. Similarities and differences with cradle-to-farm-gate LCAs of raw milk found in the literature

The cradle-to-farm-gate stages of milk production and dairy products are known to bear the greatest impacts of their life cycle, as for many potential environmental impacts, raw milk production was found to be the main contributor for several product types (Üçtuğ, 2019).

A few studies have been found assessing different milk production systems from cradle-to-farm-gate across the globe. Initially, the authors Thomassen et al. (2008), assessed the milk produced in the Netherlands.

Table 4
Main characteristics of the three EPDs.

EPDs of processed milk	Reference	Year of publication	Geographical area	Brand	Functional unit	% protein	% fat
Fresh whole high quality "Selezione Mugello" milk (packed in 1 L Tetra Top) (Register S–P-01367)	Mukki (2018)	2018	Italy	Mukki	1 L of product and related packaging	3.5	3.8
Granarolo High Quality milk in PET bottles (S–P-00118)	Granarolo (2019b)	2017	Italy	Granarolo	1 kg of Granarolo High Quality milk in 0.5L PET bottles	3.4	3.6
Granarolo Più Giorni ESL milk - whole milk (in 1L PET bottles) (Register S–P-01041)	Granarolo (2019a)	2019	Italy	Granarolo	1 L of Granarolo Più Giorni milk (whole) pasteurized at high temperature (ESL)	3.2	3.6

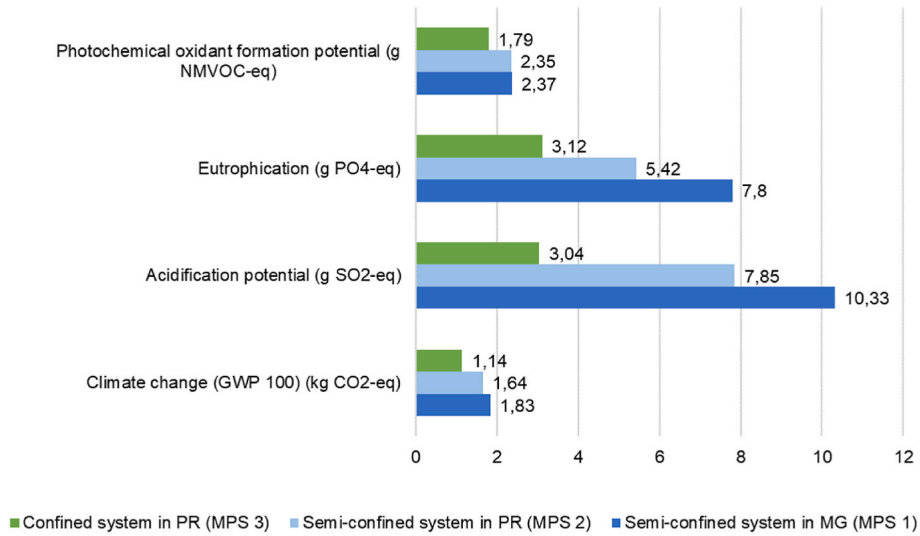

Fig. 4. Main results of LCAs of MPSs.

Table 5
Main results of valid EPDs.

LCIA method	Impact category	Reference unit	Mukki (2018)	Granarolo (2019a)	Granarolo (2019b)
IPCC 2013	Climate change total - (GWP 100)	kg CO_2-eq	1.74	1.7	2.1
CML	Acidification potential - average Europe	g SO_2-eq	13.37	36	30
CML	Eutrophication - generic	g PO_4-eq	7.7	9	9.8
ReCiPE	Photochemical oxidant formation potential	g NMVOC-eq	–	6	3.7

In addition, Ledgard et al. (2019), assessed 3 milk production systems in China (in Shaanxi, Hebei, and Beijing) and 3 (with low (0–10%), medium (10–20%), and high (20–40%) brought-in feed) in New Zealand. Furthermore, Naranjo et al. (2020), analyzed the milk produced in the United States. The methods used to assess their impacts across many categories also often differ, as shown hereafter. In the following year, Brizga et al. (2021), investigated the milk produced in Latvia.

Thomassen et al. (2008), assessing the milk produced in the Netherlands, found 10.9g SO_2-eq/kg FPCM for acidification (EDIP97 updated version 2.3), which is close to what was found for the MPS 1, which was 10.01g SO_2-eq/kg FPCM (CML (baseline) [v4.4, January 2015]). Nonetheless, different results were found for MPS 2, 7.61g SO_2-eq/kg FPCM, and MPS 3, 2.95g SO_2-eq/kg FPCM. Brizga et al. (2021), in turn, found that for the milk produced in Latvia impacts of terrestrial acidification reached the figure of 14g SO_2-eq/kg FPCM (ReCiPE 2016 (H) V1.02). The common hotspots for acidification (both in this study and the studies found in the literature) have been identified as ammonia emissions (such as from N fertilizer), transport, and production of feed components (such as maize).

Climate change impacts can be seen more widespread in the literature. For the Dutch milk, Thomassen et al. (2008) found 1.56 kg CO_2-eq/kg FPCM (EDIP97 updated version 2.3), whereas for the Latvian milk, Brizga et al. (2021) found 0.93 kg CO_2-eq/kg FPCM (ReCiPE 2016 (H) V1.02). Ledgard et al. (2019) assessed the Chinese and New Zealand milk systems, and found that for the Chinese milk climate change impacts (with characterization factors based on Myhre et al., 2013) ranged between 1.02 and 1.43 kg CO_2-eq/kg FPCM, while the results ranged between 0.71 and 0.74 kg CO_2-eq/kg FPCM for New Zealand. For the milk produced in the United States, Naranjo et al. (2020) found that for a system with high production cows, climate change impacts accounted for 1.16 kg CO_2-eq/kg FPCM (IPCC GWP (100)). In Brazil, different results were found (IPCC GWP (100)) for MPS 1, 1.77 kg CO_2-eq/kg FPCM, MPS 2, 1.59 kg CO_2-eq/kg FPCM, and MPS 3, 1.11 kg CO_2-eq/kg FPCM. The hotspots for this impact category have been reported as manure management and enteric fermentation (Brizga et al., 2021; Ledgard et al., 2019), followed by crop production for feed (Naranjo et al., 2020; Thomassen et al., 2008).

In general, emissions relative to a unit of milk (1L or 1 kg FPCM) are highly dependent on the productivity of cows in the system, which will vary depending on a number of variables, such as size of dairy farms and the respective level of technology of facilities, feed variations, and general management/handling practices.

4. Discussion

4.1. Current context of Brazilian milk and dairy products

Brazil is one of the largest milk producers in the world, and in 2019 alone Brazil exported 99 of the 34,520 million liters of milk produced in the country (Carvalho and Rocha, 2019). This large production consumes significant amounts of resources and generates significant amounts of waste, and with it comes the responsibility for managing the environmental impacts of the respective operations.

Having in mind that the largest portion of the environmental impacts of the production of milk are derived from raw material acquisition (from cradle - extraction of natural resources) up to the farm-gate (Fantin et al., 2012), the cradle-to-farm-gate LCA of milk produced in Brazil, in comparison to the cradle-to-farm-gate LCA results of EPDs for whole milk published in the International EPD system shows that the milk produced in Brazil, either in semi-confined or confined systems has lower environmental impacts than the Italian milk commercialized by Granarolo (2019a, 2019b) or Mukki (2018). Further comparisons could not be made as those were the only milk producers with published EPDs.

EPDs bring about great transparency with regard to the environmental sustainability of products and an analogy can be made with “nutritional labels” of food products but related to the environmental performance. EPDs provide improvements and contribute to sustainable development, can influence consumers and encourage a cleaner production, making products more competitive. Making the environmental performance of the milk available via EPDs can open doors for export to markets with stricter regulations. On top of that, it can help set (and potentially raise) a bar for the performance of milk production systems with regard to their environmental performance, encouraging other producers to be aware of the impacts of their practices, and bringing to light best practices in the sector. Therefore, performing LCAs of milk production can lead to two important paths. First, developing EPDs can be a source of competitive advantage for companies in the sector. Second, building LCIs (and subsequently performing LCAs) can help expand the knowledge on environmental performance within the sector with more regionalized information, providing more robust data, and generating new levels of comparison.

4.2. Environmental product declarations as drivers for market strategy of Brazilian milk and dairy products

Brazil being a country whose economy is highly based on agribusiness (more than 20% of gross domestic product (Statista, 2019)) and with a great potential for milk production, identifying such potential in terms of environmental efficiency from-cradle-to-farm-gate, places Brazil in an envious place among its potential competitors. From a market perspective, it can be seen a great potential for the milk produced in Brazil to be subject to export to other countries whose milk production systems have a worse environmental performance. Moreover, one should bear in mind that milk is also the raw material for a number of dairy products (e.g., cheese, butter, yogurt, whey protein, and others) and it contributes to the environmental performance of those products as well.

In fact, Brazil's territorial space is large. Many states in Brazil are even larger than whole European countries. Therefore, a few milk production systems in Brazil are semi-confined (as presented in this study, e.g., semi-confined system - Minas Gerais state, and semi-confined system - Paraná state). Moreover, Brazilian milk production systems could serve as a benchmark for other countries, especially the ones with high volumes of milk production, not only because of the environmental performance, but for the entire system management which is responsible for such performance.

Furthermore, there is a trend among customers, especially in the food sector, around their concern with environmental issues, which influences purchase decisions (Herbes et al., 2018), and customers have direct contact with the product (for example, going on a frequent basis to the supermarket) and being part of a business-to-consumer communication (Del Borghi et al., 2020). In this sense, EPDs of dairy products might help disseminate relevant environmental information to consumers, allowing the identification of the potential environmental impacts generated throughout the production process and in the life cycle of such products (Toniolo et al., 2019). Nonetheless, it also has a potential for the opening of new markets.

5. Conclusion

The novelty of this research is unveiling of the impacts of MPSs in the two states who are the largest producers of milk in the country, as no other LCA study of milk production in Brazil has tackled either of these states. Brazil is a country of wide dimensions, and this research proves that milk production in different geographical locations within the country, even though "close" can differ to a significant extent. Moreover, by assessing the environmental impacts of the MPS in the two most representative states of milk production in Brazil (Paraná and Minas Gerais), and analyzing the environmental performance of said systems (at the farm-gate), this study also highlights the potential to develop EPDs of milk and dairy products that originate from milk produced in Brazil. This is especially so in light of the existence of other EPDs of milk published in EPD Program Operators worldwide. This emphasizes the importance of publishing EPDs, which allow the promotion of a more sustainable development, sensitizing consumers and encouraging a cleaner production, on top of opening up a competitive advantage for companies in the sector.

The results point to the confined system in the state of PR (MPS 2) as responsible for the lowest GHG emissions per kg FPCM of milk. In the three MPS, enteric and fossil CH_4 emissions were responsible for the largest contribution to GHG impacts. However, in the confined system (MPS 3), food production was the main responsible for the impacts in the acidification category. The use of inorganic fertilizers for feed production was responsible for the greatest contribution to the eutrophication potential. As for the POCP, the main contributors were emissions of methane and emissions deriving from deforestation, and emissions from transportation.

The results of this study can serve as inspiration for seeking environmental improvements of MPSs in other regions of the country (due to the wide territorial extension of Brazil), and also move towards international limits. The results of this study can also be useful as standard data for specific inventories from other locations where certain input variables are not available. Moreover, this analysis can help guide and support research and development of milk production, and also facilitate and influence the development of EPD for food products, which have been growing over the past few years.

Prospects to this research should be mentioned. The present research contributes to the theoretical and practical aspects. The work brings to the light of the scientific literature a brief list of studies that evaluated the life cycle of milk production in the world, and comparison with cradle-to-farm-gate LCAs. In practical aspects, three documents of EPDs for dairy products are presented. In addition, some environmental product declarations as drivers for market strategy of Brazilian milk and dairy products are presented to provide insights for producers and stakeholders in the dairy sector.

Limitations to this study should be mentioned. For the three MPS presented, primary data was obtained for the milk production at the farm (gate-to-gate) and all upstream processes were modeled based on selected generic data (ecoinvent 3.7). The two mesoregions (Zona da Mata, and Campos Gerais) were selected for being the largest producers of the milk produced in Brazil, and the production systems (confined and semi-confined) were selected for being the most representative in each mesoregion; however, the three systems reported (confined Campos Gerais; semi-confined Campos Gerais, and semi-confined Zona da Mata) might not be representative of any one isolated property within the regions or in other regions of the country. Furthermore, one should also bear in mind that the comparisons are based on the impact categories and LCIA methods described in the methods section.

Credit author statement

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Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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