Environmental Science and Pollution Research (2022) 29:21259–21274
https://doi.org/10.1007/s11356-021-17317-5

RESEARCH ARTICLE

Environmental life cycle assessment of cow milk in a conventional semi-intensive Brazilian production system

Laurine Santos Carvalho[1,2] · Camila Daniele Willers[1,2] · Bruna Borges Soares[3,4,5] · Alex Rodrigues Nogueira[5] · José Adolfo de Almeida Neto[6] · Luciano Brito Rodrigues[5,7]

Received: 30 March 2021 / Accepted: 28 October 2021 / Published online: 9 November 2021

Abstract
The environmental performance of cow milk produced in a conventional semi-intensive system was assessed using a cradle-to-farm gate attributional life cycle assessment. The impacts of 1 kg FPCM—fat and protein corrected milk were obtained considering six midpoint impact categories from the ReCiPe 2016 method: climate change (CC), terrestrial acidification (TA), freshwater eutrophication (FE), land use (LU), water consumption (WC), and fossil resource scarcity (FRS). The modeling of the product system and calculating the environmental impacts considered the use of SimaPro™ software. Enteric methane and nitrogen emissions and inputs for feeding animals (fertilization for pasture production, use of seed in corn crops, and milk replacer in calves feed) were the main contributors to impacts in milk production in most categories. In addition, the indirect energy use and wastewater generation in milking and milk cooling also were relevant. Literature-based strategies are suggested to mitigate the identified environmental impacts to achieve the best environmental performance without decreasing technical and quality milk production. We emphasize the importance of improving productivity per milk cow, knowing the origin of the supply chain inputs, and using it efficiently to produce animal feeds as the main strategies to improve milk's environmental performance. Changes in allocation methods did not substantially differ in impact categories. Sensitivity analysis foregrounds the consistency of results and conclusions of the current study despite the uncertainties associated with methodological choices, simplifications, suppositions, and the use and adaptation of international databases.

Keywords Life cycle assessment · Environmental management · Impact assessment · Life cycle inventory · Milk · Livestock · Dairy chain

Introduction

Dairy farming has a relevant contribution to economic and social development. Worldwide, around 150 million families work in milk production. Most of them comprise small

Responsible Editor: Philippe Loubet

✉ Luciano Brito Rodrigues
rodrigueslb@uesb.edu.br

1 Instituto Federal de Educação, Ciência e Tecnologia da Bahia—IFBA, Bahia, Seabra/Vitória da Conquista, Brazil

2 Environmental Sciences Graduate Program, Universidade Estadual do Sudoeste da Bahia—UESB, Itapetinga, Bahia, Brazil

3 Techno-Science and Innovation Centre, Universidade Federal do Sul da Bahia—UFSB, Itabuna, Bahia, Brazil

4 Development and Environment Graduate Program, Universidade Estadual de Santa Cruz—UESC, Ilhéus, Bahia, Brazil

5 Materials and Environment Research Group, Universidade Estadual do Sudoeste da Bahia—UESB, Itapetinga, Bahia, Brazil

6 Department of Agricultural and Environmental Sciences, Universidade Estadual de Santa Cruz—UESC, Ilhéus, Bahia, Brazil

7 Department of Rural and Animal Technology, Universidade Estadual do Sudoeste da Bahia—UESB, BR 415, km 03, Itapetinga, Bahia 45700-000, Brazil

farmers from developing countries, and this activity is the main activity for their livelihoods (FAO 2021).

The nutritional relevance of milk makes it still one of the top products from the agricultural and livestock industries. Milk is also considered a highly beneficial food because of its fundamental nutrients (Pereira 2014; Mörschbächer et al. 2017).

Historically, Brazil has been ranked among the top five milk-producing countries, reaching around 23.5 million metric tons (MMT) in 2020 (STATISTA 2021; USDA 2020). For 2021, despite the adverse economic consequences stemming from the COVID-19 pandemic, a 1.3% increase in production is forecasted compared to the previous year once the dairy sector was not as significantly impacted as other sectors from a global perspective (USDA 2020).

In addition to the benefits derived from promoting economic activity, the correlation between milk production and the associated environmental issues must be considered. GHG emissions and manure, water consumption, deforestation, and demand for resources are environmental aspects usually associated with milk production, which requires proper management due to a growing trend towards sustainable practices in the activity. Fertilizers are another crucial environmental aspect resulting in emissions to soil, water, and air. Relevant emissions are derived from nitrous oxide due to fertilizers used for grains and pasture production. It also contributes to carbon emissions related to energy demanded by fertilizer production and transport (Willers et al. 2017). These emissions are subsequently converted to CO_2-eq using appropriate global warming potential (GWP) factors. Lastly, fertilizers may cause eutrophication of water bodies by runoff of phosphorus and nitrogen compounds and groundwater contamination by nitrate leaching.

In this sense, life cycle assessment (LCA) method has been widely accepted and used to identify and evaluate the environmental impacts associated with the life cycle of products and processes worldwide, including Brazil (Willers and Rodrigues 2014; Owsianiak et al. 2018). Several LCA studies have been performed in the past two decades to assess the environmental impacts of cow milk production in intensive and semi-intensive systems and conventional and organic management. According to Finnegan and Goggins (2021), many LCA studies worldwide were performed to estimate the GWP of raw milk production. This statement confirms that most LCA studies focus on CO_2-eq emissions due to worldly increasing attention regarding global warming (Yan et al. 2013). Nevertheless, the assessment of other impact categories is also valuable for these studies. It would allow a comprehensive view of the contributions from environmental aspects, supporting substantiating future propositions of suitable solutions to reduce the critical points identified.

Seó et al. (2017) summarized the LCA studies on dairy cattle from 2008 to 2014, including milk production and critically analyzing other impact categories beyond GWP, most frequently addressed in the literature. Following previous reviews, Carvalho et al. (2018) updated the LCA studies on milk production from 2015 to 2018, like those by Bacenetti et al. (2016), Salvador et al. (2016), Woldegebriel et al. (2017), and Zucali et al. (2018).

It is noteworthy that LCA studies on milk are continually required and relevant. Studies by Drews et al. (2020), Berton et al. (2020), Pirlo and Lolli (2019), and Wang et al. (2018), to cite some, show that the demand for studies on the influence of the type of milk, handling strategies, the technology employed, geographical coverage, and assessment methods needs to be investigated.

Regarding Brazilian LCA studies on cow milk, research initiatives have been conducted since 2010 (Willers et al. 2010; Olszensvski 2011; Léis 2013). Willers et al. (2010) performed a life cycle inventory analysis for milk production in Brazilian Northeast and therefore did not consider the impact assessment phase and its categories. Léis et al. (2015) investigated the carbon footprint of milk production, thus, not including other impact categories. Recently, Brazilian LCA studies on milk and dairy products of buffalo (Soares et al. 2019; Alves et al. 2019) and goat (Cabral et al. 2020) have been published. Moreover, Ruviaro et al. (2020) used the life cycle perspective to assess economic costs by dairy production systems in Southern Brazil. However, no study regarding the environmental impacts of cow milk could be found. Since Brazil is a relevant player in the cow milk production market, LCA studies are still needed. Beyond the knowledge of the environmental impacts and resource use of such activity, the results can also support the planning of further action to reduce critical points identified, contributing to improvements in the life cycle of milk and dairy products.

As Santos Jr et al. (2017) noted for cheese production, 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. Besides, results can serve as benchmarking of best practices for their impact mitigation, improving the whole production chain, as Ferreira et al. (2020) proposed.

This study evaluates the environmental impacts of cow milk from Bahia state, which ranks eighth among the Brazilian producers and first in the Northeastern region (USDA 2020). The investigation is aimed at assessing the primary stage of the milk value chain and to further contribute to developing the life cycle inventory of the Brazilian agricultural and livestock products database.

Materials and methods

The research was performed considering the requirements of both ISO 14040 and ISO14044 standards (ISO 2006a, 2006b).

Product system

The product system comprises a farm in the Middle Southwest region of Bahia state (Fig. 1), chosen because of its production volume and technology level.

The milk production system is semi-intensive. The herd comprises 128 animals, Girolando and mixed-race with a blood degree within 1/2 and 3/4 Holstein, featuring 52 lactating cows, 38 dry cows, 18 heifers, and 20 calves. Cattle feed includes pasture, corn silage, concentrate, and mineral salt supplementation.

Pasture area consists of 67.8 hectares, of which 16% is irrigated. Rotational grazing occurs in an area divided into 100 paddocks fertilized annually with phosphate and nitrogen products. Previous soil analysis showed that potassium fertilization was not necessary.

Milk productivity averaged 970 L per day (6,808.65 L per cow per year), and lactating cows are fed according to their average daily milk production:

- High productivity cows (21 cows yielding 19 L) feed on pasture and concentrate as a supplement
- Intermediate productivity cows (15 cows yielding 15 L) exclusively feed on pasture
- Low productivity cows (16 cows yielding 8 L) feed post-grazing residues, comprising a 25–30 cm height pasture, in which intermediate productivity cows have previously been fed

The feeding strategy for heifers comprises pasture, concentrate, and mineral salt supplementation. Calves are fed twice a day with a commercial milk replacer, which is succeeded by pasture and concentrate feed around the 45th to 60th day of life. Moreover, the diet of dry cows is composed of pasture and mineral supplementation.

Mechanical milking occurs initially in the morning for all lactating cows, and a second milking is performed in the evening only for high productivity lactating cows. The milk is cooled at 4 °C in a 2050 L-capacity tank and stored to be sent on alternate days for processing in dairy industries located in the region.

Goal and scope definition

The main goal of this study is to perform a life cycle impact assessment of milk produced on a semi-intensive farm system.

Function and functional unit

The product system's function is to provide refrigerated raw milk for primary consumption and raw material for dairy products.

The functional unit considered 1 kg FPCM—fat and protein corrected milk, representing the equivalent milk mass

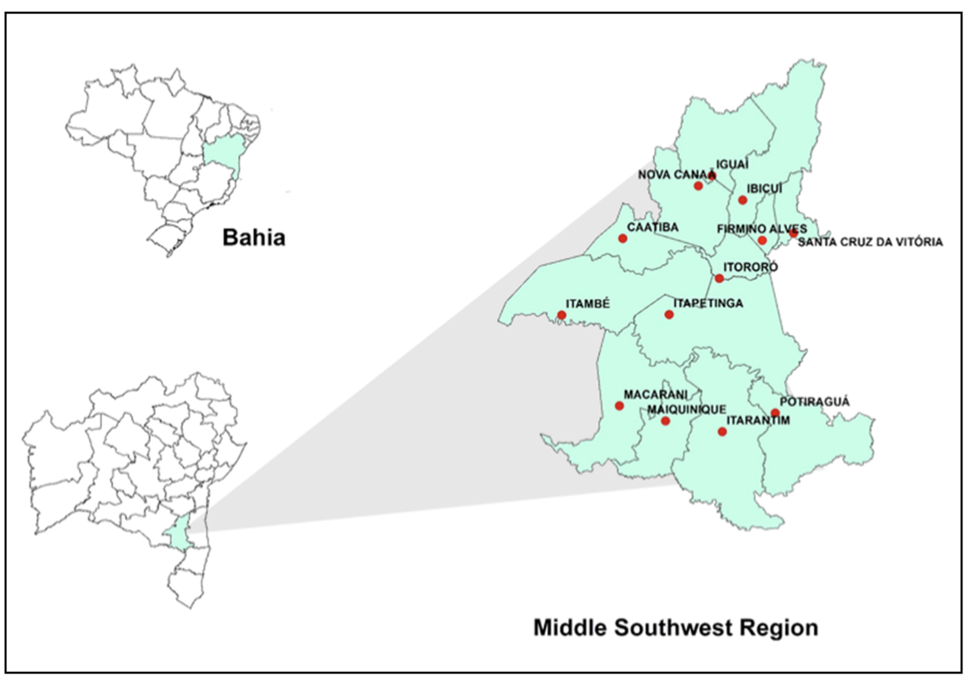

Fig. 1 Middle Southwest region of Bahia, Northeast Brazil

by fat and protein standard content. According to the International Dairy Federation, FPCM is calculated by Eq. 1 (IDF 2015):

$$kgFPCM = MP \times [(0.1226 \times \%F) + (0.0776 \times \%P) + 0.2534] \quad (1)$$

where MP is the milk produced, in kg; %*F* is the fat content per kg of milk; %*P* is the protein content per kg of milk.

The *F* and *P* percentages were standardized at 4% fat and 3.3% milk protein, as recommended by the IDF (2015). According to the IDF, the FPCM assures a fair comparison between farms with a different breed or feed management.

System boundary

The system boundary for this study is characterized as from cradle-to-farm gate (Fig. 2). The product system comprises the farm's geographical boundaries, including the transport to the dairy industry. Seven unit processes were included: pasture production, corn silage production, concentrate production, mineral salt production, cattle breeding, milking and milk cooling, and transport.

Inventory analysis

The study considered primary and secondary data. Primary data were obtained through on-site visits at the farm, including interviews with the staff of the milking and farm machinery sectors. If these were missing, secondary data included ecoinvent® v3.6 and Agri-footprint databases, literature, and theoretical models.

Primary data comprised information on inputs for animal feed (pasture, corn silage, concentrate, and mineral salt), water and electric energy consumption, agricultural pesticides, materials for cleaning, and agricultural operations. Some medicines and materials for artificial insemination were disregarded as they represent much less than 1% of the system inputs in terms of mass (Johnson and Schwartz

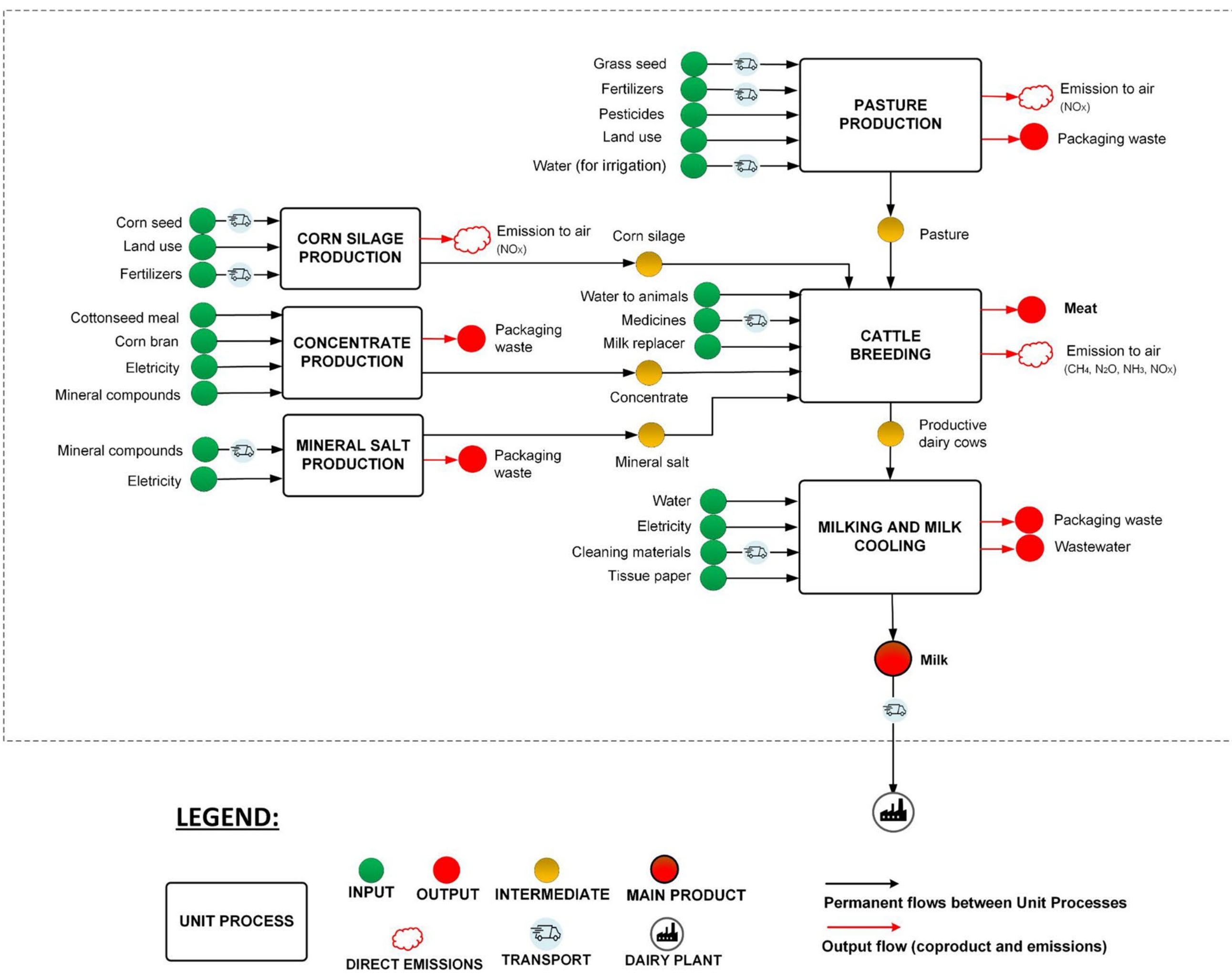

Fig. 2 System boundary

2002). Besides, they result in non-significant impacts (Ross et al. 2014). Buildings, infrastructure, equipment, and human work were also not included in the system boundary.

The primary water for animal watering was determined by the number of animals per category (Campos 2006). The animal feed was calculated according to its composition and the amounts of carbohydrates, proteins, micro, and macrominerals required. Cleaning materials, fertilizers, agriculture defensives (e.g., pesticides, insecticides, and herbicides), and medicines (antiparasitic products and insecticides) were quantified according to their chemical composition. The same occurred for milking, whose utensils (e.g., syringes and tissue paper) and cleaning materials were accounted for according to composition, mainly featuring plastic materials and disinfectants.

The electricity consumption was obtained from calculating the consumption of equipment used in the dairy farm, i.e., the milking machine, the feed mixer, and the two pumps used to collect water. The fuel consumption required for agricultural activities considered the equipment's operating time (tractor) and the area to be managed. The water for cleaning the milking parlor and equipment was quantified according to Willers et al. (2014). The water for irrigation was calculated by technical methods related to the system's discharge data and function time. The transport of inputs to the farm was calculated based on the distance between the retail stores and the farm, number of trips, and type of vehicle used. Similarly, milk transport to the dairy plant considered the distance between the farm and the dairy industry and the alternate collection days.

The generation of solid waste, wastewater, and air emissions was also considered. The wastewater was estimated based on the water consumption in the milking process, whereas the solid wastes considered the amount of material discarded by the staff (e.g., disposable gloves, styrofoam box, and milk feeding bottle for calf).

The CH_4 emissions from enteric fermentation and manure management and N_2O emissions from manure management were estimated using the equations of the Intergovernmental Panel on Climate Change—IPCC guidelines (IPCC 2006a, 2006b).

The life cycle inventory (Table 1) of milk was performed, comprising the assumptions described.

Impact assessment

The ReCiPe 2016 method (Huijbregts et al. 2017), an update from ReCiPe 2008 (Goedkoop et al. 2009) version 1.04, was used to create a correlation between input and output data and environmental impacts. Six midpoint categories were considered for this study: climate change (CC, in kg CO_2-eq), terrestrial acidification (TA, in kg SO_2-eq), freshwater eutrophication (FE, in kg P-eq), land use (LU, in m^2.year), water consumption (WC, in m^3), and fossil resource scarcity (FRS, in kg oil-eq).

Such categories were chosen according to the product analyzed and frequency of use in the literature in similar research. The modeling of the product system and the calculation of environmental impacts were performed using SimaPro™ software, version 9.1.0.7. Further information on data and the processes chosen for modeling the product system are available in Supplementary Material.

Allocation and sensitivity analysis

Multifunctional problems are common in LCA studies. Milk production cannot occur exclusively in a product system since other co-products are generated, e.g., meat, horns, calves, and leather. Thus, the impacts need to be distributed, or allocated, among them adequately.

According to ISO 14040 (ISO 2006a), material and energy flows and emissions shall be appropriately allocated to the products considered to reflect physical relations correctly. In other words, allocation is aimed at representing how such physical relations (e.g., mass and protein content) change with quantitative modifications in the products obtained (Ramirez et al. 2008). In some cases, these physical relations cannot be established or used. Thus, the inputs and outputs can be allocated to the co-products proportionally, according to their economic value (ISO 14044 2006b). Nonetheless, susceptibility to market fluctuations is a drawback for the economic allocation (Guinée et al., 2004). Thus, using average economic values is recommended to minimize this effect (Ramirez et al. 2008).

Roer et al. (2013) used economic allocation to share the impacts between the outputs (milk, carcasses, surplus offspring, and manure) in a combined milk and meat production in Norway. Feitz et al. (2007) recommend using allocation based on physical–chemical properties of the processes and emissions, such as mass, volume, or energy, to avoid the errors caused by the economic allocation.

In this study, the allocation considered milk and meat as co-products, with meat comprising the heifers, calves, or dry cows (unproductive cows) sold for slaughter. Thus, the sensitivity analysis compared physical and economic allocation methods to verify changes from impact categories results. Besides, a scenario with no allocation was also considered, in which impacts were attributed entirely to milk. The sensitivity analysis is a complementary data quality assessment method that evaluates consequences stemming from each allocation choice or identifies the significance of data and changes of methods on the life cycle impact assessment.

Physical allocation for the LCA milk study was calculated according to Eqs. 2 and 3 (IDF 2015):

Table 1 Inventory for 1 kg of milk produced in semi-intensive system

Unit process	Inputs/outputs/emissions	Unit	Amount
Concentrate production	**Inputs**		
	Cottonseed meal (protein feed)	g	3.0724
	Corn bran	g	11.66
	Industrial plant infrastructure	kg	5.46E-12
	Phosphate rock (proxy for dicalcium phosphate)	mg	88.76
	Sulfur	mg	16.39
	Magnesium sulfate	mg	23.01
	Cobalt (proxy for cobalt sulfate)	mg	0.0081
	Copper sulfate	mg	0.4582
	Iron sulfate	mg	0.9277
	Iodine (proxy for potassium iodate)	mg	0.0171
	Manganese sulfate	mg	2.8167
	Selenium (proxy for sodium selenite)	mg	0.0082
	Zinc sulfate	mg	2.1478
	Electricity	kWh	4.78E-5
Mineral salt production	**Input**		
	Industrial plant infrastructure	kg	1.99E-12
	Sulfur	mg	59.95
	Phosphate rock (proxy for dicalcium phosphate)	mg	224,82
	Magnesium sulfate	mg	148.54
	Cobalt (proxy for cobalt sulfate)	mg	0.2498
	Copper sulfate	mg	8.3826
	Salt (sodium chloride)	mg	814.35
	Iron sulfate	mg	14.9337
	Iodine (proxy for potassium iodate)	mg	0.2998
	Manganese sulfate	mg	13.0533
	Selenium (proxy for sodium selenite)	mg	0.0499
	Zinc sulfate	mg	33.0861
	Electricity	kWh	1.75E-5

Table 1 (continued)

Unit process	Inputs/outputs/emissions	Unit	Amount
Pasture production	**Inputs**		
	Land occupation	m^2.year	0.9159
	Grass seed	g	0.5660
	Phosphoric acid	mg	5.1000
	Pyrethroid compound, in pesticide	g	0.0080
	Organophosphorus compound, in pesticide	g	0.1500
	2-methyl-1-butanol, in pesticide	mg	0.1800
	Benzal chloride, in pesticide	mg	2.6000
	Ethoxylated compound, in pesticide	mg	0.4300
	Pyridine compound, in pesticide	mg	1.7000
	Phenol, in pesticide	mg	0.3000
	Ethanol, in pesticide	mg	20.00
	Boric acid, in pesticide	mg	0.3500
	Phosphane, in pesticide	mg	0.0003
	O-cresol, in pesticide	mg	0.00001
	[Thio]Carbamate compound, in pesticide	mg	0.1000
	Polyethylene, in packaging	g	1.7000
	Irrigation	L	0.5150
	Urea, as N	g	9.1590
	Single superphosphate, as P_2O_5	g	4.5795
	Fertilizing, by broadcaster	ha	0.0014
	Emissions to air		
	Nitrous oxide	g	1.1000
	Waste to treatment		
	Waste polyethylene	g	1.7000

Table 1 (continued)

Unit process	Inputs/outputs/emissions	Unit	Amount
Milking and milk cooling	**Inputs**		
	Water	L	0.3769
	Tissue paper	mg	130.0
	Milking, operation	kg	1.00
	Chlorine	mg	47.0
	Cleaning material	mg	132.6
	Polypropylene, in packaging	mg	123.7
	Polyvinylchloride, in packaging	mg	3.4
	Polyethylene, in packaging	mg	3.77
	Polystyrene, in packaging	mg	3.43
	Emissions to water		
	Phosphorus	mg	60.19
	Nitrate	mg	270.48
	Chemical oxygen demand	mg	4.3925
	Solids, inorganic	kg	22.4
	Waste to treatment		
	Waste polyethylene	mg	3.77
	Waste polypropylene	mg	123.7
	Waste polystyrene	mg	3.43
	Waste paperboard	mg	130.0
Corn silage production	**Inputs**		
	Land occupation	m^2.year	0.00153
	Corn seed	kg	0.09
	Urea, as N	mg	0.126
	Single superphosphate, as P_2O_5	mg	0.124
	Emissions to air		
	Nitrogen oxides	mg	0.069
Transports	**Inputs**		
	Transport, lorry	tkm	0.0105
	Transport, light vehicle	tkm	0.0105
Cattle breeding	**Inputs**		
	Water	L	0.1461
	Milk replacer	g	1.2490
	Vermifuge	mg	0.9000
	Latex gloves	mg	1.7495
	Emission to air		
	Methane	kg	0.0295

$$\mathrm{BMR} = \frac{M_{\mathrm{meat}}}{M_{\mathrm{milk}}} \quad (2)$$

$$\mathrm{AF} = 1 - 6.04 \times \mathrm{BMR} \quad (3)$$

where *BMR* is the ratio $M_{\mathrm{meat}}/M_{\mathrm{milk}}$; M_{meat} is the sum of live weight of all animals sold, including male calves and cows at the end of the production cycle; M_{milk} is the sum of milk sold during the production cycle (around 85 months of milk production) in kg FPCM. AF is the allocation factor for milk.

Economic allocation was calculated according to Casey and Holden (2005). The economical rates for the sum of meat and the sum of milk for the life cycle of the dairy cow were obtained from Animal Production Statistics (IBGE 2020).

Results and discussion

The environmental impacts of milk for 1 kg FPCM are depicted in Fig. 3.

Results were compared with other cradle-to-farm gate LCA studies of milk production (Table 2).

Climate change

The environmental burden of cow's milk production in the climate change (CC) corresponded to 1.41 kg CO_2-eq kg $FPCM^{-1}$. The main contributors for the CC category are related to cattle breeding (65.7%), followed by pasture production (24.3%) and corn silage production (7.4%). The CH_4 and N_2O were the principal emissions from enteric fermentation and manure deposited on pasture (in minor proportion). Thus, the carbon footprint of the farm products is directly related to enteric methane emissions and nitrogen deposition rates in the pasture.

The value found in the current study for a semi-intensive system is relatively lower compared to those found by González-Quintero et al. (2021), whose emissions ranged from 2.1 to 4.2 kg CO_2-eq, considering four clusters in Colombian farms with a feeding strategy based on grazing. Wilkes et al. (2020) observed that in farms with different feeding systems, the amount of kg CO_2-eq was significantly higher in pure grazing systems than those from zero-grazing to semi-grazing. Therefore, such results would explain the lower value found in our study (in a semi-intensive system) once the pasture-based feed is directly correlated with the intensity of GHG emissions due to enteric fermentation (Sabia et al. 2020).

Conversely, the value was higher than those obtained by Rotz et al. (2020), between 0.86 and 1.17 kg of CO_2-eq per kg of FPCM, in representative dairy farms of various regions of Pennsylvania, United States. The lowest value found for the cited authors can be associated with high milk production levels per cow. Systems of low production contribute to a greater intensity of GHG emissions.

Regarding the GHG distribution, a similar trend was found for González-Quintero et al. (2021). The authors reported that methane was the main contributor to the CC category since the lower inputs used at farms and most of the emissions were from animals. In the milk produced in Australia, Gollnow et al. (2014) identified that enteric fermentation, especially in lactating cows, contributes 57% to the emissions. The manure from grazing animals is released into the soil, contributing 9% to N_2O and 1% to CH_4 emissions. Feed conversion efficiency improvements could effectively reduce such emissions.

The main contributions of both unit processes, pasture production and corn silage production, in the CC category

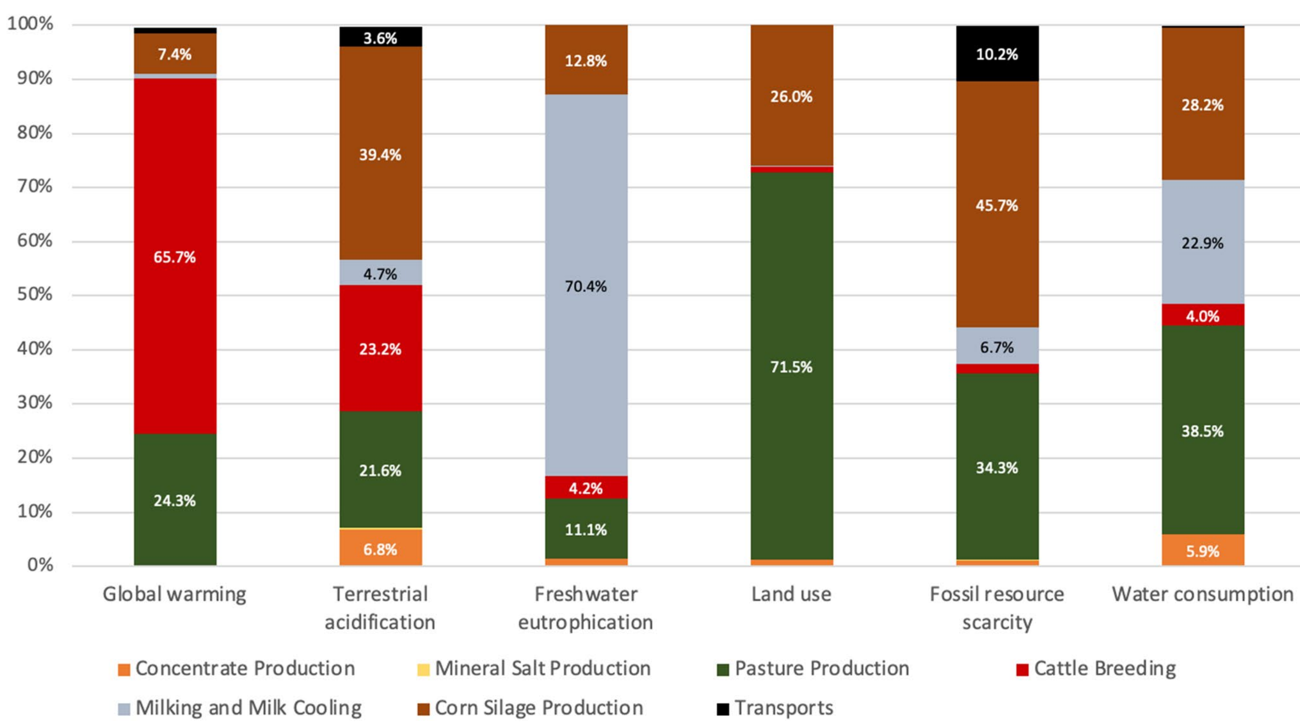

Fig. 3 Life cycle impact assessment

Table 2 Life cycle assessment studies of cow milk production in cradle-to-farm gate approach

Study	Country	Functional unit	Goal	Main critical points
González-Quintero et al. (2021)	Colombia	1 kg FPCM	Estimate the environmental impact of 1313 dual-purpose farms in Colombia	Greenhouse gas (GHG) in dual-purpose cattle systems comes directly from enteric fermentation and manure deposited on pasture
Wilkes et al. (2020)	Kenya	1 kg FPCM	Determine the significant differences in the carbon footprint (CF) of farms with different feeding systems (zero-grazing, grazing, and mixed systems) and identify factors associated with variability in CF between farms	- In individual cow level, variation in milk yields; - At the farm level, feed characteristics, manure management practices, and herd size and composition
Berton et al. (2020)	Italy	1 kg FPCM	Evaluate the effect of different Alpine dairy farming systems on the environmental footprint, production efficiency, and competition between feed and food	- Different farm management practices influenced the results since traditional and intensive dairy systems showed considerable variability in the impacts assessed
Rotz et al. (2020)	United States	1 kg FPCM	Assess environmental footprints of dairy farms in Pennsylvania	- Enteric fermentation (CH_4 enteric), use of electricity in milking and milk cooling, energy used to produce feed, and ammonia emissions from pastures, barns, and manure storages
Drews et al. (2020)	Germany	1 kg ECM	Investigate the development of environmental impacts caused by milk production over a decade	- Energy-corrected milk yield (ECM) - ECM from roughage feed efficiency - Use of concentrates
Pirlo and Lolli (2019)	Italy	1 kg FPCM	Evaluate the impact of organic milk production on global warming potential (GWP), acidification potential (ACP), and eutrophication potential (EUP) in comparison with the impact of the conventional milk production system	- Milk productivity - Emissions of NH_3, N_2O, and P from manure management and application
Salvador et al. (2016)	Italy	1 kg FPCM	Estimate the environmental impact of organic and conventional small-scale dairy farms in mountain areas	- Enteric emission (mainly CH_4), manure storage - Off-farm emissions - Culling rate is low in organic farms
Bacenetti et al. (2016)	Italy	1 kg FPCM	Assess different mitigation strategies of the potential environmental impacts of milk production at the farm level	- Livestock management and feeding and milking procedures - On-farm crop production - Manure management
Léis et al. (2015)	Brazil	1 kg ECM	Assess the carbon footprint per 1 kg of ECM at the farm gate for different dairy production systems in the southern region of Brazil: a confined feedlot system, a semi-confined feedlot system, and a pasture-based grazing system	- Uncertainties in feed intake data, mainly in the intake of grazing animals and silage (inaccurate farm records) - Variability of feed consumption
Gollnow et al. (2014)	Australia	1 kg ECM	Exploring the carbon footprint of milk produced by dairy cows in Australia	- Feed conversion efficiency (predominantly pasture-based feed systems) - Manure management practices (stored in anaerobic lagoons)

Data were obtained in kg P-eq by ReCiPe 2016 MidPoint method and converted in kg PO_4-eq, according to Oram (2016) are due to emissions of N_2O and CO_2 from nitrogen fertilization using urea and thermal energy for drying corn seeds. Such practices are related to pasture handling, adjusted rates of fertilization, and sowing.

Terrestrial acidification

The potential impact of milk corresponded to 1.11E-03 kg SO_2-eq for the terrestrial acidification (TA) category. The main contributions were from corn silage production (39.4%) due to grain production for feed. The following contributors are cattle breeding, mainly due to milk replacer in calves feed (23.2%) and pasture production (21.6%). The primary emissions for TA were those related to the N volatilization in the form of ammonia (NH_3). The most significant contribution from corn silage production is coming from the cultivation of corn.

The most significant contribution from corn silage production is coming from the cultivation of corn. Next, the contributions from the use of milk replacer stand out, whose elementary flow is related to the electricity required in the milk standardization process. In pasture production, the higher contributions were due to nitrogen-based fertilizers (urea).

The TA emissions were lower than Berton et al. (2020), 21.1 ± 4.3 g SO_2-eq. per 1 kg FPCM, considering the variability between and within dairy systems in Italy. The difference is due to the conditions of the dairy systems studied, comprising small, traditional, and low-input farms and large, intensive, and high-input farms. In this case, the systems distinguished in terms of herd size, management (e.g., feeding system, facilities, and equipment), breeds of cattle raised, and, consequently, in the environmental effects on the TA category.

The value was also lower than those by Salvador et al. (2016), when the physical allocation was considered (21.73 g SO_2-eq. per 1 kg FPCM), whose results were obtained from small-scale dairy farms with more extensive and less efficient management systems. As in our study, Salvador et al. (2016) state the influence of animal feed as a relevant contribution to acidification.

Freshwater eutrophication

The freshwater eutrophication category (FE) results were 2.39E-04 kg PO_4-eq per 1 kg FPCM, considering the conversion of P to PO_4-eq, according to Oram (2016).

The main contributor to the FE category was the unit process milking and milk cooling (70.4%), followed by corn silage production (12.8%) and pasture production (11.1%). In the milking and cooling milk unit process, the elementary flows are derived from the indirect energy use and wastewater generation from cleaning of utensils, equipment, and the milking parlor floor where the phosphorus and phosphate (PO_4^{3-}) emissions played an important role. The use of seed in corn crop production and the application of nitrogen fertilization in the pasture treatment were the main elementary flows for corn silage production and pasture production, respectively. According to Roy et al. (2009), eutrophication is the most significant environmental impact on agricultural production. The authors report that nitrogenized fertilization increases production and economic efficiency while reducing the environmental efficiency of production.

Land use

The environmental effect of milk in the land use category (LU) was 0.64 in m^2.year crop-eq per 1 kg FPCM, whose significant contributions were pasture production (71.5%) and corn silage production (26%). The impact attributed to pasture production is due to the land transformation and occupation, while in the production of corn silage it is its use for the cultivation of corn.

The land requirement was lower than the study by Berton et al. (2020), found in different Alpine farming systems in Italy (1.4 m^2.year to obtain 1 kg FPCM). This difference is probably associated with productivity.

Regarding the contributions, the significant participation of pasture in land occupation is also reported by Roer et al. (2013), who cited forage production as one of the main contributing flows for the LU category, with 63%–66%. The study considered a system comprising three typical farms representing Norway's most relevant milk production regions (central, central-southeast, and southwest).

Since land use is essential in semi-intensive systems, environmental improvements must focus on proper management of pastures (rotation systems and improvements in the production potential), ecosystem services, in order to increase land occupation efficiency. According to Berton et al. (2020), the ability to conserve grasslands under a land-sharing perspective, and in general the associated ecosystem services, should be considered when aiming to improve their environmental sustainability. In addition, a proper land occupation (adequate rate of animals per hectare) favors land preservation to maintain natural habitats, which is a critical point to consider.

Furthermore, an increase in milk production per area of agricultural land is accompanied by an improvement in environmental efficiency, as related by Drews et al. (2020). The authors investigated the development of agricultural land occupation caused by milk production over a decade in Germany, among other impacts.

It is noteworthy that this study did not consider the carbon sequestration capacity of pastures and corn crops since its measurement is challenging. However, it is known that this indicator is relevant in greenhouse gas compensation.

Fossil resource scarcity

The fossil resource scarcity category (FRS) resulted in 4.82E-02 kg oil-eq per 1 kg FPCM, and the most impacting unit processes were corn silage production (45.7%) and pasture production (34.3%). Transporting both inputs to farm and chilled milk to the dairy industry contributed approximately 10% of the impacts. In comparison, milking and milk cooling contributed less than 7%. The contribution to transport was due to the use of fossil fuel for vehicle movements. For the milking and milk cooling, the contributor was the electric energy consumption.

Main elementary flows for the FRS category were the nitrogen-based (Urea) and phosphate fertilizers (P_2O_5), used for pasture production, and corn for silage production. Similarly, Roer et al. (2013) observed forage production as the main contributing factor for the category, ranging from 60 to 71% of environmental load.

Soares et al. (2019) also related that mineral extraction and the use of fertilizers and pesticides in non-organic agricultural practices showed an important hotspot for the use of fossil resources in buffalo milk production.

Thus, the expansion of the system boundary, including off-farms inputs (i.e., fertilizers and corn for silage production) and transport of inputs, contributed to the impacts for the FRS category. This result shows the importance of knowing the origin of the supply chain inputs to improve milk's environmental performance. Ferreira et al. (2020) changed some input parameters throughout the supply chain to reduce the impacts of cheese production.

Water consumption

Water is an essential input in dairy farms and demanded for cleaning, for irrigation purposes and for watering the herd (Palhares et al. 2020).

The water consumption (WC) was 5.87E-03 m^3 per 1 kg FPCM. The contributions were 38.5% for pasture production, 28.2% for corn silage production, 22.9% for milking and cooling milk, and 5.9% for concentrated production.

Most water consumption was related to using off-farm in corn to silage production, nitrogen-based fertilizer, and cottonseed as a protein source for concentrate production. These elementary flows represented approximately 64% of the whole water consumption.

The direct consumption occurred in the cleaning of utensils, equipment, and milking parlor (16.9%), pasture irrigation (8%), and water intake by animals (~2.26%). The estimation of the drinking water requirements of the animals is in line with typical practices for the region. Nevertheless, the values were lower than those by Palhares et al. (2020), who determined the drinking water intake for lactating cows by daily recording and measuring. For instance, water footprints observed by Palhares et al. (2020) were 502.4 L per 1 kg FPCM for an animal group fed with a 20% crude protein content diet (group 1) and 451.2 L per 1 kg FPCM for another animal group fed with a diet adjusted according to its milk production (group 2).

There is no way to reduce the water intake, as physiological animal requirements and milk production influence it. However, proper water management, such as automated watering systems, can help minimize water losses, as Palhares et al. (2020) used.

The results show that significant flows related to water consumption are present in the supply chain, off-farm, which need to be considered to improve the sustainability of milk production regarding water consumption.

Strategies to mitigate the environmental impacts

Strategies to mitigate the environmental impacts are suggested to achieve the best environmental performance without production decrease. Further, the implementation of such literature-based strategies can allow verifying their results.

It is possible to mitigate the environmental impacts in CC, TA, FE, FRS, and WC categories by using less nitrogen- and phosphate-based fertilizers. The use of animal manure, green fertilization, and composting are examples of alternative practices. Besides, synthetic fertilizers should be replaced by biological ones such as nitrogen-based compounds derived from the biological fixation of nitrogen from the atmosphere by leguminous plants and by phosphorus cycling from residues (e.g., sawdust, biochar, manure, and chicken bed) derived from the farm or agroindustries nearby.

As suggested by Bacenetti et al. (2016), an increase in milking frequency, from two to three per day, is another strategy that may reduce impacts in CC, TA, and FE categories, respectively, by 10%, 11%, and 12%. These authors state that milking three times a day results in an increase of feed efficiency due to the higher milk yield at constant feed intake, compared with milking twice, which is the current practice in most dairies (including the farm analyzed).

However, the authors remark that additional milking increases electric energy consumption, thus, being a trade-off to be analyzed. Thus, it is noteworthy that this proposition must include efficient resource consumption (e.g., energy, cleaning agents, and water). Pirlo and Lolli (2019) observed that GHG emissions for 1 kg of FPCM were reduced significantly by increasing the average milk production per cow in conventional and organic systems. The results suggest that increased milk production is an effective mitigation strategy to improve the environmental profile of milk in dairy farms.

Agricultural pasture handling, an adequate fertilization rate according to soil requirements, and efficient cultivation practices can increase the quality and quantity of feed produced and, consequently, reduce the GHG emissions due to inappropriate fertilization. Since the system is partially self-sufficient regarding animal feeding, production and transport of feed purchased did not influence the GHG emissions.

Suggestions to reduce the terrestrial acidification potential of milk at the farm include the efficient use of inputs for the production of animal feeds. Pasture production, for example, can employ techniques to reduce NH_3 losses by improving the amount of N to be used in pasture or optimizing the time and rate of fertilizer application (Pirlo and Lolli 2019). Other strategies involve adjusting the suckling periods of calves with the milking process or using waste milk in feeding calves, thus, reducing or avoiding the milk replacer as input.

The integrated crop-livestock system (ICLS) is remarkably relevant for production to mitigate impacts in the LU category. This mitigation occurs through the use of production systems that make intensive use of the available resources in agricultural systems, combined with soil quality improvement (Lemaire et al. 2014). The benefits of ICLS include reducing pasture degradation, increasing soil fertility due to the accumulation of organic matter, improvement of nutrient cycling, increased fertilizer efficiency, and better soil aggregation (Salton et al. 2014).

Salton et al. (2014) state that the ICLS system was very efficient in carbon soil accumulation and reducing greenhouse gas emissions. Thus, they affirmed that the ICLS system is agronomical, environmentally effective, and sustainable based on soil attributes.

Some strategies to reduce water consumption are suggested at the farm level, like those by Willers et al. (2014), including pressure washers for cleaning and dry-cleaning in the milking parlor (at the end of the process scraping manure). Regarding irrigation, the drip system is a technique that applies water exactly where it is needed, reducing waste and increasing efficiency.

Allocation

According to IDF (2015), physical allocation is adequate for reflecting the underlying use of feed energy and the physiological feed requirements for milk and meat production. Therefore, this was the base scenario for our sensitivity analysis.

The physical allocation factor for milk in the current study reached 90.94%. In contrast, Bacenetti et al. (2016) reported 82.4% and Gollnow et al. (2014) 78.2% as allocation factors. This rate complies with IDF (2015), indicating a range between 90 and 100% of the environmental load for milk production rather than meat. When the physical allocation between meat and milk is analyzed, greater efficiency is detected in the current analysis (94.7% for milk production) compared to others. It may result in greater productive efficiency, warranting that most resources, inputs, wastes, and emissions are linked to milk production. Pirlo and Lolli (2019) did not identify significant differences in the impact categories CC, TA, and FE for 1 kg of FPCM produced in conventional or organic farms using economic and physical allocation criteria.

The economic allocation yielded an environmental load sharing of 94.7% and 5.3% for milk and meat, respectively. These rates align with Léis (2013), who reported 90% of the environmental load for milk and 10% for meat.

Table 3 shows the sensitivity analysis for the allocation methods considered.

According to Baldini et al. (2017), comparing the different allocation methods within the same analysis is highly useful to understand the consistency of results. There was no substantial variation of the environmental impact categories considered due to the different allocation methods. The differences were approximately 4%, with a discrete increase in milk environmental impacts using economic allocation, and approximately 10%, when no allocation criterion was used and all environmental impacts were attributed to milk.

Rafiee et al. (2016) state that economic allocation is preferable for distributing milk and meat production emissions. Baldini et al. (2017) confirmed this statement when

Table 3 Sensitivity analysis for different allocation factors

Impact categories	Unit	Physical allocation		Economic allocation		No allocation (all impacts for milk)
		Milk (90.94%)	Beef (9.06%)	Milk (94.7%)	Beef (5.3%)	Milk (100%)
Climate change	kg CO_2-eq/kg FPCM	1.41	0.14	1.47	0.082	1.55
Terrestrial acidification	g SO_2-eq/kg FPCM	1.11E-03	1.10E-04	1.15E-03	6.46E-05	1.22E-03
Freshwater eutrophication	g PO_4-eq/kg FPCM	2.39E-04	2.38E-05	2.49E-04	1.39E-05	2.63E-04
Land use	m^2.year crop-eq/kg FPCM	0.64	6.42E-02	0.67	3.76E-02	0.71
Fossil resource scarcity	In kg oil-eq/kg FPCM	4.82E-02	4.80E-03	5.02E-02	2.81E-03	5.30E-02
Water consumption	m^3/kg FPCM	5.87E-03	5.85E-04	6.12E-03	3.24E-04	6.46E-03

reviewing the main allocation methods used in LCA studies on milk production. The authors identified that 15 out of 44 research works employed economic allocation as the criterion for partitioning the environmental burdens among milk and meat, while the other allocation assumptions (system expansion, protein content, no allocation, mass, biological, and other methods) were used in the remaining studies.

However, economic allocation is not the best method within the production phase at the farm since milk and meat prices constantly change and may not give consistent results when distributing environmental impacts between milk and meat products.

Conclusions

Pasture production, corn silage production, and cattle breeding (specifically in the CC category) were the main contributors for the seven impact categories considered in this study.

In the impact assessment, sensitivity analysis showed no more than 11% changes between the physical, economic, and zero allocation on milk and meat production. The sensitivity analysis enhances the consistency of results and conclusions of the current study despite the uncertainties associated with methodological choices, simplifications, suppositions, and the use and adaptation of international databases.

Literature-based strategies are suggested to mitigate the identified environmental impacts to achieve the best farm environmental performance without decreased milk production. We recommend improving the overall environmental performance of the semi-intensive milk production system by (1) observing the use of inputs with high environmental impact (e.g., fertilizers and seed corn crops); (2) improving productivity per lactating cow; and (3) reducing superfluous fertilizer application, improving nutrient flow from the farm through fertilization according to the soil's nutritional needs. According to the literature review, despite several previous studies on LCA of milk production, this work was the first to study a semi-intensive cow milk production system in Brazil's northeastern region, particularly in the State of Bahia. The results can contribute to regional databases and give incentives to future studies on the environmental impacts of milk supply chains. Moreover, it may be used by the academic community and dairy manufacturers and producers, supporting best marketing practices, such as the environmental product declaration.

This study follows the growing tendency to use the LCA methodology in Brazilian agricultural and livestock production systems. The results can be useful locally and globally, mainly in countries with similar climatic conditions and production management techniques.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-021-17317-5.

Acknowledgements The authors gratefully acknowledge the grants from Coordenação de Aperfeiçoamento de Pessoal de Nível Superior Capes (Finance Code 001), the Conselho Nacional de Desenvolvimento Científico e Tecnológico—CNPq (476725/2012-7; 313293/2014-7; (381479/2019-6), and the Fundação de Amparo à Pesquisa do Estado da Bahia—Fapesb (APP0056/2011; PAM0017/2014) for the financial support to the development of this research.

Author contribution All authors contributed to the conception and design of the study. Laurine Santos Carvalho performed data collection, initial modeling, and writing the initial version of the text. Camila Daniele Willers helped to discuss research, the results and wrote the initial version of the text. Bruna Borges Soares discussed results, wrote, and improved the final version of the text. Alex Rodrigues Nogueira revised the modeling, the writing, and discussed the results for the final version of the text. José Adolfo de Almeida Neto helped develop research, discuss results, revise, and text writing. Luciano Brito Rodrigues is the head of research, supervising, discussing the results, revising, and writing all manuscript versions.

Funding The funding received in the context of the development of this research is described in the Acknowledgements.

Data availability Data used to perform the research are included in the article. Besides, additional information on data used in inventory is available in Supplement Material.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Alves EC, Soares BB, Almeida Neto JA, Rodrigues LB (2019) Strategies for reducing the environmental impacts of organic mozzarella cheese production. J Clean Prod 223(20):226–237. https://doi.org/10.1016/j.jclepro.2019.03.006

Bacenetti J, Bava L, Zucali M, Lovarelli D, Sandrucci A, Tamburini A, Fiala M (2016) Anaerobic digestion and milking frequency as mitigation strategies of the environmental burden in the milk production system. Sci Total Environ 539(1):450–459. https://doi.org/10.1016/j.scitotenv.2015.09.015

Baldini C, Gardoni D, Guarino M (2017) A critical review of the recent evolution of life cycle assessment applied to milk production. J Clean Prod 140(Part 2):421–435. https://doi.org/10.1016/j.jclepro.2016.06.078

Berton M, Bittante G, Zendri F, Ramanzin M, Schiavon S, Sturaro E (2020) Environmental impact and efficiency of use of resources of different mountain dairy farming systems. Agric Syst 181:102806. https://doi.org/10.1016/j.agsy.2020.102806

Cabral CFS, Veiga LBE, Araújo MG, de Souza SLQ (2020) Environmental life cycle assessment of goat cheese production in Brazil: a path towards sustainability. LWT 129:109550. https://doi.org/10.1016/j.lwt.2020.109550

Campos AT (2006) Importância da água para bovinos de leite. Instrução Técnica para o Produtor de Leite, número 31. Embrapa Gado de Leite. 2a edição: Revista e atualizada. ISSN: 1518–3254. (in Portuguese)

Carvalho LS, Willers CD, Maranduba HL, Robra S, Almeida Neto JA, Rodrigues LB (2018) Contributions of life cycle assessment to the sustainability of milk production. In: Hertz Anke (ed) Dairy Farming: Operations Management, Animal Welfare and Milk Production, vol 1, 1st edn. Nova Publishers, New York, pp 63–96

Casey JW, Holden NM (2005) The relationship between greenhouse gas emissions and the intensity of milk production in Ireland. J Environ Qual 34(2):429–436. https://doi.org/10.2134/jeq2005.0429

Drews J, Czycholl I, Krieter J (2020) A life cycle assessment study of dairy farms in northern Germany: the influence of performance parameters on environmental efficiency. J Environ Manag 273 Article number 111127. https://doi.org/10.1016/j.jenvman.2020.111127

FAO – Food and Agriculture Organization of the United Nations (2021) Gateway to dairy production and products. http://www.fao.org/dairy-production-products/production/en/#:~:text=In%20the%20last%20three%20decades,%2C%20China%2C%20Pakistan%20and%20Brazil

Feitz AJ, Lundie S, Dennien G, Morain M, Jones M (2007) Generation of an industry-specific physico-chemical allocation matrix: application in the dairy industry and implications for systems analysis. Int J Life Cycle Assess 12(2):119–117. https://doi.org/10.1065/lca2005.10.228

Ferreira FU, Robra S, Ribeiro PCC, Gomes CFS, Almeida Neto JA, Rodrigues LB (2020) Towards a contribution to sustainable management of a dairy supply chain. Prod 30:e20190019. https://doi.org/10.1590/0103-6513.20190019

Finnegan W, Goggins J (2021). Environmental impact of the dairy industry. In: Galanakis CM (ed), Environmental impact of agro-food industry and food consumption, 1st Edition, pp 129–146, Academic Press. https://doi.org/10.1016/C2019-0-03292-X

Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J, Van Zelm R (2009) ReCiPe 2008 – A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. First edition. Report I: Characterization

Gollnow S, Lundie S, Moore AD, Mclaren J, Van Buuren N, Stahle P, Christie K, Thylmann D, Rehl T (2014) Carbon footprint of milk production from dairy cows in Australia. Int Dairy J 37(1):31–38. https://doi.org/10.1016/j.idairyj.2014.02.005

González-Quintero R, Kristensen T, Sánchez-Pinzón MS, Bolívar-Vergara DM, Chirinda N, Arango J, Knudsen MT (2021) Carbon footprint, non-renewable energy and land use of dual-purpose cattle systems in Colombia using a life cycle assessment approach. LivestSci 104330https://doi.org/10.1016/j.livsci.2020.104330

Guinée JB, Heijungs R, Huppes G (2004) Economic allocation: examples and derived decision tree. Int J Life Cycle Assess 9(23) https://doi.org/10.1007/BF02978533

Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira MDM, Zijp M, Hollander A, van Zelm R (2017) ReCiPe 2016: a harmonized life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess 22:138–147. https://doi.org/10.1007/s11367-016-1246-y

IBGE – Instituto Brasileiro de Geografia e Estatística (2020) Indicadores IBGE: estatística da produção pecuária. Dezembro de 2020. IBGE, Rio de Janeiro. https://biblioteca.ibge.gov.br/index.php/biblioteca-catalogo?id=72380&view=detalhes (in Portuguese)

IDF – International Dairy Federation (2015) A common carbon footprint approach for the dairy sector – the IDF guide to standard life cycle assessment methodology. Bulletin of International Dairy Federation 479/2015, 60pp https://store.fil-idf.org/product/a-common-carbon-footprint-approach-for-the-dairy-sector-the-idf-guide-to-standard-life-cycle-assessment-methodology/

IPCC – Intergovernmental Panel On Climate Change (2006a) Guidelines for national greenhouse gas inventories. Agriculture, Forestry and Other Land Use – Emissions from Livestock and Manure Management. v. 4, chap 10.

IPCC – Intergovernmental Panel on Climate Change (2006b) Guidelines for national greenhouse gas inventories. Agriculture, Forestry and Other Land Use – N_2O Emissions from Managed Soils, and CO_2 Emissions from Lime and Urea Application. v. 4, chap 11.

ISO – International Organization for Standardization (2006a) ISO 14040: Environmental management – life cycle assessment – principles and framework. Geneva.

ISO – International Organization for Standardization, 2006b. ISO 14044: Environmental management – life cycle assessment – requirements and guidelines. Geneva.

Johnson D, Schwartz D (2002) Milk production costs. University of Maryland. <https://www.arec.umd.edu/sites/arec.umd.edu/files/files/documents/Archive/Milk%20Production%20Costs.pdf >

Léis CM (2013) Desempenho ambiental de três sistemas de produção de leite no sul do Brasil pela abordagem da Avaliação do Ciclo de Vida. Phd Thesis in Environmental Engineering. Universidade Federal de Santa Catarina. Florianópolis, SC, Brazil (in Portuguese)

Léis CM, Cherubini E, Ruviaro CF, Silva VP, Lampert VN, Spies A, Soares SR (2015) Carbon footprint of milk production in Brazil: a comparative case study. Int J Life Cycle Assess 20:46–60. https://doi.org/10.1007/s11367-014-0813-3

Lemaire G, Franzluebbers A, Carvalho PCF, Dedieu B (2014) Integrated crop–livestock systems: strategies to achieve synergy between agricultural production and environmental quality. Agric Ecosyst Environ 190:4–8. https://doi.org/10.1016/j.agee.2013.08.009

Mörschbächer V, Rempel C, Maciel M (2017) Microbiological quality of refrigerated raw milk in the dairy farm and after transport to the processing dairy plant. Arq Inst Biol 84 https://doi.org/10.1590/1808-1657000422016

Olszensvski FT (2011) Avaliação do ciclo de vida da produção de leite em sistema semi extensivo e intensivo: estudo aplicado. Master Thesis in Environmental Engineering. Universidade Federal de Santa Catarina, Florianópolis, SC, Brazil (in Portuguese)

Oram B (2016) Conversion factors for water quality. Water Research Center. http://www.water-research.net/index.php/conversion-factors-for-water-quality on 4/1/2016

Owsianiak M, Bjørn A, Laurent A, Molin C, Ryberg MW (2018) LCA applications. In: Hauschild MZ, Rosenbaum RK, Olsen SI (eds) Life cycle assessment: theory and practice. Springer International Publishing AG, Cham Switzerland, pp 31–42

Palhares JCP, Novelli TI, Morelli M (2020) Best practice production to reduce the water footprint of dairy milk. Revista Ambiente Água 15(1):e2454. https://doi.org/10.4136/ambi-agua.2454

Pereira PC (2014) Milk nutritional composition and its role in human health. Nutrition 30(6):619–627. https://doi.org/10.1016/j.nut.2013.10.011

Pirlo G, Lolli S (2019) Environmental impact of milk production from samples of organic and conventional farms in Lombardy (Italy). J Clean Prod 211:962–971. https://doi.org/10.1016/j.jclepro.2018.11.070

Rafiee S, Khoshnevisan B, Mohammadi I, Aghbashlo M, Mousazadeh M, Clark S (2016) Sustainability evaluation of pasteurized milk production with a life cycle assessment approach: an Iranian case study. Sci Total Environ 562(15):614–627. https://doi.org/10.1016/j.scitotenv.2016.04.070

Ramirez PKS, Soares SR, Souza DM de, Silva Junior VM da (2008) Allocation methods in life cycle assessment: a critical review. 15th CIRP International Conference on Life Cycle Engineering: Conference Proceedings. LCE
Roer AG, Johansen A, Bakken AK, Daugstad K, Fystro G, Strømmana AH (2013) Environmental impacts of combined milk and meat production in Norway according to a life cycle assessment with expanded system boundaries. Livest Sci 155(2–3):384–396. https://doi.org/10.1016/j.livsci.2013.05.004
Ross SA, Chagunda MGG, Topp CFE, Ennos R (2014) Effect of cattle genotype and feeding regime on greenhouse gas emissions intensity in high producing dairy cows. Livest Sci 170:158–171. https://doi.org/10.1016/j.livsci.2014.09.011
Rotz CA, Stout RC, Holly MA, Kleinman PJ (2020) Regional environmental assessment of dairy farms. J Dairy Sci 103(4):3275–3288. https://doi.org/10.3168/jds.2019-17388
Roy P, Nei D, Orikasa T, Xu Q, Okadome H, Nakamura H, Shiina T (2009) A review of life cycle assessment (LCA) on some food products. J Food Eng 90(1):1–10. https://doi.org/10.1016/j.jfoodeng.2008.06.016
Ruviaro CF, Leis CM, Florindo TJ, Florindo GIBM, Costa JS, Tang WZ, Pinto AT, Soares SR (2020) Life cycle cost analysis of dairy production systems in Southern Brazil. Sci Total Environ 741:140273. https://doi.org/10.1016/j.scitotenv.2020.140273
Sabia E, Kühl S, Flach L, Lambertz C, Gauly M (2020) Effect of feed concentrate intake on the environmental impact of dairy cows in an alpine mountain region including soil carbon sequestration and effect on biodiversity. Sustainability 12(5):2128. https://doi.org/10.3390/su12052128
Salton JC, Mercante FM, Tomazi M, Zanatta JA, Concenço G, Silva WM, Retore M (2014) Integrated crop-livestock system in tropical Brazil: toward a sustainable production system. Agric Ecosyst Environ 190:70–79. https://doi.org/10.1016/j.agee.2013.09.023
Salvador S, Corazzin M, Piasentier E, Bovolenta S (2016) Environmental assessment of small-scale dairy farms with multifunctionality in mountain areas. J Clean Prod 124:94–102. https://doi.org/10.1016/j.jclepro.2016.03.001
Santos HCM Jr, Maranduba HL, Almeida Neto JA, Rodrigues LB (2017) Life cycle assessment of cheese production process in a small-sized dairy industry in Brazil. Environ Sci Pollut Res 24:3470–3482. https://doi.org/10.1007/s11356-016-8084-0
Soares BB, Alves EC, Maranduba HL, da Silva FF, Fernandes SAA, Almeida Neto JA, Rodrigues LB (2019) Effect of handling and feeding strategies in the environmental performance of buffalo milk in Northeastern Brazil. Int J Life Cycle Assess 24:1129–1138. https://doi.org/10.1007/s11367-018-1547-4
Seó HLS, Machado Filho LCP, Ruviaro CF, de Léis CM (2017) Life Cycle Assessment in dairy cattle and opportunities to Brazil. Eng Sanit Ambient 22:221–237. https://doi.org/10.1590/s1413-41522016149096(inPortuguese)
Statista (2021) Major producers of cow milk worldwide in 2020, by country. https://www.statista.com/statistics/268191/cow-milk-production-worldwide-top-producers/
USDA - United States Department of Agriculture (2020) Dairy and products annual. Report Number: BR2020–0042. USDA – Foreign Agricultural Service. https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Dairy%20and%20Products%20Annual_Brasilia_Brazil_10-15-2020
Wang X, Ledgard S, Luo J, Guo Y, Zhao Z, Guo L, Liu S, Zhang N, Duan X, Ma L (2018) Environmental impacts and resource use of milk production on the North China Plain, based on life cycle assessment. Sci Total Environ 625:486–495. https://doi.org/10.1016/j.scitotenv.2017.12.259
Wilkes A, Wassie S, Fraval S, van Dijk S (2020) Variation in the carbon footprint of milk production on smallholder dairy farms in central Kenya. J Clean Prod 265:121780. https://doi.org/10.1016/j.jclepro.2020.121780
Willers CD, Rodrigues LB, Silva NL (2010) Inventário de ciclo de vida da produção de leite em uma unidade experimental em Itapetinga – BA. II Congresso Brasileiro em Gestão do Ciclo de Vida de Produtos e Serviços, 2010, Florianópolis, SC (in Portuguese)
Willers CD, Ferraz SP, Carvalho LS, Rodrigues LB (2014) Determination of indirect water consumption and suggestions for cleaner production initiatives for the milk-producing sector in a Brazilian middle-sized dairy farming. J Clean Prod 72(1):146–152. https://doi.org/10.1016/j.jclepro.2014.02.055
Willers CD, Rodrigues LB (2014) A critical evaluation of Brazilian life cycle assessment studies. Int J Life Cycle Assess 19(1):144–152. https://doi.org/10.1007/s11367-013-0608-y
Willers CD, Maranduba HL, Almeida Neto JA, Rodrigues LB (2017) Environmental impact assessment of a semi-intensive beef cattle production in Brazil's northeast. Int J Life Cycle Assess 22(4):516–524. https://doi.org/10.1007/s11367-016-1062-4
Woldegebriel D, Udo H, Viets T, van der Harstb E, Potting J (2017) Environmental impact of milk production across an intensification gradient in Ethiopia. Livest Sci 206:28–36. https://doi.org/10.1016/j.livsci.2017.10.005
Yan MJ, Humphreys J, Holden NH (2013) The carbon footprint of pasture-based milk production: can white clover make a difference? J Dairy Sci 96:857–865. https://doi.org/10.3168/jds.2012-5904
Zucali M, Bacenetti J, Tamburini A, Nonini L, Sandrucci A, Bava L (2018) Environmental impact assessment of different cropping systems of home-grown feed for milk production. J Clean Prod 172:3734–3746. https://doi.org/10.1016/j.jclepro.2017.07.048