Preparing for net zero greenhouse gas emissions in 2050: lifecycle emissions of dairy products in Brazil

Preparando-se para emissões líquidas zero de gases de efeito estufa em 2050: emissões do ciclo de vida de produtos lácteos no Brasil

Preparándose para cero emisiones netas de gases de efecto invernadero en 2050: emisiones del ciclo de vida de los productos lácteos en Brasil

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Antonio de Sant'Anna Limongi França
PhD in Innovation
Institution: Universidade de São Paulo
Address: São Paulo, São Paulo, Brasil
E-mail: antonio.limongi@hx8.com.br

Alexandre de Oliveira e Aguiar
PhD in Chemical Engineering
Institution: Universidade de São Paulo
Address: São Paulo, São Paulo, Brasil
E-mail: alexandre@aguiar.eng.br

Marcelo Schneck de Paula Pessoa
PhD in Electrical Engineering
Institution: Universidade de São Paulo
Address: São Paulo, São Paulo, Brasil
E-mail: mpessoa@usp.br

João Amato Neto
PhD in Production Engineering
Institution: Universidade de São Paulo
Address: São Paulo, São Paulo, Brasil
E-mail: amato@usp.br

Sérgio Almeida Pacca
PhD in Agronomy
Institution: Universidade de São Paulo
Address: São Paulo, São Paulo, Brasil
E-mail: spacca@usp.br

ABSTRACT
Dairy products play an important role in human nutrition and the world economy. Livestock farming, including cows rearing to produce milk and dairy products, is one of the world's major sources of greenhouse gas emissions. Progress towards net zero goals requires monitoring emissions from companies and products, and greenhouse gas

inventories are essential. This work quantifies greenhouse gas emissions from milk production, considering the milk delivered at the farm gate and the milk delivered at the cooperative gate. Emissions accounting was based on greenhouse gas inventories for two units and lifecycle emissions for major farm inputs. Results have shown that milk production on the farm emits 0.57 kg CO_{2e} / liter, with enteric fermentation accounting for more than 90% of emissions at the farm gate, and more than 50% at the milk processing unit gate. Dairy production adds 0.533 kg CO_{2e} / liter to the emissions coming from raw milk, most of which comes from wastewater treatment. Thus, the footprint of dairy products is 1.103 kg CO_{2e} / liter of processed milk. The producers' cooperative's greenhouse gas emissions are essentially indirect and amount to 0.626 kg CO2e/liter of milk delivered to customers, in which emissions from purchased milk account for more than 85% and emissions from transportation account for around 15%.

Keywords: dairy products, greenhouse gas inventory, milk production, climate change mitigation, lifecycle greenhouse gas emissions.

RESUMO
Os produtos lácteos desempenham um papel importante na nutrição humana e na economia mundial. A pecuária, incluindo a criação de vacas para produzir leite e produtos lácteos, é uma das maiores fontes de emissão de gases de efeito estufa do mundo. O progresso em direção às metas de zero líquido exige o monitoramento das emissões de empresas e produtos, e os inventários de gases de efeito estufa são essenciais. Este trabalho quantifica as emissões de gases de efeito estufa da produção de leite, considerando o leite entregue na porta da fazenda e o leite entregue na porta da cooperativa. A contabilidade das emissões foi baseada em inventários de gases de efeito estufa para duas unidades e emissões de ciclo de vida para os principais insumos agrícolas. Os resultados mostraram que a produção de leite na fazenda emite 0,57 kg de CO2e / litro, com a fermentação entérica sendo responsável por mais de 90% das emissões na porta da fazenda e mais de 50% na porta da unidade de processamento de leite. A produção de laticínios acrescenta 0,533 kg de CO2e / litro às emissões provenientes do leite cru, a maior parte proveniente do tratamento de águas residuais. Assim, a pegada dos produtos lácteos é de 1,103 kg de CO2e / litro de leite processado. As emissões de gases de efeito estufa da cooperativa de produtores são essencialmente indiretas e totalizam 0,626 kg CO2e/litro de leite entregue aos clientes, em que as emissões do leite comprado representam mais de 85% e as emissões do transporte representam cerca de 15%.

Palavras-chave: produtos lácteos, inventário de gases de efeito estufa, produção de leite, mitigação de mudanças climáticas, emissões de gases de efeito estufa do ciclo de vida.

RESUMEN
Los productos lácteos desempeñan un papel importante en la nutrición humana y la economía mundial. La ganadería, incluida la cría de vacas para producir leche y productos lácteos, es una de las principales fuentes mundiales de emisiones de gases de efecto invernadero. Para avanzar hacia el objetivo de cero emisiones netas es necesario controlar las emisiones de las empresas y los productos, por lo que es esencial disponer de inventarios de gases de efecto invernadero. Este trabajo cuantifica las emisiones de gases de efecto invernadero de la producción de leche, considerando la leche entregada en la granja y la entregada en la cooperativa. La contabilidad de las emisiones se basó en los inventarios de gases de efecto invernadero de dos unidades y en las emisiones del ciclo

de vida de los principales insumos de la explotación. Los resultados han mostrado que la producción de leche en la granja emite 0,57 kg CO2e / litro, siendo la fermentación entérica responsable de más del 90% de las emisiones en la puerta de la granja, y de más del 50% en la puerta de la unidad de procesado de la leche. La producción láctea añade 0,533 kg CO2e / litro a las emisiones procedentes de la leche cruda, la mayor parte de las cuales procede del tratamiento de aguas residuales. Así, la huella de los productos lácteos es de 1,103 kg CO2e / litro de leche procesada. Las emisiones de gases de efecto invernadero de la cooperativa de productores son esencialmente indirectas y ascienden a 0,626 kg CO2e / litro de leche entregada a los clientes, en las que las emisiones procedentes de la leche comprada representan más del 85% y las emisiones procedentes del transporte en torno al 15%.

Palabras clave: productos lácteos, inventario de gases de efecto invernadero, producción de leche, mitigación del cambio climático, ciclo de vida de las emisiones de gases de efecto invernadero.

1 INTRODUCTION

Sustainability is taking shape on the world stage, and climate change stands out in this context since the 1990s. During the Conference of the Parts – COP26, it was noted that degraded forests, unproductive pastureland, archaic cropping methods, intensive use of fossil fuels, and waste generation slow down the progress toward global sustainability because they release greenhouse gas emissions (GHG) (WAYCARBON, 2021). The Intergovernmental Panel on Climate Change warns that the planet must reduce GHG emissions by 43% by 2030 and reach net zero emissions by 2050 to limit global warming to 1.5%, following the Paris Agreement (IPCC, 2023)

According to the Greenhouse Gas Emissions Assessment System, Brazil emitted 2.42 million metric tons of carbon dioxide equivalent (CO_{2e}) in 2021, 49% of which corresponded to emissions from changes in land use and forests, i.e. deforestation. Agriculture was responsible for 25% of total emissions. Energy was responsible for 18% of emissions, industrial processes for 4.45%, and waste disposal for 3.76% (SEEG, 2024). This emissions profile puts Brazil in the spotlight, with outstanding international relevance, due to its food and fodder potential (Aubertin and Jesus, 2021). It also brings about a significant worldwide potential in carbon credits, based on forest conservation, restoration, and good practices in agribusiness. Moreover, Brazil is the second largest emitter of methane gas through enteric fermentation from dairy cows (York, et al., 2018).

The dairy industry and its products play an important role in nutrition and GHG emissions worldwide. According to FAO and CDP (2018), more than 6 billion people worldwide consume milk and dairy products. In African and Asian countries, these products represent between 2 and 4% of the energy intake, with a consumption of less than 30 kg/year per capita, whereas in more developed countries they represent 11% of the energy intake or more than 150 kg/year per capita. This shows the importance of increasing dairy product supply, especially in less developed countries (Vilela al, 2016). However, increasing dairy product supply entails increasing the pressure on natural resources, including GHG emissions. The objective of this work is to assess GHG lifecycle emissions from milk production, considering a single dairy farm and a cooperative. GHG accounting was based on emissions inventories and lifecycle emissions for farm inputs.

2 ACCOUNTING FOR GHG EMISSIONS FROM THE DAIRY SUPPLY CHAIN

The dairy industry includes various products: pasteurized milk, skimmed milk, cheese, cream, butter, condensed milk, condensed milk fudge, yogurt, fermented beverages, and ice cream. Several processes are required to produce distinct products (Jerônimo et al., 2012). GHG emissions in dairy processing are due to, for example, energy consumption in production, fugitive emissions from refrigerant gases, waste disposal, wastewater treatment, and emissions from raw materials and product transportation.

Moreover, GHG is released along the supply chain, and milk lifecycle emissions range from 1.3 to 1.4 $kgCO_{2e}$/kg FPCM (fat and protein corrected milk) in more developed regions, to a range of 4.1 to 6.7 $kgCO_{2e}$/kg FPCM (FAO and CDP, 2018) in less developed regions.

According to Aránguiz (2022), "milk and dairy products account for about 14% of world agricultural trade". He also points out that "in particular, whole milk powder (WMP) and skimmed milk powder (SMP) are the most traded agricultural products in the world in terms of percentage of traded production, while fresh dairy products are the least traded agricultural products with less than 1% of traded production".

Clay et al. (2020) mention that environmental impacts commonly studied in the dairy industry include GHG emissions, water and soil pollution, biodiversity loss, changes in nutrient cycling, especially nitrogen and phosphorus, and land use change. Three GHGs stand out: CO_2, mainly from energy use and land-use change; CH_4 from enteric fermentation and manure disposal; and N_2O from feed production and excreta disposal. The magnitude of the impact varies according to the production method. Among the producers that publish their data, the Italian company Granarolo (2010) reports a footprint of 0.65 kg CO_{2e} /l excluding land use change and 1.3 kg CO_{2e} per liter of milk purchased as raw material.

The dairy processing industry receives milk from a variety of sources, each with its management system and practices. Farms are required to ensure the quality of the milk produced, according to the regulatory framework, and considering the parties involved in the supply chain (Vogel et al., 2022). To achieve this objective, each farm has its characteristics. Some of them use confined feedlot systems, others pasture-based grazing systems, and some of them annually switch land use between pasture and cropping.

The individual choice of farm practices leads to different results in terms of GHG emissions (Naranjo et al., 2020), depending on each farm's specific methods of management, feeding, and waste management. Concerning feeding, different types of nutrients lead to different eructation characteristics (elimination of gas through the mouth) (Olszensvski, 2011; Maciel et al., 2022; MAPA, 2017).

Piotto (2017) studied emissions from beef cattle in a rotational or continuous grazing system. The study concluded that CO_2 and N_2O emissions were not affected by the grazing method. However, CH_4 emissions were higher in the fertilized rotational system than in the continuous grazing system.

Mazzetto et al. (2022) carried out a literature review on published milk footprints, at the national level, around the world. Harmonized results showed that milk production lifecycle emissions ranged from 0.74 in New Zealand to 5.99 kg CO_{2e}/FCPM in Tanzania. No Brazilian milk production study satisfied the inclusion criteria. The share of enteric fermentation emissions varied from 34% in Tanzania to 86% in Costa Rica. The authors also produced a linear regression demonstrating that the higher the yield (liters of FCPM/cow) the lower the carbon footprint was.

Brazil ranks sixth in the world in terms of milk production, with approximately 36 billion liters per year in 2021 (FAO, 2023). In Brazil, Léis et al. (2015) estimated emissions based on different production systems and drew attention to results including or excluding emissions from land use change, a factor not always considered in inventories and scarce milk footprints. Without considering land use change, the reported emissions are 0.54, 0.78, and 0.74 kg CO_{2e}/liter of milk (energy-corrected milk) in the confined, semi-confined, and unconfined feedlot systems, respectively. When land use change is considered, emissions increase to 0.78, 1.06, and 1.01 kg CO_{2e}/liter.

Santos et al. (2022) applied a life cycle assessment (LCA) in a dairy plant in Viçosa, Minas Gerais State, in Brazil, and discovered that milk production releases 1,545 kg CO_{2e}/kg of milk (1,63 kg CO_{2e}/liter). The LCA estimated the emissions of different dairy products, including dulce de leche, yogurt, butter, cheese, and cheese spread. Milk production was responsible for 72.6% to 97.5% of the lifecycle CO2e emissions for dulce de leche and cheese, respectively. Another LCA of milk production in Brazil estimates that a system with a biodigester emits 0.8835 kg of CO2 eq. per 1 kg of milk, whereas a system without the residues treatment technology emits 1.1622 kg of CO2 eq. per 1 kg of milk (Maciel et al. 2022).

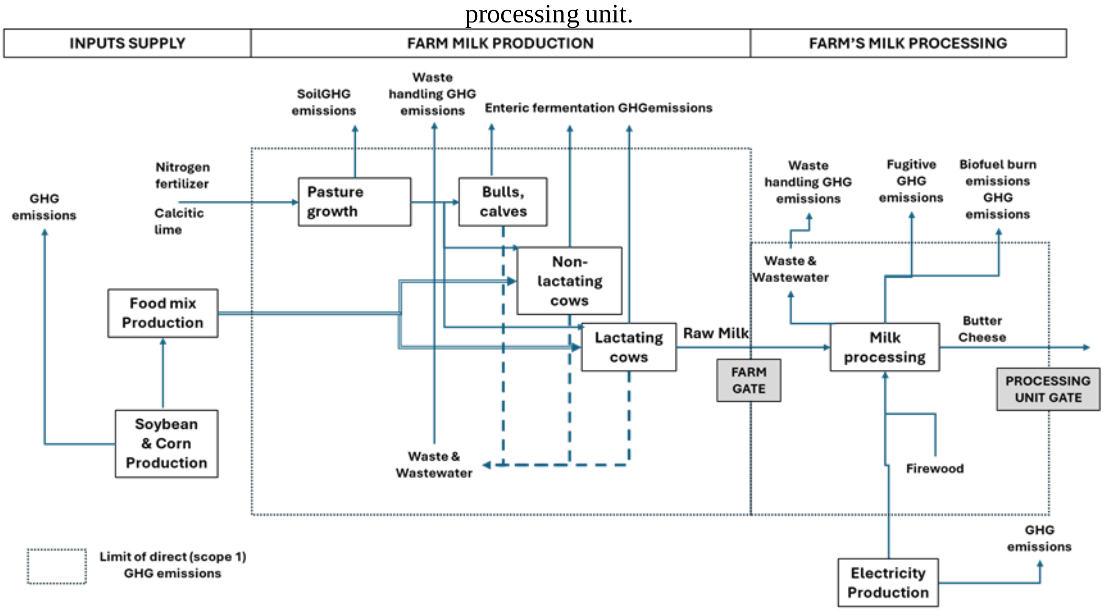
DANONE (2017) reports in Brazil total emissions of 3,213,115 tCO_{2e} in Scope 1, 6,940,307 tCO_{2e} in Scope 2, and 381,046,987 tCO_{2e} in Scope 3. Out of the Scope 3 emissions, 253,320,000 tCO_{2e} are related to milk production and 110,410,812 tCO_{2e} to upstream and downstream transport and distribution-related emissions. The production of purchased milk accounts for more than 66% of Scope 3 emissions and more than 60% of the total emissions of DANONE's products.

As an example of the evolution of farming practices and milk production methods, Capper et al (2009) report that between 1944 and 2007, CO_{2e} emissions from milk production in the United States decreased from 3.66 to 1.35 kg CO_{2e}/liter. In Brazil, average enteric methane emissions decreased from about 28 to just over 16 g CH_4/kg milk between 2000 and 2020 (Bueno, 2022).

3 METHODS

The carbon footprint was estimated based on information collected from the field and carbon accounting tools such as the GHG Protocol, which was complemented with lifecycle emissions based on information from Renovacalc (ANP, 2024). GHG Protocol is used to quantify emissions coming from organizations and their supply chains and is consistent with international standards. The Brazilian GHG Protocol Program developed the inventory tool applied to the case studies in version 2023.0.2. The tool is adapted to the language of the scopes that identify direct emissions (Scope 1), indirect emissions related to purchased energy (Scope 2), and other indirect emissions (Scope 3) (WRI, BCSD, 2004). The emission factors are adapted to the Brazilian context, e.g. regarding the presence of biofuels mixed with commercial fossil fuels, and to the Brazilian electricity generation mix. Renovacalc estimates lifecycle emissions for biofuels produced in Brazil from sugarcane, soybeans, and corn and compares its lifecycle GHG emissions with emissions from fossil fuels, determining the certified GHG emission reductions based on biofuels tool is part of the National Biofuels Policy, approved by law 13,576, of December 26, 2017, and it was used to estimate lifecycle emissions for cows' feeding mix (soybeans and corn) and soil amendments (limestone and nitrogen fertilizer). Figure 1 presents energy and material flows that have been inventoried in the farm's assessment.

Figure 1. Flows that have been included in the assessment of the milk produced at the farm and its processing unit.



Source: the authors

In different situations, the GHG Protocol tool allows emissions to be estimated as (Eq. 1):

$$E = Q \cdot F \qquad (1)$$

In this expression, E is greenhouse gas emissions (CO_2, CH_4, N_2O, and so on) of the specific activity; Q is a quantity of material or activity (such as fuel or electricity consumed, or miles traveled); and F is an emission factor that indicates how much of the relevant GHG is emitted for each unit of consumed material or performed activity. It is important to notice that as a GHG Protocol rule, biogenic emissions (those accepted as being part of natural processes, even if they are part of anthropogenic activities) are reported separately, so they are not included in our assessment.

Q data is obtained in the field from management records such as invoices, reports, measurements, and other available sources. Emission factors are included in the calculation tool, which includes emission factors specific to Brazil, such as electricity and gasoline type C, which contains ethanol. Emissions are summed up by the calculation tool for each type of gas and converted into CO_2 equivalents, using the Global Warming Potential for each GHG.

In Case 1, the WRI-Brasil tool (FGV, n.d.), which uses the logic of the “Centro de Estudos em Sustentabilidade da Fundação Getúlio Vargas” tool but provides parameters specific to the agricultural sector, was used to supply the emission factors relevant to milk production at the farm.

The GHG Protocol demands a series of data based on a specific calendar year that were collected directly from the field. Emission factors for electricity and gasoline are updated every year, and therefore, 2022 representative data was adopted in the calculations.

To estimate the carbon footprint of milk production we added the lifecycle emissions for limestone and fertilizers applied to the pastureland and the lifecycle emissions for corn and soybeans production, which are part of the ' feeding mix. The functional unit to report the results was 1 liter of milk. Laboratory tests demonstrated that the milk produced at the farm is like the fat protein corrected milk (FCPM) adopted by the IPCC (2006) and the Gold Standard (2016). It means that the share of fat and protein in the milk is, respectively, 4 and 3.3% (IPCC 2006, Gold Standard 2016).

3.1 FIELD DATA COLLECTION

Data were collected in two case studies:

- Case 1: A dairy farm integrated with a milk processing plant.
- Case 2: A dairy cooperative.

Data acquisition was facilitated by previous contacts between one of the researchers and the agronomist working for the organization, in case 1, and the board of directors of the organization, in case 2. Case 2 includes a feed production facility and feed distribution, a supply store for the coops’ members and their respective farms.

In case 1, data collection involved an environmental engineer who is a member of the owner's family and an agronomist, who works for the farm. In case 2, the data collection involved people from the board of directors and the administration of the cooperative. Due to the lack of a specific BOD analysis for the effluent available, a concentration of 2400 mg BOD/l, which is the median value reported by Loures (2011), was adopted in our assessment, because we consider the author's case to be similar to ours.

Regarding Organization 2, it is important to note that there is no strict control of the distances covered by the vehicles used to collect milk from the supplier farms, deliver milk to industrial customers, and distribute inputs to cooperative members. The information was obtained verbally and is approximate. Transportation from farm to storage is performed typically by independent professionals and travels are shared with other customers that will deliver to the same storage place. Allocating emissions is a challenge under these circumstances. GHG Protocol does not offer specific directions, so, we have allocated based on the total travel distance and the share of transported milk in average trips, regardless of the specific location of the cooperative's member farm or other clients.

4 RESULTS OF THE FIELD RESEARCH

Two case studies, in the Taubaté region, in Sao Paulo State, Brazil (Figure 2), are presented. The milk production of an integrated farm with milk processing was analyzed through the production of various products, including yogurt, cheese, and dulce de leche (Organization 1). The second case deals with the GHG emissions of a dairy cooperative (Organization 2).

Figure 2. Region in which Case 1 (farm) and Case 2 (Cooperative) are located.

Source: the authors

4.1 ORGANIZATION 1 – FARM AND PROCESSING UNIT

The milk farm and a milk processing plant for dairy products production were established over 20 years ago, occupying an area of almost 100 hectares, with a herd of 122 cows, including lactating cows, dry cows, heifers, calves, and bulls.

Production in 2022 averaged 600 liters per day, all of which is sent to the milk processing plant next to the farm. According to the owners, the quality of the produced milk is monitored monthly, in terms of protein and fat content. From a livestock management point of view, there is a nutritional balance for each category of animals on the farm.

The production of dairy products is traded in the region by the managers themselves.

4.1.1 Structure of the Emissions Inventory

The inventory relies on information consolidated by shareholders.

Scopes 1, 2, and 3 were considered. Since this is a set of activities managed under the same command, the operational activities were all considered in scope 1. Scope 2 covered issues related to the purchase of electricity from the national grid. The inventory was based on the "Tier 1" assumption, which is recommended as an initial level when available data do not allow for a more detailed analysis (IPCC, 2006)

However, GHG emissions associated with milk production on farms, from the perspective of the dairy plants that purchase this milk, are included in Scope 3 of the GHG inventory as "upstream" emissions and represent a significant part of the supply chain emissions of dairy products. For instance, the GHG inventory of the Brazilian branch of the multinational company Danone reports 381 million tons of tCO_{2e} as scope 3 emissions, which are 38 times the sum of emissions from scopes 1 and 2. Moreover, about 66% of the Scope 3 emissions are related to milk production.

Transportation of inputs received from third parties and waste sent to processing plants for recycling or even to sanitary landfills, in another municipality in the region, were considered in scope 3.

In addition, lifecycle emissions from feed and other inputs were estimated based on original data plus lifecycle GHG emissions. The cows are fed with pasture and a supplement mix made from soybean, corn, and other additives. The annual consumption of corn and soybeans is 23576 kg and 6840 kg, respectively. Lifecycle GHG emissions from soybeans and corn production are estimated based on typical values for Brazilian farms (Matsuura et al. 2018). Inputs for corn and soybeans cropping are their respective lifecycle emissions are presented in Table 1. Accordingly, lifecycle emissions for corn and soybeans are, respectively, 97.12 and 166.82 g CO_2e/kg. Therefore, total lifecycle emissions from feed production are 3,401.6 kg CO_2e.

Table 1: Typical mass of inputs (kg) per metric ton of produced grain and their respective lifecycle emissions.

Input	Corn	Soybeans	Renovacalc lifecycle emissions
Limestone	42.3	249	36.8 g CO_2e/kg
Gypsum		53.3	2.8 g CO_2e/kg
corn seeds	4.6		1,566.1 g CO_2e/kg
soybean seeds		17.39	1,802.4 g CO_2e/kg
N fertilizer	12.6	2.8	3,211.2 g CO_2e/kg
P fertilizer	10.9	27.2	2,367.7 g CO_2e/kg
K fertilizer	11.2	32.7	455.2 g CO_2e/kg
diesel fuel (liters)	4.8	10.7	3.539,70 g CO_2e/L

Source: Matsuura et al. 2018 and ANP 2024

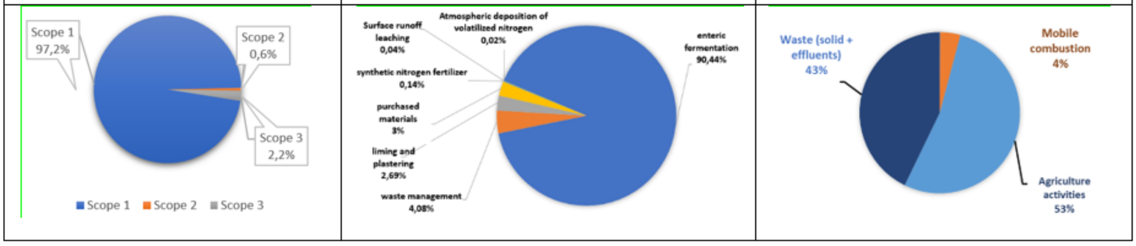
Besides the inputs in the production of corn and soybeans, 7,400 kg of limestone and 1,494 kg of nitrogen fertilizer are applied to the pasture per year. Annual lifecycle emissions for manufacturing these soil amendments, which are equal to 5,070.1 kg CO_2e, are considered in the calculations. In conclusion, the manufacturing of farm inputs releases 8,471.75 kg CO_2e per year.

4.1.2 Emission Results, Organization 1

Total emissions from Organization 1 in 2022 accounted for 244.637 tCO2e, and most emissions are related to Scope 1. About 53% of Scope 1 emissions are from agriculture, out of which enteric fermentation accounts for 92,85% of emissions from agriculture (Figure 3).

Figure 3. Distribution of emissions according to scope and source category in Organization 1.

Emissions by scope – limited to farm activities	Breakdown of emissions - agricultural activities	Breakdown of Scope 1 emissions – farm + milk processing



Source: the authors

Therefore, enteric fermentation, which releases methane, a GHG with a GWP of 28, is the main source of emissions in Organization 1's milk production. Because the farm and the milk processing plant are located next to each other, emissions due to milk transportation are negligible.

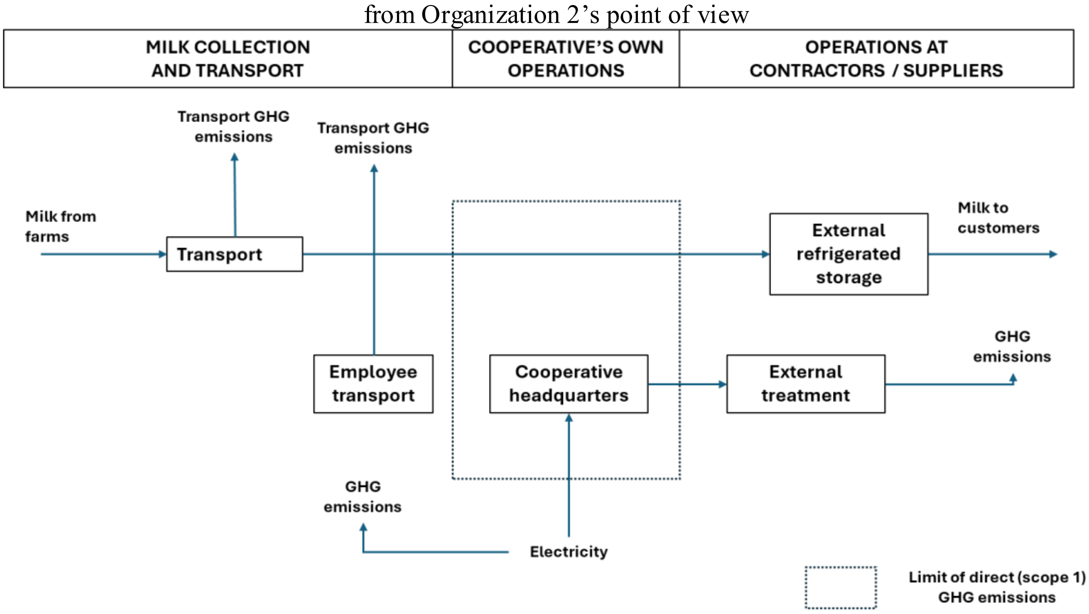
The GHG emissions per liter of milk were assessed at the farm gate and the milk processing plant gate. In the case of milk production on the farm, with a total of 136,3 tCO_{2e}/year, and a herd of 122 animals, the footprint is 1,117 kg CO_{2e}/animal/year. The average production of 600 liters/day running 365 days/year equates to a footprint of 0.62 kg CO_{2e}/l.

At the milk processing plant gate, total emissions are 248,04 tCO_{2e}/year, which, considering 600 liters of milk per day over 365 days a year, results in 1.13 $kgCO_{2e}$/l of processed milk.

4.2 CASE OF ORGANIZATION 2 - MILK PRODUCERS' COOPERATIVE

The cooperative, established more than 75 years ago, brings together about 150 milk producers. In addition to collecting about 15,000 liters of milk per day and delivering it to the service provider, which stores it for later distribution, it buys raw materials to produce feed, orders their processing, and distributes the feed to the cooperative members who buy it. Finally, it has a store that sells supplies, accessories, and vaccines, among other things. The head office is in the urban area and comprises an office, a store, and a storage area for materials. Figure 4 shows the activities and processes that are included in the greenhouse gas emissions accounting.

Figure 4. Mass flows that have been included in the carbon footprint calculations for the milk produced from Organization 2's point of view



Source: the authors

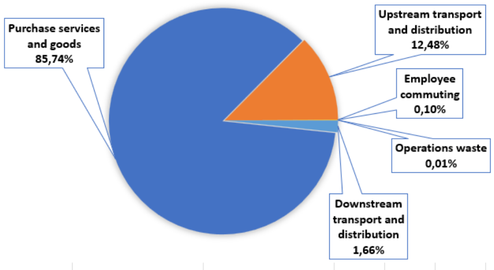
4.2.1 Inventory Structure

The inventory used the consolidation by shareholding control option. There were no Scope 1 emissions as the cooperative does not own any vehicles, fuel burning equipment, and in 2022 no refrigeration or air conditioning equipment, it does not conduct any agricultural activities on its property, nor does it generate any energy, nor does it treat any waste or wastewater. The electricity used by the utility originates indirect scope 2 emissions. Most emissions come from Scope 3 sources, such as milk production on the farms, transport of inputs, and transport of milk. Table 06 shows the elements that make up the inventory.

4.2.2 Results

Emissions from Organization 2 in 2022 account for 3926,2 t CO_{2e}, and most emissions (99.99%) are related to Scope 3. About 86.4% of Scope 3 emissions are related to milk procurement, whereas upstream transport and distribution account for 11.8% of the Scope 3 emissions (Figure 3). Results do not include biogenic emissions, which account for 54.70 t CO_{2e} (Scope 3, transportation and distribution, upstream and downstream) in 2022. The carbon footprint of the milk at the cooperative's gate is 0.717 kg CO_{2e}/l. Figure 5 shows the breakdown of Scope 3 emissions.

Figure 5. Breakdown of Scope 3 emissions for organization 2.



Source: the authors

Considering a herd of 122 animals, the emission per animal is 2.005 tCO_{2e}/year. Considering that milk is produced 365 days a year at an average rate of 15,000 liters per day.

5 DISCUSSION

5.1 PRODUCTION PERFORMANCE RESULTS

In Organization 1 (farm and milk processing plant), emissions were estimated at 0.62kg CO_{2e}/l milk, which is slightly lower than life cycle emissions of 0.74 kg CO_{2e}/l milk estimated based on three farms located in the Southern region of Brazil (Léis et al. 2015). Our result is lower than the range from a literature review of milk production LCAs in different countries, excluding Brazil, which reports a range between 0.74 and 5.99 kg CO_2/FPCM (Mazzetto et al. 2022). The results in Organization 1 are also lower than the reported by Maciel et al (2022) in a Farm in Brazil. Their calculation resulted in 1.1 and 1.2 kgCO2e/l milk in different situations, but they did not report the farm's location. In contrast, Santos et al (2022) reported lifecycle emissions of 1.4 kgCO2eq per liter of milk in the region of Viçosa (MG, Brazil), which is twice as great as our results.

One controversial emission source for milk LCAs is land use change, and several studies assume stable land use change. Nonetheless, the inventory published by the Granarolo company in Italy states that emissions with and without land use change effects are 1.30 kg CO2/liter of milk and 0.65 kg CO2/liter of milk (Granarolo, 2010). In the case of Organization 1, which was assessed in our study, land use change was earlier than 20 years ago, making this effect out of the considerations by the GHG Protocol.

Enteric fermentation, which releases methane, is the most significant GHG source from dairy farms, but small farmers are not tackling this problem, either because of a lack of information or because there are no cost-competitive local feed supplements available.

Therefore, preparing annual GHG inventories and investing in local methane emissions monitoring might facilitate the search for local feed alternatives at competitive costs. Internalizing the cost of climate change through a regulated market is also relevant. Lifecycle emissions from the production of farm inputs are negligible and account for less than 7% of the lifecycle emissions from milk production.

Although results could be considered representative of the regional reality, and comparable to published results that rely on the same approach, data on nutrient and pesticide flows, destination of waste and wastewater, and fossil fuel consumption might be analyzed more accurately.

Transport is responsible for around 12% of the cooperative's GHG emissions. Although it is less than enteric fermentation emissions, the potential for emission reductions is considerable. This makes the regional concentration discussed by Xu et al (2023) an important theme for further studies, once local and wholesale suppliers favor lower freight emissions. Expected future actions could include more energy-efficient displacement and adopting biofuels or electric trucks.

In the case of milk processing for dairy products, it is important to remark that effluent treatment seems to be a major source of uncertainty. The literature shows a wide variation in the composition of dairy effluents. Saraiva et al (2009) indicate a variation between 450 and 4790 mg/l BOD in the wastewater. Stasinakis et al (2022) in their literature review show a variation between 375 and 11000 mg BOD/kg organic matter, including data from Europe and Asia. Loures (2011) reported literature values between 1292 and 60000 mg/l BOD. The same author measured 2300 and 2400 mg/l BOD for effluents in a dairy farm, in the same region, and with activities comparable to Organization 1.

Several emission factors, used in the inventory, should be adapted to reflect the local reality more precisely. Moreover, there is a mismatch between the description of activities, such as the type of pasture management, feed, and manure management, and the terminology and techniques used in the local farms. In this sense, calculation tools need to evolve to better reflect local terminology and practices. More research on emission factors for practices that have not yet been considered is needed. One example is manure management, in which modeling requires knowing the organic load and nitrogen content of the manure, for which data are not always available in the literature, and when they are, there is a large margin of error that significantly influences the estimated emissions. Finally, it would be necessary to study the characteristics of the effluents, wastes, and emissions in the treatment processes used. Sometimes these treatments are relatively rudimentary, such as stone bed filtration and activated carbon followed by land disposal, which also jeopardizes data acquisition. The relevance of this emission source demands low-carbon technologies to reduce emissions.

6 CONCLUSIONS

Our results can be used as a reference for studies on other production chains involving small rural producers, as well as cooperatives or buyers who industrialize the products acquired from rural properties, advancing in the quest for net zero GHG emissions.

The study is based on the cases of two organizations in the interior of the State of São Paulo. However, it is representative of the reality of small Brazilian farms in the sector. It is therefore expected that many of the difficulties identified will be faced by producers of the same size or even larger.

The quality of estimations is one aspect that has not been much discussed in the literature. The fact that emissions at the farm are mainly concentrated in one source of category - namely enteric fermentation, should lead future research to concentrate on improvements in its quality. When looking at milk processing, waste and wastewater management seems to be a major issue. Because other emission sources such as electricity consumption or even transport are less important, they might be assessed with simple methods.

Therefore, the definition of climate actions and net zero plans should concentrate on reducing emissions from enteric fermentation, at the farm, and from waste handling, at milk processing. That does not mean that we should not find better transport ways to reduce emissions from fossil fuels or find better ways of making the soil more fertile, to avoid N2O emissions. Working on recovering land for pasture quality, studying feed composition, and recovering energy from waste and wastewater (as examples, only) could have higher quantitative impacts.

From the results of this research, it became clear that organizations need to advance in their structuring to obtain more consistent data to improve the quality of the inventory in subsequent years. It also became clear that the surveyed organizations do not have emission reduction strategies based on inventories, which should lead to the implementation of future projects. Possible actions include improving the transportation of milk and raw materials using electric vehicles or vehicles powered by renewable fuels such as ethanol or biodiesel and improving the management of cattle feed to reduce emissions. Indeed, enteric methane emissions are responsible for most of the GHG emissions related to milk production and alternative cattle feed is one alternative to curb such emissions. Although electricity consumption is not significant in the organizations studied, the implementation of electricity generation systems using renewable sources such as photovoltaic or biogas could be considered.

The way to net zero emissions is by organizing the data and creating new greenhouse gas (GHG) emission inventories, already considering the best practices resulting from good climate change mitigation, carbon dioxide removal, and adaptation projects in the dairy chain. The authors´ recommendations are:

1. An evolution in the structuring of operations data, to obtain and keep adequate records for the preparation of more accurate annual GHG inventories.
2. Further analysis of the causes of emissions, both in Organization 1 (farm and dairy) and Organization 2 (cooperative), to make decisions and initiatives aimed at reducing emissions in the production chain.
3. Further studies into best practices for reducing greenhouse gas emissions, as well as their removal through land use change initiatives.
4. Expanding the number of farms to be involved, to increase understanding of the frequency and extension of the issues aiming at implementing solutions in the whole chain.

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