Sustainable Production and Consumption 37 (2023)

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc

The environmental impact of permanent meadows-based farms: A comparison among different dairy farm management systems of an Italian cheese

Giulia Rencricca [a,*], Federico Froldi [b,*], Maurizio Moschini [b], Marco Trevisan [a], Sami Ghnimi [c,d], Lucrezia Lamastra [a,*]

[a] Department for Sustainable Food Process (DiSTAS), Università Cattolica del Sacro Cuore, via Emilia Parmense 84, 29122 Piacenza, Italy
[b] Department of Animal Science, Food and Nutrition (DIANA), Università Cattolica del Sacro Cuore, via Emilia Parmense 84, 29122 Piacenza, Italy
[c] Laboratoire d'Automatique, de Génie des Procédés et de Génie Pharmaceutique, CNRS, Université Claude Bernard Lyon 1, Villeurbanne, France
[d] ISARA, 23 Rue Jean Baldassini, 69007 Lyon, France

ARTICLE INFO

Article history:
Received 29 November 2022
Received in revised form 14 February 2023
Accepted 15 February 2023
Available online 21 February 2023

Editor: Dr. Cecile Bessou

Keywords:
Life cycle assessment
Product environmental footprint
Environmental sustainability
Milk
Dairy
Dairy farm systems

ABSTRACT

The environmental impact of dairy production is heavily influenced by milk farm efficiency, farm characteristics, and farming activities, such as feed management. The existing research on the environmental impacts of the differently managed dairy farm systems is often in contrast and difficult to be compared. Thus, the present study aimed to assess the environmental impacts of milk used for the same cheese by comparing four dairy farm systems different for feed management choices, geographical area, herd size and milk productivity. A Life Cycle Assessment was performed following the Product Environmental Footprint methodology using primary data collected in 70 farms and one average cheese factory. The results showed that the raw milk production phase was the most significant contributor to the environmental impacts of cheese production. The self-produced feed and purchased feed resulted as the main hotspot processes, covering 64–77 % of the total impact. In fact, among the four different farm systems, the Permanent Meadows Farms showed the best environmental performance, with the lowest values registered for 14 of 19 impact indicators. Similar impacts were observed for the North Italy Representative Farms, while Small Plain Farms disclosed the highest outcomes, resulting most impacting than the Mountain Farms. Results demonstrate that different feed management choices can affect the final cheese impact and could be considered by private and public policies focused on green transformation objectives.

1. Introduction

Dairy products and milk are consumed regularly by >80 % of the world's population (FAO and GDP, 2018), being an essential source of major nutrients (Bava et al., 2018; Rozenberg et al., 2016). However, due to the high quantity of natural resources and input necessary for production (Guzmán-Luna et al., 2022), cattle milk is responsible for 2.9 % of total greenhouse gas emissions globally (Gerber et al., 2013), while at the European level, the dairy industry is responsible for 27 % of greenhouse gas emissions from food production (Sandström et al., 2018). Several researchers have applied LCA to evaluate the environmental performance of different dairy products (Canellada et al., 2018; Dalla Riva et al., 2018; Finnegan et al., 2018). However, a direct comparison of the results of similar types of dairy products or dairy farm systems is difficult due to the diverse methodological choices employed in the existing literature

Abbreviations: A, Acidification terrestrial and freshwater; CC, Climate change; CC-biogenic, Climate change - biogenic; CC-LTU, Climate change - land use and transformation; CC-fossil, Climate change - fossil; DM, Dry matter; DMI, Dry matter intake; EF, Environmental Footprint; FE, Eutrophication freshwater; FPCM, Fat and protein corrected milk; FU, Functional unit; F-RD, Resource use, mineral and metals; FWE, Ecotoxicity freshwater; HT-C, Cancer human health effects; HT-NC, Non-cancer human health effects; IR-HH, Ionising radiation, human health; LCA, Life Cycle Assessment; LU, Land use; ME, Eutrophication Marine; MF, Mountain Farms; M-RD, Resource use, energy carriers; NIRF, North Italy Representative Farms; OD, Ozone depletion; PDO, Protected Designation of Origin; PEF, Product Environmental Footprint; PEFCR, Product Environmental Footprint Category Rule; PM, Particulate matter formation; PMF, Permanent Meadows Farms; POF, Photochemical ozone formation, Human Health; SPF, Small Plain Farms; WRD, Water scarcity.

* Corresponding authors.
E-mail addresses: giulia.rencricca@unicatt.it (G. Rencricca), federico.froldi@unicatt.it (F. Froldi), lucrezia.lamastra@unicatt.it (L. Lamastra).

https://doi.org/10.1016/j.spc.2023.02.012
2352-5509/

since the decisions made by practitioners have a significant impact on the findings (Baldini et al., 2017; Egas et al., 2020). The European Commission launched the Product Environmental Footprint (PEF) method (European Commission, 2013) to harmonise the LCA methodological choices. Therefore, the PEF methodology was developed to establish a common approach to evaluate environmental performances by providing specific criteria to conduct a PEF-compliant study based on LCA analysis, including 19 impact categories (Zampori and Pant, 2019). Product Environmental Footprint Category Rules, a more specific set of rules and steps to be followed, have been released for the dairy sector to improve the reliability and representativeness of PEF studies and their results (EDA, 2018; Zampori and Pant, 2019).

Generally, the application of the new PEF methodology, in particular the Product Environmental Footprint Category Rule (PEFCR) for the dairy sector, has not been widely used. In Italy, Famiglietti et al. (2019) and, more recently, Lovarelli et al. (2022) and Froldi et al. (2022b) employed the PEF methodology for different PDO Italian cheeses (Protected Designation of Origin). Whereas, at a broader European level, only Egas et al. (2020) applied the PEF method to evaluate a traditional dairy farm in Catalonia. The PEF methodology has never been used to investigate the impacts of different farm management systems producing milk for the same PDO. PDO are certified products constrained by production regulations that guarantee adherence to specific quality standards and production areas (European Union, 2012) that are favoured by customers that recognise the quality and the environmental value of PDO products contemporarily (Goudis and Skuras, 2020; Lovarelli et al., 2022). Approximately 22 % of Italian milk produced is used to produce Grana Padano, a PDO Italian hard cheese (CLAL, 2022). Following the Grana Padano production regulation, milk comes from cows reared in vast defined geographical areas in Northern Italy Po plain (European Commission, 2011), but that could be different for farm and feed management. At least 75 % of the dry matter of fodder for the dairy cattle should be produced on the farm or in the same production mentioned area. The dairy cattle diet includes fresh fodder, hay, straw, and silage, with some exceptions for the latter that is expressly excluded from the Trentingrana sub-regulation. Other farms feed the cattle mainly through self-produced hay.

Despite the methodological differences, the existing literature confirms that most of the environmental impacts of the dairy supply chain are caused by raw milk production (Canellada et al., 2018; Famiglietti et al., 2019; Finnegan et al., 2018). Impacts related to raw milk production might change in different dairy management systems depending on feed management decisions, farm efficiency, herd size and slurry management (Berton et al., 2020; Froldi et al., 2022b; Lorenz et al., 2019). Animal feeding is a crucial aspect of the cattle sector in terms of productivity and environmental sustainability (Zucali et al., 2018), contributing from 34 % to 86 % of the environmental impacts (González-García et al., 2013). Although there is much research on the subject, the results are often in contrast and difficult to compare. Some studies concluded that a seasonal pasture and the grass-based dairy system had lower environmental impact compared to a confinement one (Guerci et al., 2013b; O'Brien et al., 2012), while others found that fresh forage system was the most impacting crop in the dairy system (Gislon et al., 2020; Zucali et al., 2018). Therefore, diverse geographical positions and feed management, such as mountain, permanent meadows and traditional farms, could lead to different results due to different methodological approaches and production regulations (Berton et al., 2021; Gislon et al., 2020; Lovarelli et al., 2022). Mountain traditional farms with highland summer grazing systems are more impactful than non-summer grazing intensive ones (Guerci et al., 2014) even though the transition from the first dairy farming system to the second one can slightly improve their environmental footprint (Berton et al., 2020). In some cases, the exploitation of highland pasture can be a mitigation strategy (Penati et al., 2013). Moreover, none of the above-cited articles compared, through the same approach, farms that differ in farming and feed management that produce milk for the same cheese, including permanent meadows farms in the analysis.

Therefore, the objective of the present study, to complete a framework that is still necessary for current literature, was to assess the environmental impact of Grana Padano production through the PEF method, considering cheese factory and raw milk production from four different dairy farming systems and determining which system is the most environmentally friendly.

2. Material and methods

LCA is a practical international methodology that assesses a product's environmental impact by measuring the effects of all inputs and outputs involved with each stage of a product life cycle (Famiglietti et al., 2019). In this study, an LCA analysis was performed according to the PEF method and following the PEFCR rules, specific for dairy products (EDA, 2018; Zampori and Pant, 2019).

2.1. Goal

The goal of this study was to assess the environmental impact of Grana Padano cheese produced in Italy, based on using milk produced in four different dairy systems. Furthermore, the four dairy systems are compared to each other. The production area was Northern Italy, accordingly to the PDO specification rules (EU) No 584/2011 (European Commission, 2011).

2.2. Functional unit

The present study considered two different functional units:

1) The functional unit for the raw milk production at the Dairy Farm was 1 kg of fat and protein corrected milk (FPCM), following the PEFCR (EDA, 2018) and IDF (2015). To calculate the corrected milk, the following formula was applied, obtaining a value of FPCM corrected to 4 % fat and 3.3 % protein:

$$\mathrm{FPCM} = \mathrm{Production}\frac{\mathrm{kg}}{\mathrm{yr}} x(0.1226\ x\ Fat\% + 0.0776\ x\ True\ Protein\% +\ 0.2534)$$

2) The functional unit for the cheese-making process at the Cheese Factory was 1 kg of hard cheese 12 months ripened without packaging, in line with Bava et al. (2018).

2.3. System boundary and allocation

Fig. 1 represents the cheese making production chain considered in this study, and the red dotted line denotes the system boundary. To perform the LCA analysis, the production process was divided into two sub-systems: a) raw milk production at the Dairy Farm and b) cheese making process at the Cheese Factory, with all inputs and outputs as summarised in Fig. 1. The Dairy Farm included on-farm activities as feed production and storage, manure, slurry, and livestock management, use of energy and water and off-farm activities as the production of farm inputs such as fertilisers, pesticides, seeds, feed concentrate, fodder, and bedding materials. The Cheese Factory encompassed the transport of raw milk to the cheese factory and the milk transformation in cheese, including cleaning agents, the production and transport of non-dairy ingredients, the ripening phase and the transport of output.

As specified by the PEFCR guide, small contributions processes can be excluded, such as medicines, cleaning products at the dairy farm, calf rennet, lysozyme production and capital goods (i.e., machinery) (EDA, 2018).

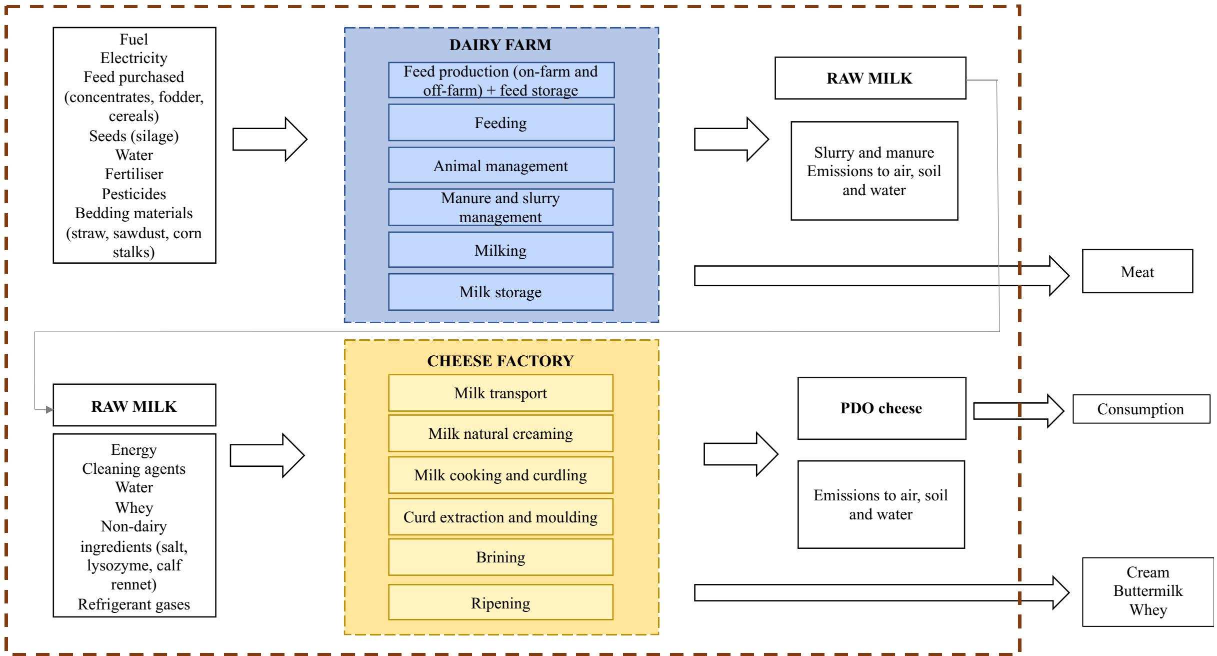


Fig. 1. Production process and system boundary considered for the studied system.
The figure shows the production process to produce cheese. The red dotted line presents the system boundary considered for the study. Transport of inputs entering the Dairy Farm was not considered in the analysis. Transports of inputs entering the Cheese Factory and transports of output were considered in the analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The system boundary is from "cradle to gate", including the cheese factory. The analysis evaluated on-farm and off-farm activities, while packaging, distribution, consumption, and end-of-life of the cheese were not encompassed in the assessment.

The allocation procedure at the farm level is based on the bio-physical relation between milk and the main co-product, meat, following what is recommended by IDF (2015) and by PEFCR (EDA, 2018). At the cheese factory level, dry matter (DM) content allocation is used between the cheese and each co-product (i.e., cream, whey, and butter).

2.4. Inventory data collection

All activity data were collected in 2019 from 70 farms in the Grana Padano area, including the Po valley and North Italy Mountains, and from one representative cheese factory. The farms have been selected to be representative of diverse management systems resulting in four different dairy management systems covering technological, geographical, and time-related representativeness, according to the PEF's data quality criteria:

– North Italy Representative Farms (NIRF), embodying the average dairy farms in Northern Italy present in the Po plain that make milk for Grana Padano cheese production. The cattle feed was based on silage feed (primarily corn silage), forage, protein ingredients (such as soybean meal), corn cereals, alfalfa, and compound feed. In this farm system, cattle were not allowed to graze.
– Mountain Farms (MF), representative of farms located in Alpine mountain areas that produce milk destined for the Trentingrana cheese making. For this farm system, silage feed was not allowed. The cattle were fed without silage feed and protein ingredients, but mainly with forage and compound feed, with small amounts of alfalfa and corn feed. The herd grazed for four months during the summer season, except for the calves.
– Small Plain Farms (SPF), representative of farms similar in herd size and milk yield per cow to the Mountain ones but located in the Po plain that produce milk for Grana Padano cheese. The feed management was the same as in NIRF, and the cattle were not allowed to graze.
– Permanent Meadows Farms (PMF), representative of farms located in the Po plain where the cattle were fed principally with forage, compound feed and small quantities of alfalfa and corn feed, without silage feed and protein ingredients. In this system, the forage has spontaneously grown solely in the grassland of the farm and, during warmer seasons, has been left to dry into hay. Therefore, the milk produced is commonly known as "hay milk", destined to produce Grana Padano cheese as well. Differentiating from the other plain systems, in PMF, meadows were never alternated with other crops, and there was no ploughing or harrowing, only mowing and irrigation. The cattle had the possibility to go in the outdoor paddock during the summer season.

The surveys were conducted by compiling a questionnaire with farmers, and data collected referred to one year of production. The questionnaire for the Dairy Farm collected activity data on farm characteristics, input, milk productivity and feed management system, including crop production and feed choices (type and quantity of crop cultivated, type and quantity of purchased feed, presence of silage).

The collected activity data have been then grouped into eight different groups, which identify the different processes in the Dairy Farm phase:

– Water used, including drinking water, cleaning water and cooling water.
– Purchased feed, including cultivation area and emissions.
– Energy used, including electricity, total diesel, liquefied petroleum gas, methane, and gasoline used for farm activities, breeding, crop, and feed cultivation.
– Self-produced feed, including the arable land and permanent pasture and meadows areas, seeds, irrigation water, artificial fertilisers and pesticides used and their emissions.

– Bedding materials, including the quantity and the production of cereal straw, calcium carbonate, lime, corn stalks, coconut fibre, sawdust, and woodchips.
– Manure management emissions, including emissions from manure storage, manure application and heavy metals.
– Enteric fermentation emissions, including methane emissions.
– Animal housing emissions, including the number and category of animals (i.e., lactating cows, dry cows, heifers, young heifers, and calves) and their housing period, the quantity of cereals straw per year used for the animal housing and the MJ intake per day per animal category.

The direct emissions generated from enteric fermentation, manure storage, manure application, nitrogen fertiliser application, artificial fertiliser application, animal housing, silage feeding, and urea application were calculated from the primary data collected, according to the definite methodology references listed in Table S1.

The questionnaire for the Cheese Factory phase has collected data on:

– Raw milk transport.
– Non-dairy inputs, including salt, refrigerant gases, cleaning agents, plastic shrink and pallets.
– Transports, excluding raw milk transport.
– Energy and water consumption, including heat, electricity and water consumption.

The background data were gathered from the EF 2.0 database and included the production of the Dairy Farm inputs, the Cheese Factory inputs (excluding raw milk production), and transports (Zampori and Pant, 2019).

2.5. Life cycle impacts assessment

Following the PEFCR methodology, the 19 following impact indicators were analysed: climate change (CC, kg CO_2 eq), climate change-fossil (CC-fossil, kg CO_2 eq), climate change-biogenic (CC-biogenic, kg CO_2 eq), climate change - land use and transformation (CC-LTU, kg CO_2 eq), ozone depletion (OD, kg CFC-11 eq), ionising radiation - human health (IR-HH, kBq U^{235} eq), photochemical ozone formation - human health (POF, kg NMVOC eq), particulate matter formation (PM, disease incidence), human toxicity – non-cancer effects (HT- NC, CTUh), human toxicity – cancer effects (HT- C, CTUh), acidification (A, mol H+ eq), eutrophication freshwater (FE, kg P eq), marine eutrophication (ME, kg N eq), terrestrial eutrophication (TE, mol N eq), ecotoxcity freshwater (FWE, CTUe), land use (LU, pt), water scarcity (WRD, $m^3$of deprived water), resource use, fossil (F-RD, MJ), and resource use, mineral and metals (M-RD, Kg Sb eq).

The emissions and impacts modelling utilised for this research are under the PEFCR guidelines. All the activity data were introduced in the SimaPro® software, version 9.0.0.35 (PRé Consultants, 2019). The reference dataset was EF Method 2.0 V1.00/Global (2010)/ with tox categories. The characterisation, normalisation, and weighting factors were from the EF Method 2.0/Global (2010) (Zampori and Pant, 2019).

3. Result and discussion

3.1. Life cycle inventory results

The average collected data for the Dairy Farm are reported in Tables 1 and 2. The dairy efficiency is shown as the ratio of the average production of FPCM dairy milk per year and cows' average dry matter intake. The milk production intensity was calculated as the quantity of FPCM milk in relation to the total average hectare of farms. The total averages kg of DM was calculated by regrouping the different crops into categories: forage (including dry forage wheat/lolium multiflorum dry, polyphyte meadows and herbarium mixture), alfalfa, cereals (including barley grains and wheat grains), corn, corn silage, silage (including wheat, sorghum, barley and lolium multiflorum silage), protein ingredients (including soybean meal, sunflower and flax), compound feed and other (e.g., fats and hydrogenated oils) (Table 2). Compound feed included all the commercial products for different classes of

Table 1
Average inventory data about farm characteristics, farm inputs, and milk productivity for the four farm systems.

	Unit	NIRF		MF		SPF		PMF	
		Average	min-max	Average	min-max	Average	min-max	Average	min-max
Farm characteristics									
Total farmland	ha	55.3	8–603	14.1	8–20	19.7	17–24	19.1	14–21
Permanent meadows and grassland	ha	14.6	0–163	14.1	8–20	9.4	0–19	19.1	14–21
Crop arable land	ha	40.7	41–440	–	–	10.3	0–18	–	–
Total animals	n.	288	37–1910	38	25–58	58	37–77	113	76–135
Total lactating cows	n.	135	18–920	20	12–30	33	22–38	57	31–71
Farm inputs									
Electricity	kWh y^{-1}	56,308	5063–308,087	6978	3869-9573	15,719	6667-21,895	28,846	15,955-36,246
Diesel	lt y^{-1}	26,463	1768–195,413	3175	1022-7024	7692	4805-9220	5944	4533-9795
Liquefied Petroleum Gas	lt y^{-1}	1849	0–67,642	157	0–629	163	0–651	576	0–1330
Methane	m^3 y^{-1}	42	0–1981	–	–	–	–	92	0–370
Water used on the farm	m^3 y^{-1}	7528	661–50,979	668	354–1100	1239	1009-1641	3398	1720-4214
Irrigation water	m^3 y^{-1}	128,638	0–1,490,326	–	–	31,230	27,239-41,473	33,249	24,405-45,809
Pesticides	kg y^{-1}	162	0–1547	–[a]	–[a]	27	0–53	–[a]	–[a]
Artificial fertilisers	Kg N y^{-1}	4226	0–53,195	–[a]	–[a]	454	0–621	–[a]	–[a]
Bedding materials	kg y^{-1}	75,803	0–723,944	97,387	5282-370,332	32,183	24,587-63,646	50,708	11,297-85,592
Milk productivity									
Dairy efficiency	kg FPCM kg DMI^{-1}	1.13	–	1.03	–	0.67	–	1.21	–
Milk production intensity	t FPCM ha^{-1}	26.69	–	9.56	–	10.96	–	28.10	–
Annual milk production	kg y^{-1}	1,479,390	–	132,501	–	214,787	–	526,668	–
Milk yield per cow	kg FPCM d^{-1}	29.89	–	18.64	–	18.21	–	25.95	–
Raw milk allocation	%	87	75–94	83	79–88	84	78–91	90	89–92
Milk yield per year	t FPCM y^{-1}	1475	–	134	–	216	–	538	–
Milk protein content	%	3.42	3.19–3.87	3.40	3.37–3.57	3.49	3.3–3.46	3.55	3.31–3.87
Milk fat content	%	3.94	3.51–4.30	3.99	3.73–4.24	3.98	3.97–4	4.04	3.99–4.19

Abbreviations: NIRF: North Italy representative farms; MF: Mountain farms; SPF: Small plain farms; PMF: Permanent meadows farms; FPCM: fat and protein corrected milk; DMI: dry matter intake.
[a] Not allowed or used on the farm.

Table 2
Average inventory data about feed management for the four farm systems.

	Unit	NIRF		MF		SPF		PMF	
Purchased feed									
Total purchase feed	kg DM year^{-1}	650,316	min-max	75,137	min-max	115,444	min-max	217,351	min-max
Forage	% DM year^{-1}	6	0–21	4	0–20	–	–	–	–
Alfalfa	% DM year^{-1}	6	0–22	28	0–45	9	0–15	6	0–20
Cereals	% DM year^{-1}	1	0–11	0	–	1	0–6	–	–
Corn	% DM year^{-1}	17	0–51	12	0–41	17	0–48	30	0–55
Corn silage	% DM year^{-1}	11	0–60	–[a]	–[a]	22	0–41	–[a]	–[a]
Silage	% DM year^{-1}	3	0–34	–[a]	–[a]	–	–	–[a]	–[a]
Protein ingredients	% DM year^{-1}	12	0–77	–	–	21	0–46	–	–
Compound feed	% DM year^{-1}	30	0–100	56	40–74	27	0–90	63	21–100
Other	% DM year^{-1}	13	0–51	–	–	4	4–6	1	0–4
Self-produced feed									
Total self-produced feed	kg DM year^{-1}	710,524	min-max	55,940	min-max	207,094	min-max	227,698	min-max
Forage	% DM year^{-1}	23	0–23	100	100–100	49	7–100	100	100–100
Alfalfa	% DM year^{-1}	10	0–62	–	–	15	0–39	–	–
Cereals	% DM year^{-1}	0	0–11	–	–	–	–	–	–
Corn	% DM year^{-1}	3	0–21	–	–	–	–	–	–
Corn silage	% DM year^{-1}	52	0–38	–[a]	–[a]	28	0–55	–[a]	–[a]
Silage	% DM year^{-1}	12	0–71	–[a]	–[a]	8	0–23	–[a]	–[a]
Protein ingredients	% DM year^{-1}	–	–	–	–	–	–	–	–
Total feed	kg DM year^{-1}	1,360,840		131,078		322,539		445,049	
Feed self-sufficiency	%	52		43		64		51	
Land productivity	t DM ha^{-1}	13		4		11		12	

The min-max percentage reports the minimum and maximum range for each feed related to the four farm systems.
Abbreviations: NIRF: North Italy representative farms; MF: Mountain farms; SPF: Small plain farms; PMF: Permanent meadows farms; DM: dry matter.
[a] Not allowed or used on the farm.

reared animals (lactating cows, dry cows, heifers, young heifers and calves). Detailed compound feed composition is explained in Table S2.

The feed self-sufficiency was determined as the proportion of the amount of self-produced feed (kg of DM) to the yearly dry matter consumption. The land productivity was estimated considering the tons of DM self-produced yearly on the total hectares of the farms. All the feed sold was removed from the self-produced average.

The different farm systems included farming activities of varied intensity in terms of milk yield per cow (kg d^{-1}), herd size, dairy efficiency (kg FPCM kg DMI^{-1}) and milk production intensity, ranging from the more intensive system (NIRF) and moderately intensive (PMF) to small farm systems (MF and SPF) (Table 1). NIRF farm system included the largest farms, while MF was the most minor, for lactating cows (135 and 20 respectively), the number of inputs and milk output (1,479,389 and 134,388 kg/y respectively). However, the PMF system has the most significant dairy efficiency rate (1.21 FPCM kg DMI^{-1}), and although MF represents the smallest farms, for this farm system DE and milk yield per cow were slightly higher compared to SPF (1.03; 0.67 kg FPCM kg DMI^{-1} and 18.64; 18.21 kg FPCM d^{-1} respectively). Similarly, the milk production intensity level was higher for PMF than for NIRF (28.10 and 26.69 t FPCM ha^{-1}, respectively) (Table 1).

The analysed dairy farm systems also differed for feed production and feed purchased (Table 2). NIRF had the most significant farm extent (55.3 ha), followed by SPF (19.7 ha), PMF (19.1 ha) and MF (14.1 ha). For NIRF, on average, 52 % of the feed intake was produced on-farm, mainly corn production, while only 26 % of the farmland was destined as permanent meadows. MF and PMF farmlands are entirely used to produce local hay and, in MF farms for pasture, hence significant volumes of alfalfa, corn, and compound feed are imported to compensate for the lack of concentrated feed. Even though the forage produced by PMF farms corresponded only to 51 % of the total feed intake, the land productivity was the second highest after NIRF farms (12 and 13 t DM ha^{-1}, respectively). MF farm system bought more feed than it produced, resulting in low feed self-sufficiency (43 %) and registering the smallest land productivity as well. For the SPF system, almost half of the farmland was destined for permanent meadows, with forage being the major fodder produced and for which they are self-sufficient, with the highest feed self-sufficiency rate (64 %).

The collected data at the Cheese Factory are alleviable in Table S3.

3.2. Life cycle impact assessment results

The characterised results and the total single score (expressed in Pt) with toxicity categories of the environmental impact assessment for milk production related to the different farming systems are reported in Table 3. According to the PEF methodology, the single score refers to weighted results expressed with a dimensionless value (Pt). Total characterised results and the total single score for 1 kg of Grana Padano cheese at the Cheese Factory level are available in Table S4.

According to the weighted LCA results for the cheese production process considered, the NIRF system contributed 94 % of the overall impact (Fig. 2). Some modest variations were recorded among the different farm systems, with a contribution of 96 % for SPF, 95 % for MF and 93 % for PMF systems (Fig. S1), with an average of 95 %. Thus, as expected, the findings of this study support those of Famiglietti et al. (2019), who observed that the dairy farm phase is responsible for around 97 % of environmental impacts associated with the life cycle of cheese, and Lovarelli et al. (2022), who reported that raw milk accounted for 93 % of the cheese's total impact.

Considering only the Cheese Factory, energy and water consumption accounted for 94 % of the related impact, followed by raw milk transport (3 %) and non-dairy inputs (3 %), while the impact of the other transports was negligible.

According to the PEFCR, the most relevant life cycle stages contribute to at least 80 % of one impact category (EDA, 2018). Therefore, the discussion of the results will focus on the most significant contributor to impacts, the Dairy Farm.

Table 3
Characterised and weighted results for 1 kg of FPCM for the four farm systems considered.

Impact indicator	Unit	NIRF	MF	SPF	PMF
Climate change (CC)	kg CO_2 eq	1.9148	2.0201	2.3919	1.9136
Ozone depletion (OD)	kg CFC-11 eq	6.99×10^{-10}	1.42×10^{-9}	9.41×10^{-10}	4.81×10^{-10}
Ionising radiation, HH (IR-HH)	kBq U^{235} eq	1.48×10^{-2}	2.08×10^{-2}	2.39×10^{-2}	1.52×10^{-2}
Photochemical ozone formation, HH (POF)	kg NMVOC eq	8.35×10^{-3}	6.25×10^{-3}	1.16×10^{-2}	3.74×10^{-3}
Particulate matter formation (PM)	disease inc.	6.4×10^{-8}	1.09×10^{-7}	1.06×10^{-7}	6.08×10^{-8}
Non-cancer human health effects (HT-NC)	CTUh	2.43×10^{-6}	3.84×10^{-6}	4.51×10^{-6}	2.46×10^{-6}
Cancer human health effects (HT-C)	CTUh	2.52×10^{-8}	5.49×10^{-8}	4.98×10^{-8}	2.22×10^{-8}
Acidification terrestrial and freshwater (A)	mol H+ eq	5.92×10^{-3}	1.05×10^{-2}	9.97×10^{-3}	5.51×10^{-3}
Eutrophication freshwater (FE)	kg P eq	1.50×10^{-4}	4.14×10^{-4}	3.16×10^{-4}	1.22×10^{-4}
Eutrophication marine (ME)	kg N eq	6.41×10^{-3}	1.05×10^{-2}	9.82×10^{-3}	5.70×10^{-3}
Eutrophication terrestrial (TE)	mol N eq	8.56×10^{-2}	1.20×10^{-1}	1.28×10^{-1}	8.28×10^{-2}
Ecotoxicity freshwater (FWE)	CTUe	10.8945	14.2896	13.4558	7.7314
Land use (LU)	Pt	1.94×10^{2}	3.60×10^{2}	3.17×10^{2}	1.76×10^{2}
Water scarcity (WRD)	m^3 depriv.	5.3584	1.2936	9.0337	4.1558
Resource use, mineral and metals (F-RD)	kg Sb eq	2.86×10^{-7}	4.84×10^{-7}	3.90×10^{-7}	1.80×10^{-7}
Resource use, energy carriers (M-RD)	MJ	3.7634	5.3490	6.1522	3.4907
Climate change - fossil (CC-fossil)	kg CO_2 eq	4.95×10^{-1}	7.30×10^{-1}	7.90×10^{-1}	4.69×10^{-1}
Climate change - biogenic (CC-biogenic)	kg CO_2 eq	1.1047	1.1641	1.1917	1.1230
Climate change - land use and transform. (CC-LTU)	kg CO_2 eq	3.15×10^{-1}	1.26×10^{-1}	4.10×10^{-1}	3.21×10^{-1}
Total single score (weighted results)	Pt	2.86×10^{-4}	3.71×10^{-4}	4.40×10^{-4}	2.62×10^{-4}

Abbreviations: NIRF: North Italy representative farms; MF: Mountain farms; SPF: Small plain farms; PMF: Permanent meadows farms.

3.2.1. Dairy systems environmental impacts

The PMF system showed the lowest values for all the impact indicators except for IR-HH, HT-NC and CC-biogenic, which were similar but slightly better for NIRF, and for WRD and CC-LTU impacts, which were reported as minor in MF. CC impact indicator resulted similar in PMF and NIRF. SPF was the most impacting dairy system; indeed, out of 19 impact categories, ten were greater for this farm system. The remaining nine impact indicators resulted higher for the MF system; however, it reported the lowest result for WRD and CC-LTU. NIRF registered lower emissions than SPF for all impacts, whereas it had higher effects than MF for POF, WRD and CC-LTU.

As indicated by the total single score in Table 3, the PMF system showed the best environmental performance overall. This farm system was characterised by the highest dairy efficiency rate and good milk productivity with fewer resources used compared to the other systems. PMF had a different farm management system, including better herd management, land management and diverse feed management. Indeed, the PMF system mainly used feed such as polyphyte meadows and hay (forage), did not use artificial fertilisers and pesticides, did not purchase protein ingredients or silage, and used less gasoline. This result supports the findings of O'Brien et al. (2012) and Guerci et al. (2013b), who concluded that the seasonal pasture-based system could have lower environmental impacts than a confinement dairy system due to lower resource use and pollutants. On the other hand, the present results are in contrast with Gislon et al. (2020) and Zucali et al. (2018), who found that the hay and fresh forage system was the most impacting crop system. The findings of this study are dependent on efficiency, and hence the farm system that can minimise input while maximising output has a lower impact, needing fewer maintenance requirements per unit of product (Faverdin et al., 2022). The high PMF's dairy efficiency is also explained by the high raw milk allocation for this farm system (90 %). The correlation between high dairy efficiency and environmental sustainability confirms Battini et al. (2016) and Lovarelli et al. (2019, 2022) studies. However, due to the proficient conversion of ingested DM into milk, this study also shows that less intensive farms such as PMF can obtain high dairy efficiency even with reduced milk yield per cow compared to other farm systems such as NIRF one. Additionally, PMF farms are an interesting option for the dairy industry from an environmental, but also from commercial standpoint, as demonstrated by Palmieri et al. (2021), who researched the potential market for hay milk in Italy and showed how consumers have a great interest in this product.

SPF system obtained the highest environmental impact overall. This farm system represents the North Italy representative farms but in

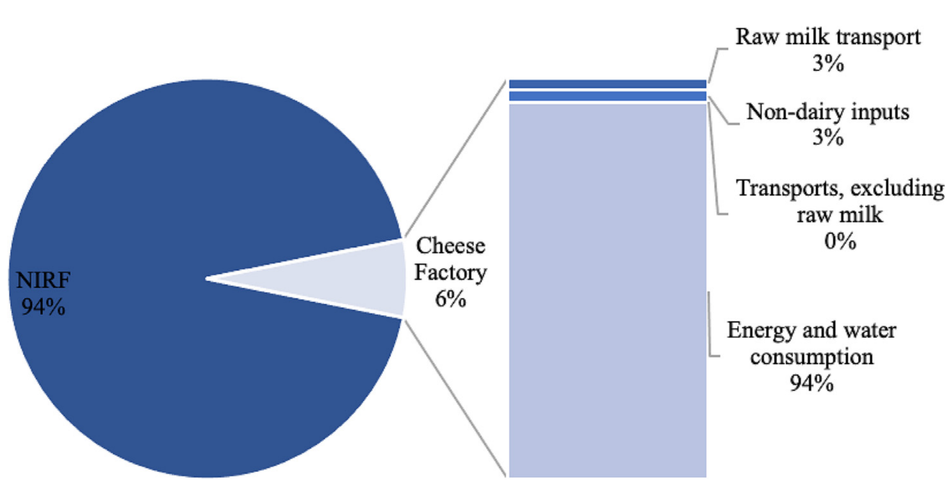


Fig. 2. Impact share between Cheese Factory and Dairy Farm (NIRF system).

smaller herd size and less land extent than the NIRF category. Therefore, while having the same dairy system and following the exact feed specifications, SPF and NIRF had different productivity levels. NIRF system used more inputs in relation to herd size in terms of energy, water, pesticides, artificial fertilisers, and bedding materials, and it produced the highest quantity of milk, which resulted in a high dairy efficiency and lesser environmental impacts, in line with Froldi et al. (2022b).

Although the MF system gathered the smallest farms in terms of herd size, milk productivity and land productivity, it resulted slightly more environmentally friendly than the SPF lowland system. Indeed, compared to SPF, in MF, smaller inputs were used (e.g., lower use of electricity and water, no use of pesticides and artificial fertilisers), and, despite the lowest land productivity, milk production level and similar milk yield per cow, this farm system recorded a higher dairy efficiency. Therefore, MF did not have the worst environmental results but had difficulties achieving good ones, also limited by the environment, as pointed out by Guerci et al. (2014), who highlighted as a restraint of mountain farms the adverse climate condition of the alpine area. MF was characterised by specific features and constraints, and it would be difficult to convert their farm system. However, it is essential to preserve the alpine livestock system in its original state since it provides significant benefits to the local community, such as the maintenance of livestock biodiversity and the traditional landscape of meadows and pastures, which are particularly relevant in terms of culture, tourism, and biodiversity (Sturaro et al., 2013). The presence of the Consortium in the Alpine mountains area to produce Trentingrana cheese allows farmers to maintain the original traditional practices of dairy farms while not making losses from an economic perspective and contributing to the local society. Furthermore, as described by Berton et al. (2020), the mountain feed management system is low based on potential human edible compound feed, resulting in an efficient food balance due to the conversion into food of human nonedible feed.

Considering the total weighted results with tox categories expressed as a single score reported by Egas et al. (2020) for raw milk production, the present study registered higher values. Indeed, 13 PEF impact indicators resulted lower than the one of this study, while PM and A indicators resulted higher compared to all the four farm systems of the present study, and POF, which resulted higher than for the PMF system. Compared only to the results of the NIRF system, similar values were founded by Lovarelli et al., 2019 on an Italian PDO production for CC, IR-HH, A, and CC-fossil. In contrast, OD, POF, PM, HT-C, FE, TE, FWE, WRD, M-RD, F-RD and CC-biogenic were higher, while ME, HT-NC and LU were lower. The outcomes of the four farming systems of this study were lower compared to Famiglietti et al. (2019) results for the indicators OD, PM, A, HT-C, FWE (only for PMF category), TE (for NIRF and PMF systems), ME, LU, M-RD and IR-HH (only for NIRF category), while higher values were found for the remain impact indicators, including CC.

Precise comparisons between different LCA studies and the present one must be done carefully because of the different methodological choices due to the adoption of the PEF method and the high number of impacts considered. However, results on a few impact categories can still be compared with some studies. The results reported in this study for the NIRF system were slightly higher than those found by Bava et al. (2018) for CC, FE, FWE and POF impact indicators, while lower for OD, A, ME and M-RD and similar for TE. Gislon et al. (2020), who assessed the environmental impacts of farm systems based on permanent meadows and alfalfa and conventional farm systems, found higher A, TE and ME impacts, while CC, FWE and partly F-RD lower compared to NIRF and PMF. Berton et al. (2021), considering only mountain farms, found higher CC than the value reported in this study. High differences in CC values were due to the application of the new update method (IPCC guidelines 2019) used to calculate enteric fermentation and manure management emissions, as already shown by Froldi et al. (2022b).

3.2.2. Processes contribution of the farm systems to the environmental impacts

The following paragraph illustrates the contribution of the eight farm processes listed in paragraph 2.4, referred to the four farm systems investigated. Fig. 3 displays the environmental performance of the different identified processes for each impact category, while Fig. 4 explains the influence of the processes on the total single score of each farm system. The vast range of the results is due to the different farms' characteristics.

Results show that self-produced and purchased feed are the most impacting processes for each farm system, covering 64 % to 77 % of the total impact. Remarkably, the main contributor to the environmental impact of milk production for each farm system was self-produced feed, ranging from 39 % for MF to 47 % for SPF, followed by purchased feed, covering from 25 % (MF) to 35 % (NIRF and PMF) of the total impact. However, also if self-produced feed was responsible for 40 % of the impact related to PMF, the single impact score in absolute value in Pt was the lowest (Fig. 4). It can be seen from Fig. 4 that self-produced feed was the main impacting process for all the farm systems, followed by purchased feed. However, the self-produced feed was the highest impacting process only for some impact categories, while purchased feed contributed highly to every impact indicator (Fig. 3). This could be explained by the strong influence on the HT-NC impact category by self-produced feed (72 % -77 %), supporting existing results (Famiglietti et al., 2019; Froldi et al., 2022b). The substantial impact of self-produced feed on HT-NC is due to the PEFCR methodology's assumption that 100 % of pesticide application emissions are released to the soil. Self-produced feed influenced partly HT-C (36 %–57 %), LU (29 %–40 %), FE (22 %–68 %), ME (21 %–35 %), and FWE (15 %–31 %) as well. The contribution of self-produced feed to WRD was between 67 % and 73 % for PMF, NIRF and SPF, while for MF it was <1 %.

The impact share of the self-produced feed process was greater for SPF and NIRF than the other farm systems. These farm systems registered the highest rate of feed self-sufficiency due to the cultivation of corn and different silage feed, which have high yields. The corn and silage production, however, led to high use of artificial fertilisers that release into air nitrous oxide, ammonia, and nitrogen oxides and into water nitrate, phosphorus, and phosphate emissions, contributing deeply to ME, FE impacts and FWE (Famiglietti et al., 2019; Froldi et al., 2022b). These farm systems also used urea in the fields as fertiliser, emitting carbon dioxide (IPCC, 2006), influencing CC impact. Furthermore, NIRF and SPF were the only farm systems using silage feed, recognised as a contributor to volatile organic compounds emissions into the environment generated by fermentation during feed ensiling (Hafner et al., 2013).

Purchased feed was the second most impactful process. SPF and NIRF environmental outcomes of purchased feed were notably higher than for MF and PMF. The purchased feed significantly affected all impact categories and highly on LU, IR-HH, OD, PM, A, FE, ME, FWE, F-RD and M-RD, similar to González-García et al. (2013) results, ranging from 52 % to 91 %. Purchase feed also impacted HT-C for 41 %–58 % in SPF, NIRF and PMF, while only for 21 % in MF. Unlike the other farm systems, MF purchased feed highly influenced WRD impact, accounting for 63 % of the total impact of the related process.

Table 4 shows the purchased feed with the highest impact for each farm system, the percentage of the total impact share, and the most affected impact category. For each of the four farm systems, the feed for lactating cows had the highest impact, ranging from 65 % for MF to 27 % for SPF of the total feed purchased process's impact. This is followed by corn production in flour, flakes, or ensiled. When silage feed was allowed as feed, it covered 19 % (NIRF) and 24 % (SPF) of the total impact, with the corn silage being more impacting than other silage. Similarly, soybean meal ranged from 6 % (NIRF) to 16 % (SPF). Due to their feed management restrictions, the different compound feeds were more impactful for MF and PMF

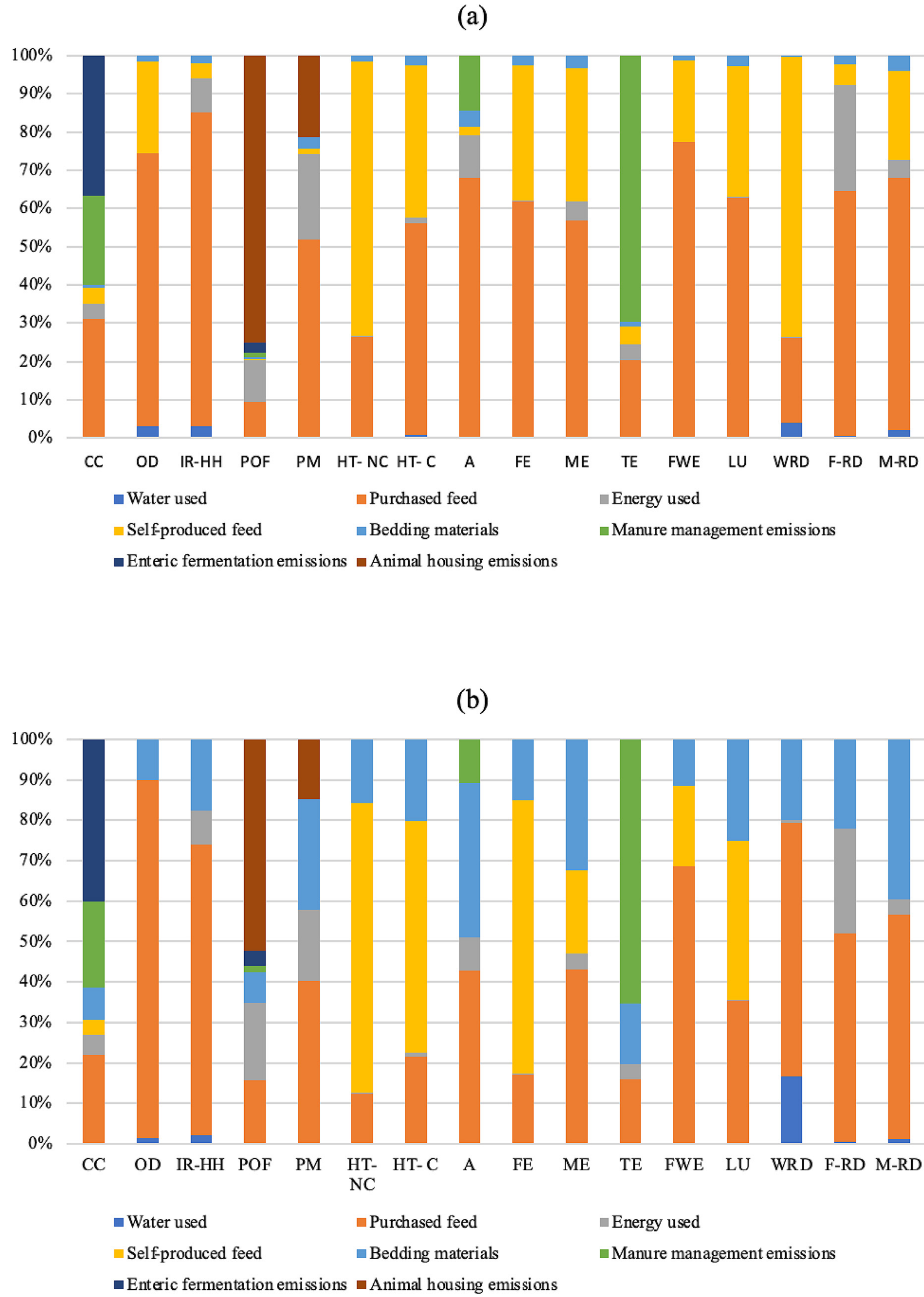
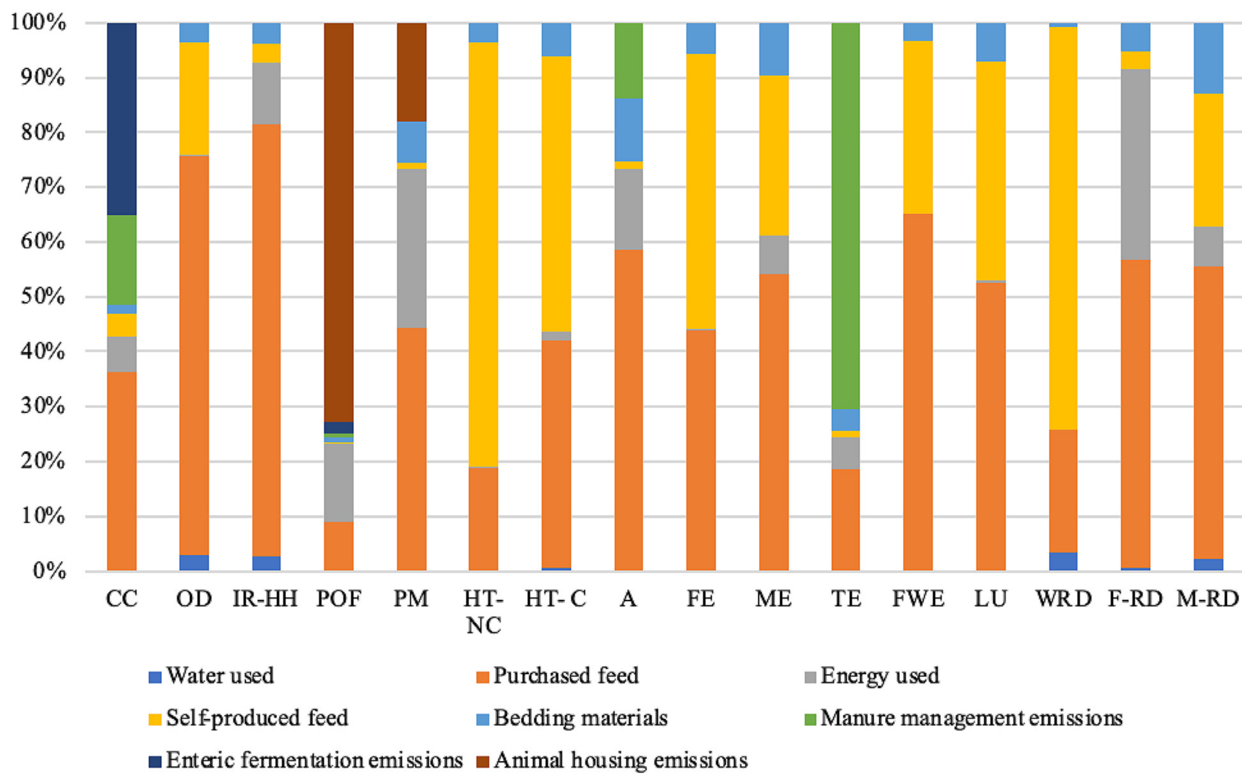


Fig. 3. Processes contribution to each impact category in (a) NIRF: North Italy Representative Farms, (b) MF: Mountain Farms, (c) SPF: Small Plain Farms, (d), PMF: Permanent Meadows Farms.
Abbreviations: CC: Climate change; OD: Ozone depletion; IR-HH: Ionising radiation, HH; POF: Photochemical ozone formation, HH; PM: Particulate matter formation; HT-NC: Non-cancer human health effects; HT-C: Cancer human health effects; A: Acidification terrestrial and freshwater; FE: Eutrophication freshwater; ME: Eutrophication marine; TE: Eutrophication terrestrial; FWE: Ecotoxicity freshwater; LU: Land use; WRD: Water scarcity; F-RD: Resource use, mineral and metals; M-RD: Resource use, energy carriers.

(c)



(d)

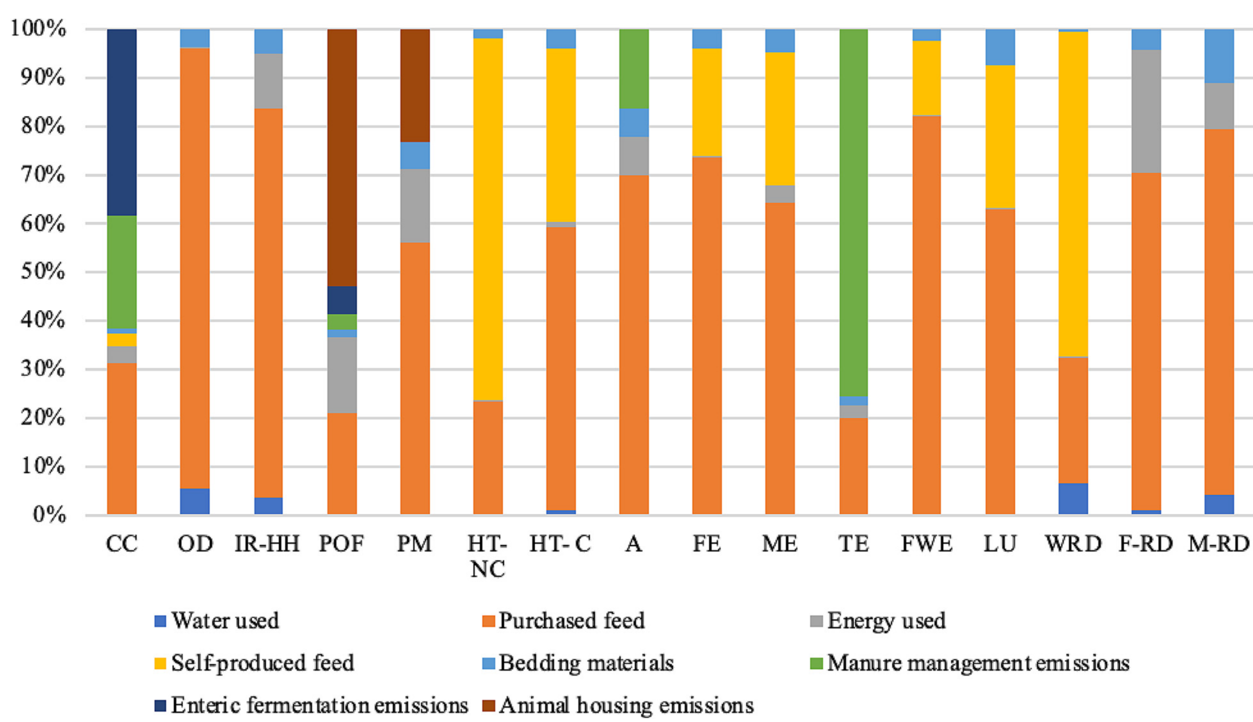


Fig. 3 (*continued*).

systems, together with alfalfa for the MF system. All these feeds contributed mostly HT-NC and FWE impacts, mainly caused by heavy metals from manure application on the field and the use of pesticides and artificial fertilisers. Alfalfa feed significantly influenced LU and soybean meal CC.

Manure management emissions accounted from 7 % to 10 % of the total weighted impact for the different farm systems, contributing from 16 % to 23 % to CC, similar to Battini et al. (2016) and Froldi et al. (2022b). Manure management contributed as well to TE (65 %–76 %), as reported in Froldi et al. (2022b), and to A (11 %–16 %).

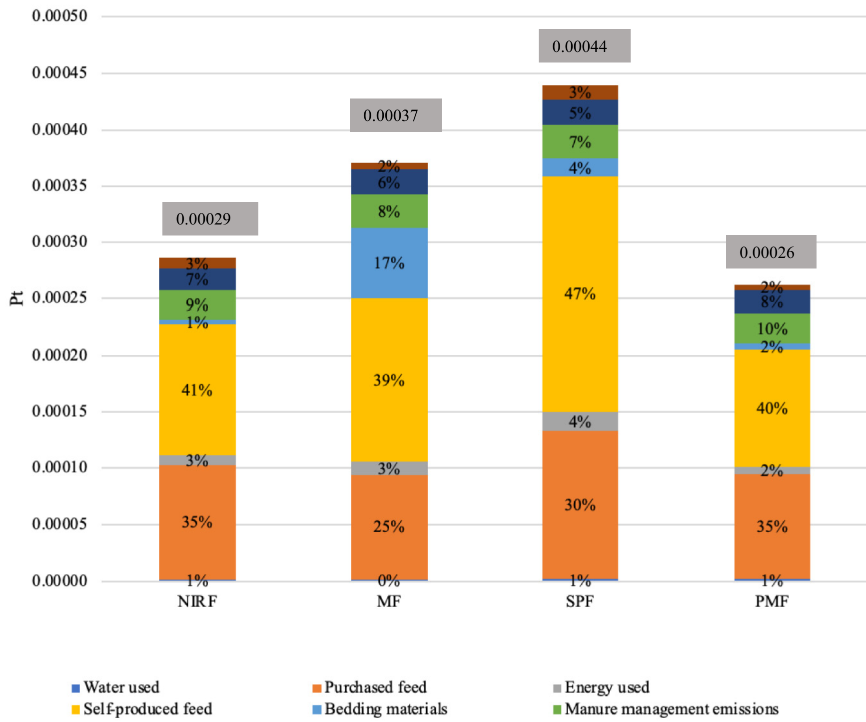


Fig. 4. Process contribution to the total score for each farm system considered.
Abbreviations: NIRF: North Italy Representative Farms; MF: Mountain Farms; SPF: Small Plain Farms; PMF: Permanent Meadows Farms.
The values in the grey boxes represent the total single score (Pt) for each farm system.

Enteric fermentation emissions accounted for 5 %–8 % of the total impact. This process influenced mostly CC (35 %–40 %) due to methane emissions, confirming literature findings (Berton et al., 2021; Gislon et al., 2020; Guerci et al., 2013a). A factor causative to an increase of fermentation in the cow's rumen is the high quantity of forage in the feed ration (O'Brien et al., 2012), which is less digestible than silage feed (Gislon et al., 2020; Guyader et al., 2017). Indeed, the NIRF system behaved better in terms of enteric fermentation emissions than PMF, which used the highest amount of forage as feed; however, PMF registered fewer emissions than SPF. Even though NIRF and PMF have more animals and hence greater emissions from manure management and enteric fermentation, they registered lower results than the other farm systems. It emerged from the results that one of the benefits of more intensive farming is the lower nitrogen oxides, phosphorus, methane, and ammonia emissions per unit of output.

Impacts derived from the MF system behaved differently compared to the other farms. Bedding materials emissions was one of the smallest processes for all farm systems except for MF, where it was the third impacting process covering 17 % of the total impact. In MF, the share of bedding materials emissions influenced 39 % M-RD and 38 % A. In fact, this farm system purchased a high quantity of bedding materials, more than double compared to PMF.

Table 4
The most impacting purchased feed for each farm system considered.

Farm system	Purchased feed with the highest impacts	% of the total impact share of purchased feed	Impact category most affected
NIRF	– Compound feed lactating cows (genetically modified organism)	28	Non-cancer human health effects
	– Corn flour	19	Non-cancer human health effects
	– Corn silage	9	Non-cancer human health effects
	– Sorghum silage	6	Ecotoxicity freshwater
	– Soybean meal dehulled	6	Climate change
MF	– Compound feed lactating cows	65	Non-cancer human health effects
	– Corn flakes	18	Ecotoxicity freshwater
	– Compound feed heifers/young heifers/dry cows	7	Non-cancer human health effects
	– Alfalfa	6	Land use
	– Milk powder	3	Non-cancer human health effects
SPF	– Compound feed lactating cows (genetically modified organism)	27	Non-cancer human health effects
	– Corn silage	24	Non-cancer human health effects
	– Corn flour	19	Non-cancer human health effects
	– Soybean meal dehulled	16	Climate change
	– Dehulled sunflower flour	4	Ecotoxicity freshwater
PMF	– Compound feed lactating cows (genetically modified organism)	48	Non-cancer human health effects
	– Corn flour	24	Non-cancer human health effects
	– Corn flakes	12	Ecotoxicity freshwater
	– Compound feed calves	6	Non-cancer human health effects
	– Compound feed lactating cows	6	Non-cancer human health effects

Abbreviations: NIRF: North Italy Representative Farms; MF: Mountain Farms; SPF: Small Plain Farms; PMF: Permanent Meadows Farms.

Finally, bedding materials emissions, water used, energy used, and animal housing emissions processes accounted only for 1 %–4 % for all the farm systems, being negligible phases in this context.

It is important to highlight that self-produced and purchased feed are intrinsically interrelated. For example, large quantities of corn self-production also affect purchased feed since, as explained by Battini et al. (2016), corn silage has less protein than permanent meadows, leading to a great external dependence on protein ingredients, in particular soybean meal. Due to its cultivation, soybean considerably influences carbon dioxide emissions, affecting CC-LTU and transportation since it primarily originates from South America (Bava et al., 2018). Indeed, the soybean production process of this study (EF 2.0 dataset) has a global reference, while the use of Italian soybean would have had a lower impact (Froldi et al., 2022a). Therefore, while feed efficiency is an important parameter for increasing farm productivity, improving feed composition and ration balance, it could be equally strategic to minimise emissions. This is in line with Battini et al. (2016) and Lovarelli et al. (2019), who proposed using home-grown crops, choosing more sustainable purchased feed, and switching from imported soybean to local protein crops such as sunflower. On the other hand, a decrease in artificial fertilisers and pesticides could have a role in improving environmental performance, as for MF and PMF systems similarly. The feed management system is one of the critical aspects distinguishing SPF and NIRF from PMF, and it should receive the main attention. As highlighted by this paper and confirming Froldi et al. (2022b), farmers' choices in crop systems and land management finally affect the impact of on-farm and off-farm feed production. However, since changes in the home-grown feed are challenging for farms following Grana Padano specifications and regulations, and a switch to permanent meadows is not feasible for all the farms visited due to lack of land space and time, a deeper evaluation should be done in purchased feed context.

4. Conclusion

Grana Padano is one of the most famous PDO cheeses in the world, hence, it becomes crucial to improve its environmental sustainability. Being PDO-labelled can already guarantee socio-economic sustainability in rural areas. Additionally, the presence of the Consortium can foster environmental practices by establishing sustainable practices for all actors in the supply chain.

In the present study, the environmental impacts of four distinct farm systems were evaluated to determine the most sustainable farm management systems utilised to produce milk required for Grana Padano cheese production. In total, 70 farms were classified based on geographical position, feed management choices, herd size and productivity in North Italy Representative Farms, Mountain Farms, and Small Plain Farms, similar for herd size and milk productivity to Mountain Farms, and Permanent Meadows Farms.

The study results indicated the Dairy Farm phase as the most impacting phase for cheese manufacture, covering on average 95 % of the total cheese environmental impacts, therefore, mitigation measures should be focused on the dairy farm level. The outcomes obtained from the Dairy Farm phase assessment showed high variability among farm systems due to differences in farm characteristics. However, it emerged that Permanent Meadows Farms could have an overall lower environmental impact, which was explained by the low quantity of input (such as the lack of silage, protein ingredients, and artificial fertilisers) for high dairy efficiency. On the contrary, Small Plain Farms resulted to be the worst dairy management system due to higher resource use, lower milk output and dairy efficiency. Consequently, it would become advantageous to promote hay milk from an environmental perspective and, based on the literature, from a marketing one as well.

Self-produced and purchased feed were the main hotspot processes at the Dairy Farm level for all the farm systems, covering 64 %–77 % of the total impacts, with self-produced feed being the most impacting (39 %–47 %). A focus on purchased feed revealed that compound feed lactating cows was the most impactful feed for every farm system. At the same time, silage and soybean meal increased the total feed purchase impact by 25 %–40 %, primarily affecting HT-NC, FWE, and CC. Hence, the main attention should be on feed management choices, focusing on the importance of feed composition and ratio balance in protein and fibre content and feed yield.

However, the study has some limitations that must be considered in future research. The work was performed following the PEF methodology, which requires specific criteria defined in the PEFCR. The EF method for WRD only considers country scale level, excluding the use of characterisation factors at watershed levels and the distinction between agricultural and non-agricultural water use. Moreover, the PEF and, in general, Life Cycle Assessment methodologies evaluate only detrimental environmental impacts and exclude from the analysis the evaluation of environmental benefits, such as the effect on biodiversity, the carbon sequestration, and do not consider nutritional and organoleptic aspects. Indeed, due to a lack of scientific consensus on indicators and statistical data, they do not capture the complete range of impacts and benefits on biodiversity. Biodiversity and carbon sequestration considerations would have been significant due to their positive effect on the environment, mainly in dairy farm systems, including rural, mountain, and permanent meadows. Additionally, the inclusion of organoleptic proprieties of cheese in the definition of the functional unit, which is currently based solely on qualitative characteristics of milk, could lead to different results.

Therefore, further in-depth evaluations of various feed management practices at dairy farms and permanent meadows farms focus are necessary, considering the present study an important start. As highlighted by this work, there are still margins for the dairy industry to improve to fulfil the European Commission's ambitious green transformation objectives while also responding to the requests of increasingly aware consumers and a constantly growing market.

CRediT authorship contribution statement

Giulia Rencricca: Writing- Original draft preparation, Data Curation, Visualization, and Investigation. Federico Froldi: Writing-Reviewing and Editing, Software, Investigation, Data Curation. Marco Trevisan: Visualization, Investigation. Maurizio Moschini: Visualization, Investigation. Sami Ghnimi: Writing- Reviewing and Editing. Lucrezia Lamastra: Writing- Reviewing and Editing, Conceptualization, Methodology, Formal analysis, Supervision.

Declaration of competing interest

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

Acknowledgements

Work carried out within the LIFE TTGG Project (LIFE 16 ENV/IT/000225) with EU contribution.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2023.02.012.

References

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, 421–435.

Battini, F., Agostini, A., Tabaglio, V., Amaducci, S., 2016. Environmental impacts of different dairy farming systems in the Po Valley. J. Clean. Prod. 112, 91–102. https://doi.org/10.1016/j.jclepro.2015.09.062.

Bava, L., Bacenetti, J., Gislon, G., Pellegrino, L., D'Incecco, P., Sandrucci, A., Tamburini, A., Fiala, M., Zucali, M., 2018. Impact assessment of traditional food manufacturing: the case of Grana Padano cheese. Sci. Total Environ. 626, 1200–1209. https://doi.org/10.1016/j.scitotenv.2018.01.143.

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.

Berton, M., Bovolenta, S., Corazzin, M., Gallo, L., Pinterits, S., Ramanzin, M., Ressi, W., Spigarelli, C., Zuliani, A., Sturaro, E., 2021. Environmental impacts of milk production and processing in the Eastern Alps: a "cradle-to-dairy gate" LCA approach. J. Clean. Prod. 303, 127056.

Canellada, F., Laca, A., Laca, A., Díaz, M., 2018. Environmental impact of cheese production: a case study of a small-scale factory in southern Europe and global overview of carbon footprint. Sci. Total Environ. 635, 167–177.

CLAL, 2022. Italy: Grana Padano Cheese Production. (Accessed 10.10.22) https://www.clal.it/en/index.php?section=produzioni_grana.

Dalla Riva, A., Burek, J., Kim, D., Thoma, G., Cassandro, M., De Marchi, M., 2018. The environmental analysis of asiago PDO cheese: a case study from farm gate-to-plant gate. Ital. J. Anim. Sci. 17 (1), 250–262.

EDA, 2018. The European Dairy Association (EDA). Product Environmental Footprint Category Rules for Dairy Products. https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR-DairyProducts_2018-04-25_V1.pdf.

Egas, D., Ponsá, S., Colon, J., 2020. CalcPEFDairy: a product environmental footprint compliant tool for a tailored assessment of raw milk and dairy products. J. Environ. Manag. 260, 110049. https://doi.org/10.1016/j.jenvman.2019.110049.

European Commission, 2011. Commission Implementing Regulation (EU) No 584/2011 of 17 June 2011 Approving Non-minor Amendments to the Specification for a Name Entered in the Register of Protected Designations of Origin and Protected Geographical Indications Grana Padano (PDO).

European Commission, 2013. COM(2013) 196 final. Building the Single Market for Green Products.

European Union, 2012. Regulation (EU) No. 1151/2012 of the European Parliament and of the Council of 21 November 2012 on quality schemes for agricultural products and foodstuffs. Official Journal of the European Union, L 343, 1–29.

Famiglietti, J., Guerci, M., Proserpio, C., Ravaglia, P., Motta, M., 2019. Development and testing of the product environmental footprint milk tool: a comprehensive LCA tool for dairy products. Sci. Total Environ. 648, 1614–1626. https://doi.org/10.1016/j.scitotenv.2018.08.142.

FAO, GDP, 2018. Climate Change and the Global Dairy Cattle Sector – The Role of the Dairy Sector in a Low-carbon Future.

Faverdin, P., Guyomard, H., Puillet, L., Forslund, A., 2022. Animal board invited review: specialising and intensifying cattle production for better efficiency and less global warming: contrasting results for milk and meat co-production at different scales. Animal 16 (1), 100431.

Finnegan, W., Yan, M., Holden, N.M., Goggins, J., 2018. A review of environmental life cycle assessment studies examining cheese production. International Journal of Life Cycle Assessment 23 (9), 1773–1787. https://doi.org/10.1007/s11367-017-1407-7 Springer Verlag.

Froldi, F., Lamastra, L., Corrado, S., Moschini, M., 2022a. Carbon footprint of raw milk for direct human consumption produced in Po Valley: data input uncertainties and effect on output variance. Environ. Chall. 8, 100536.

Froldi, F., Lamastra, L., Trevisan, M., Mambretti, D., Moschini, M., 2022b. Environmental impacts of cow's milk in northern Italy: effects of farming performance. J. Clean. Prod. 132600.

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G., 2013. Tackling Climate Change Through Livestock – A Global Assessment of Emissions and Mitigation Opportunities. www.fao.org/publications.

Gislon, G., Ferrero, F., Bava, L., Borreani, G., Dal Prà, A., Pacchioli, M.T., Sandrucci, A., Zucali, M., Tabacco, E., 2020. Forage systems and sustainability of milk production: feed efficiency, environmental impacts and soil carbon stocks. J. Clean. Prod. 260, 121012.

González-García, S., Hospido, A., Moreira, M.T., Feijoo, G., Arroja, L., 2013. Environmental life cycle assessment of a Galician cheese: San Simon da Costa. J. Clean. Prod. 52, 253–262.

Goudis, A., Skuras, D., 2020. Consumers' awareness of the EU's protected designations of origin logo. Br. Food 123 (13), 1–18.

Guerci, M., Bava, L., Zucali, M., Sandrucci, A., Penati, C., Tamburini, A., 2013a. Effect of farming strategies on environmental impact of intensive dairy farms in Italy. J. Dairy Res. 80 (3), 300–308.

Guerci, M., Knudsen, M.T., Bava, L., Zucali, M., Schönbach, P., Kristensen, T., 2013b. Parameters affecting the environmental impact of a range of dairy farming systems in Denmark, Germany and Italy. J. Clean. Prod. 54, 133–141. https://doi.org/10.1016/j.jclepro.2013.04.035.

Guerci, M., Bava, L., Zucali, M., Tamburini, A., Sandrucci, A., 2014. Effect of summer grazing on carbon footprint of milk in Italian Alps: a sensitivity approach. J. Clean. Prod. 73, 236–244.

Guyader, J., Little, S., Kröbel, R., Benchaar, C., Beauchemin, K.A., 2017. Comparison of greenhouse gas emissions from corn-and barley-based dairy production systems in eastern Canada. Agric. Syst. 152, 38–46.

Guzmán-Luna, P., Mauricio-Iglesias, M., Flysjö, A., Hospido, A., 2022. Analysing the interaction between the dairy sector and climate change from a life cycle perspective: a review. Trends Food Sci. 126, 168–179.

Hafner, S.D., Howard, C., Muck, R.E., Franco, R.B., Montes, F., Green, P.G., Mitloehner, F., Trabue, S.L., Rotz, C.A., 2013. Emission of volatile organic compounds from silage: compounds, sources, and implications. Atmos. Environ. 77, 827–839.

IDF, 2015. A common carbon footprint approach for the dairy sector. The IDF Guide to Standard Life Cycle Assessment Methodology. International Dairy Federation.

IPCC, 2006. Chapter 11. N2O Emissions from managed soils, and CO2 emissions from lime and urea application. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use pp. 11.1–11.54.

Lorenz, H., Reinsch, T., Hess, S., Taube, F., 2019. Is low-input dairy farming more climate friendly? A meta-analysis of the carbon footprints of different production systems. J. Clean. Prod. 211, 161–170.

Lovarelli, D., Bava, L., Zucali, M., D'imporzano, G., Adani, F., Tamburini, A., Sandrucci, A., 2019. Improvements to dairy farms for environmental sustainability in Grana Padano and Parmigiano Reggiano production systems. Ital. J. Anim. Sci. 18 (1), 1035–1048. https://doi.org/10.1080/1828051X.2019.1611389.

Lovarelli, D., Tamburini, A., Garimberti, S., D'Imporzano, G., Adani, F., 2022. Life cycle assessment of parmigiano reggiano PDO cheese with product environmental footprint method: a case study implementing improved slurry management strategies. Sci. Total Environ. 842, 156856. https://doi.org/10.1016/J.SCITOTENV.2022.156856.

O'Brien, D., Shalloo, L., Patton, J., Buckley, F., Grainger, C., Wallace, M., 2012. A life cycle assessment of seasonal grass-based and confinement dairy farms. Agric. Syst. 107, 33–46. https://doi.org/10.1016/j.agsy.2011.11.004.

Palmieri, N., Pesce, A., Verrascina, M., Perito, M.A., 2021. Market opportunities for Hay Milk: factors influencing perceptions among Italian consumers. Animals 11 (2), 431.

Penati, C.A., Tamburini, A., Bava, L., Zucali, M., Sandrucci, A., 2013. Environmental impact of cow milk production in the central Italian Alps using life cycle assessment. Ital. J. Anim. Sci. 12 (4), e96.

PRé Consultants, 2019. SimaPro 9.0.35, LCA Software.

Rozenberg, S., Body, J.-J., Bruyere, O., Bergmann, P., Brandi, M.L., Cooper, C., Devogelaer, J.-P., Gielen, E., Goemaere, S., Kaufman, J.-M., 2016. Effects of dairy products consumption on health: benefits and beliefs—a commentary from the Belgian Bone Club and the European Society for Clinical and Economic Aspects of osteoporosis, osteoarthritis and musculoskeletal diseases. Calcif. Tissue Int. 98 (1), 1–17.

Sandström, V., Valin, H., Krisztin, T., Havlík, P., Herrero, M., Kastner, T., 2018. The role of trade in the greenhouse gas footprints of EU diets. Glob. Food Secur. 19, 48–55. https://doi.org/10.1016/J.GFS.2018.08.007.

Sturaro, E., Marchiori, E., Cocca, G., Penasa, M., Ramanzin, M., Bittante, G., 2013. Dairy systems in mountainous areas: farm animal biodiversity, milk production and destination, and land use. Livest. Sci. 158 (1–3), 157–168.

Zampori, L., Pant, R., 2019. Suggestions for updating the Product Environmental Footprint (PEF) method. Publications Office of the European Union. https://ec.europa.eu/jrc/en/publication/suggestions-updating-product-environmental-footprint-pef-method.

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.