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Environmental impacts of cow's milk in Northern Italy: Effects of farming performance

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ABSTRACT

A Life Cycle Assessment was conducted on 55 dairy farms located in Northern Italy to investigate the effect of dairy farming performance on the environmental impact of milk production. Feeds used in diet formulation were analyzed for nutrients contents by near-infrared reflectance technique, and the real composition was used to estimate methane emissions from enteric fermentation and manure handling. The functional unit was 1 kg of fat and protein corrected milk at the farm gate. The results were expressed according to the Product Environmental Footprint (PEF) method version 2.0 for 19 impact indicators through SimaPro® software v9.0.35. Five main data categories were considered: water used on the farm, off-farm feeds, energy resources, on-farm feeds, and bedding materials. Dairy farms were ranked into high-, mid-, and low-performing herds according to the average milk yield (>32.6; 25.4–32.6; <25.4 kg milk/cow/d; respectively). Statistical analysis between groups of herds was performed using JMP (JMP® Pro 15.2.0). The environmental impacts of indicators were lower ($P < 0.05$) in high-performing herds compared with low-performing herds and lower ($P < 0.05$) for climate change, climate change-biogenic, climate change-fossil, photochemical ozone formation human health (POCP), and eutrophication terrestrial when compared with mid-performing herds. Similar values among groups were observed for acidification, ionizing radiation human health, and ozone depletion potential indicators. The off-farm and on-farm feeds categories had the highest share of value of impact indicators. The enteric fermentation and manure handling significantly contributed to greenhouse gas emissions, whereas particulate matter formation and POCP were mainly related to barn management. Results from this research could be helpful in the dairy sector through the completeness of the expected impact indicators evaluated by the PEF method.

1. Introduction

The world's demand for animal proteins (meat, milk, and eggs) has increased in recent decades (FAOSTAT, 2016), driven by growing populations and incomes (Opio et al., 2012), resulting in improved quality of life, both socially and economically. Milk contributes to 27% and 10% of the global added value of livestock and agriculture (FAO, 2018), respectively, and it is one of the most produced and valuable agricultural commodities worldwide. According to OECD-FAO (2020), over the next decade (2019–2028), the demand for fresh and processed milk products is expected to increase by 2.1% and 1.5% a year, respectively. However, the dairy production sector is also responsible for a large share of environmental impacts (FAO, 2018), including greenhouse gas emissions (GHG), water resource depletion, land use, nutrients losses in air and water, freshwater and marine eutrophication, freshwater ecotoxicity and acidification (Rial-Lovera et al., 2017).

The life cycle assessment (LCA) is a methodological approach widely used for assessing the environmental impact of products and processes (FAO, 2016) and also for agricultural products from a global perspective (Bacenetti et al., 2015). LCA is based on the ISO 14040 (2006a) and ISO 14044 (2006b) standards establishing the principles, framework, requirements, and guidelines to perform the analysis (Baldini et al., 2018). The dairy industry as processed milk (Bava et al., 2018) or the production of milk (Noya et al., 2018) has been relying on LCA for environmental impacts assessment. FAO (2010) states that the dairy sector (i.e., the production of milk, the processing of milk products, the transport, and the related production of meat as a co-product from dairy farms) is responsible for 4% of the total GHG emissions in the world, 5%

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in EU-25 (Torquati et al., 2015) and 5–6% in EU-27 (Weidema et al., 2008). In Italy, the environmental impact of the dairy supply chain closely resembles the European value, with about 3–5% of total GHG emissions (Dalla Riva et al., 2017). From these, the raw milk production at the farm gate is responsible for the majority of impacts of dairy products, regardless of the adopted production systems (organic, non-organic, or mixed), characteristics of the dairy farm or the processing facility, and the methodological choices made by the LCA practitioners (Egas et al., 2020). Indeed, LCA's studies in the dairy sector were performed adopting different methodological choices, also when in compliance with the ISO 14040 (2006a) and the ISO 14044 (2006b) standards. Thus, differences within studies do not allow for direct comparison among outcomes of similar types of dairy products or similar dairy farm systems producing milk. To overcome the problem, the methodology Product Environmental Footprint (PEF), based on the "2013/179/EU Recommendation" (European Commission, 2013) and the Product Environmental Footprint Category Rules (PEFCR) for dairy products (EDA, 2018) was released. The dairy PEFCR outlines specific emission models, allocation rules and formulas (Circular Footprint Formula and Data Quality Requirements Formula), compliant inputs (in-farm direct emissions, distribution, use and end of life emissions), and parameters (allocation, product usage and storage utilization factors) to be used as inputs in LCA analysis. Independently of the methodological approaches used in the LCA analysis, the main environmental impacts of dairy cattle rearing are due to GHG release, then referring to climate change (CC) and other substances (Meul et al., 2014). The emission profile of animal products, besides the GHG associated with land use and land-use change (LUC), and fuel use, includes nitrous oxide (N_2O) and methane (CH_4) originating from biological processes in soils, manure, and livestock (Henriksson et al., 2014). Livestock breeding is responsible for 14.5% of the total anthropogenic GHG emissions, of which 19.7% are generated by dairy cattle (Gerber et al., 2013). Regional variations according to farming practices, species, rearing system, and allocation support different local contributions of the sector to the total anthropogenic GHG emissions (Philippe and Nicks, 2015), with values ranging from 8 to 18% (Herrero et al., 2015). The enteric fermentation of livestock mostly produces CH_4, while the production of feeds, dung on pastures, manure handling/storage at the farm, and application to soil are related to different types of emissions: N_2O, ammonia (NH_3), and nitrogen oxide (NO_x). These nitrogen-containing substances affect several impact indicators such as climate change, photochemical ozone formation, terrestrial and marine eutrophication, and terrestrial and freshwater acidification (Egas et al., 2019). The enteric CH_4 is largely due to ruminant livestock (Knapp et al., 2014) and globally accounts for 17% of CH_4 and 3.3% of GHG, whereas CH_4 from livestock manure accounts for 2% of CH_4 and 0.4% of GHG (Ammar et al., 2020). In Italy, most of the emissions from agriculture are related to the livestock sector (75%), of which 36.9% refers to dairy cattle, representing in 2016 about 23 million tonnes of CO_2-eq, 5.8% of national GHG (ISPRA, 2018). Nonetheless, in the last 30 years emissions from the livestock sector decreased by 13.4% (ISPRA, 2018) because of good breeding practices (Gislon et al., 2020) and increased production efficiency (Pulina et al., 2011). The number of farms with tied animals decreased over the years, whereas there was a steady upward trend in animal density in the modern high-input intensive dairy farms system (Dalla Marta and Verdi, 2019). Intensification of farming systems leads to increased milk production (Nehring et al., 2016) per unit of farm input (Udo et al., 2011) due to improved farm efficiency and the use of off-farm inputs (Jay and Morad, 2007). Because it reduces the emissions per kg of product (Yan et al., 2013), herd efficiency is relevant for environmental impacts mitigation in dairy farming (Kristensen et al., 2011).

The current study aimed to investigate the environmental impacts of milk produced for Protected Designation of Origin (PDO) cheese-making in dairy farms located in the Po Valley, in Northern Italy, through a careful collection of data up to the farm gate. PDO is characterized by production rules which include feeds allowed in animal feeding and source of feeds (i.e., percentage of homegrown and produced feeds within the PDO boundaries area). In our condition, not less than 50% of the dry matter fed to dairy cows must be from forages, with at least 75% produced within the PDO boundaries area. Animals are milked twice a day, and the milk used in the cheese-making must come from two milkings.

The analysis of environmental performances allows for identifying hotspots that could be helpful in environmental performances interpretation. The study applies the European PEF method. Results could be addressed by the European Dairy Association working table for future PEFCR updates and, because of the completeness of the environmental impact indicators, could represent a model for the dairy sector to follow in the future environmental strategies of the 2030 Agenda.

2. Materials and methods

The study was performed on 55 dairy farms producing milk for PDO hard cheese-making. Collected primary and secondary data were used for inventory data emission creation. LCA (cradle to farm gate) was assessed according to the PEF method developed by the Joint Research Centre (JRC) of the European Commission.

2.1. Functional unit

The functional unit (FU) and its reference flow used to report the results of the PEF method was 1 kg of fat (4%) and protein (3.3% of true protein) corrected milk (FPCM) at farm gate as the final product without heating, cooking or further transformation. The following equation defined by the International Dairy Federation (IDF, 2015) was used to correct milk to fat and protein standard contents:

$$FPCM\ kg/y = raw\ milk\ kg/y \times (0.1226 \times fat\ content\ \% + 0.0776 \times true\ protein\ \% + 0.2534) \quad (1)$$

Raw milk yield, fat and true protein contents were obtained as primary data.

2.2. System boundary and allocation

The system boundary for the raw milk at the farm gate included processes for farm activities related to milk production, for on-farm and off-farm feeds production (Fig. 1). The main categories of inputs were water and energy and resources (i.e., electricity, diesel, methane, liquid petroleum gas), purchase of feeds (i.e., concentrates, fodders and silages, cereals, proteic feeds), purchase of bedding materials (i.e., straw, corn stalks, sawdust), purchase of productive agricultural factors required for on-farm feeds production (seeds, fertilizers, pesticides). The produced manure from animal breeding was considered according to their handling. The manure leaving the farm (without remuneration) was not considered a co-product (EDA, 2018). Information used for sold on-farm feed production (i.e., diesel, pesticides, and chemicals) was collected but not considered to avoid further allocations to the farming system, as suggested by IDF guidelines (2015). The allocation followed a biophysical approach. It was based on milk, and the meat (i.e., culled cows, male and surplus females, sold either just after birth or in a more advanced stage of growth) was considered a co-product or secondary output.

2.3. Life cycle inventory

All the inputs and outputs have been considered according to the PEF methodology. Primary activity data regarding inputs (supplies and consumables) and outputs (products, co-products, and emissions) were collected and modeled to achieve a proper life cycle inventory (LCI) for all the considered activities (Table 1).

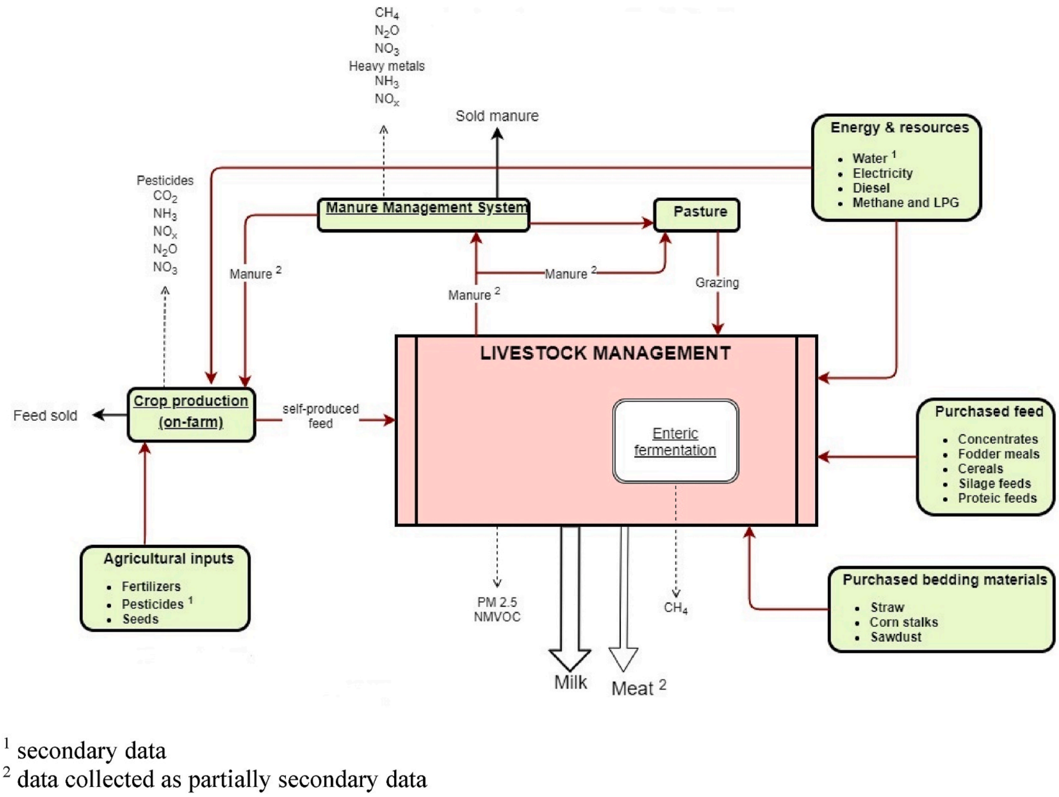

Fig. 1. System boundary scheme considered for dairy farm.

The same operator filled out a questionnaire during the farm visit (one each) for one year's primary data recording (Table 2). The primary data collected were on the farm complex: animal housing (tie *vs.* loose), manure type (slurry *vs.* solid) and management of storage (covered *vs.* uncovered tank), herd composition (breed and number of animals in each growing and productive phase), animal feeding (feeds provided as total mixed ration (TMR) *vs.* conventional feeding), feeds used in animal feeding (on-farm grown feeds *vs.* purchased feeds). In addition, data on supplies consumed during farm activities to produce on-farm feeds (seeds, fertilizers, pesticides, chemical products, energy, and water consumption) and the quantity of purchased feeds were collected (Table 1). Capital goods, i.e., stables and machinery, were not considered as inputs, as well as inputs relating to packaging materials for purchased products, plastic for silage preparation, detergents, drugs, and refrigerants.

The quantities of raw milk and co-products (produced meat, sold slurry and manure, sold feed) were also included in LCI. The farms' milk production for the survey period was obtained from the farm register, then verified with records on milk delivery to the dairy cheese-making cooperative. The herd composition was an average of the animal's presence over the survey year. It was obtained from the herd register for the following category of animals: lactating cows, dry cows, heifers (from 12 months of age to first calving), young heifers (from weaning to 12 months of age), calves (from birth until weaning). Data collected were integrated with secondary data for missing information.

The diet composition was recorded for each category of animals, and feed intake was estimated based on animal requirements. The on-farm feeds were sampled during the day of the visit: silage fodder (corn, sorghum, wheat), hay (alfalfa, cereal mix, ryegrass, meadow hay), cereal flours (corn, wheat, barley). Additional TMR samples were also collected for each category of animals. The dry matter (DM) content of collected feeds and TMR was measured after drying samples in a ventilated oven at 65 °C for 48 h (AOAC International, 2000, DM: method no. 930.15). Then, dried samples were ground (Fritsch Pulverisette 19 mill) to 0.5 mm and stored for subsequent analysis by near-infrared reflectance technique (NIR; FOSS NIRsystem 5000) for nutrients content determination.

The nutritional properties of diets were evaluated using a formulation software (Razio-Best v560) with animals nutrients requirements estimated according to the Cornell Net Carbohydrate and Protein System (CNCPS) models. The CNCPS is a mathematical and evolving model (Fox et al., 2004) that calculates cattle requirements and nutrients supply based on animal size and age, environmental condition, and composition of feeds used in diet formulation, and it can be adapted to different production situations. Tabulated feeds' compositions were replaced by the NIR measures for on-farm produced feeds. The analytical components reported on the illustrative labels collected in each dairy farm were used for off-farm feeds, trace mineral and vitamin supplements. When not available, tabulated values were used. Eight standard concentrate formulations (one for each category of animals bred, plus one for lactating cows, dry cows-heifers-young heifers, and heifers-young heifers-calves) were remodeled using the formulation software (Razio-Best v560) according to the ingredient's presence in the feedstuffs and their nutritional characteristics. The considered nutritional characteristics (as a percentage of DM) were crude protein, fats, ash, starch, sugars, neutral detergent fiber, acid detergent fiber, and acid detergent lignin. The diet evaluation also considered structural data like the category of animal bred, the season of reference, type of housing, feeding technology being used, forage quality, use of silages, number of animals bred, live weight of animals in each category of growth, number of days in milk, milk yield and milk quality (fat and protein contents).

The evaluation of the diets based on real feeds composition rather than tabulated values allowed for a tuned estimate of the expected gross energy (GE) intake, digestible energy (DE) of the diet being fed, energy in urine, ash and total volatile solids (VS) of manure. Then, estimates were used to replace the counterpart values proposed by the IPCC 2019 guidelines for calculating CH_4 emissions from enteric fermentation and manure handling (Table 3).

Table 1
Inventory data for the three groups of reference.

	Units	[a]Herds					
		High-performing		Mid-performing		Low-performing	
		Mean	SD	Mean	SD	Mean	SD
Inputs							
Off-farm feeds							
Milk powder	kg farm^{-1} year^{-1}	1851	2847	2354	2926	1994	3125
Alfalfa dry	kg farm^{-1} year^{-1}	73,051	116,548	57,172	57,770	16,135	24,363
Polyphyte hay	kg farm^{-1} year^{-1}	15,775	30,545	40,997	51,946	43,373	119,385
Compound feed	kg farm^{-1} year^{-1}	143,998	209,711	362,685	689,755	70,774	42,293
Corn silage	kg farm^{-1} year^{-1}	81,071	157,664	154,951	341,358	31,279	84,324
Corn flour	kg farm^{-1} year^{-1}	127,524	181,953	128,673	122,970	77,742	93,280
Corn flakes	kg farm^{-1} year^{-1}	436	1630	26,764	85,265	3451	12,911
Wholemeal corn mash	kg farm^{-1} year^{-1}	–	–	37,462	72,144	–	–
Wheat silage	kg farm^{-1} year^{-1}	78,833	226,531	6247	26,464	–	–
Barley flour	kg farm^{-1} year^{-1}	–	–	4773	24,800	–	–
Sorghum silage	kg farm^{-1} year^{-1}	13,116	49,074	–	–	–	–
Soybean meal	kg farm^{-1} year^{-1}	65,270	115,263	61,224	119,913	92,473	95,927
Soy flakes	kg farm^{-1} year^{-1}	8964	33,541	6158	31,997	5403	20,215
Sunflower flour	kg farm^{-1} year^{-1}	–	–	14,467	50,045	9946	21,416
Cotton seeds	kg farm^{-1} year^{-1}	7650	22,123	10,393	32,088	–	–
Beet pulp	kg farm^{-1} year^{-1}	–	–	7348	16,161	1142	4273
and cane molasses	kg farm^{-1} year^{-1}	933	3490	19,408	45,311	–	–
On-farm feeds							
Irrigation water	m^3 farm^{-1} year^{-1}	99,469	96,861	180,927	285,856	107,967	110,925
[b]Chemical fertilizers							
Urea	kg farm^{-1} year^{-1}	1914	2695	4737	9270	2334	5091
Ammonium nitrate (27%)	kg farm^{-1} year^{-1}	147	348	634	852	369	767
NPK (15-15-15)	kg farm^{-1} year^{-1}	91	288	127	413	203	383
NPK (32-0-18)	kg farm^{-1} year^{-1}	19	70	303	1574	–	–
Pesticides							
Fungicides	kg farm^{-1} year^{-1}	55	60	67	104	50	53
Herbicides	kg farm^{-1} year^{-1}	90	89	124	182	99	111
Insecticides	kg farm^{-1} year^{-1}	9	10	11	17	8	9
Seed							
Cereals	kg farm^{-1} year^{-1}	705	943	850	1212	1520	1966
Maize	kg farm^{-1} year^{-1}	472	485	829	1378	611	709
Polyphyte hay	kg farm^{-1} year^{-1}	325	461	385	443	272	331
Sorghum	kg farm^{-1} year^{-1}	19	33	60	158	30	47
Alfalfa	kg farm^{-1} year^{-1}	27	47	37	67	34	39
Energy							
Electricity	kWh farm^{-1} year^{-1}	180,783	198,901	259,297	233,112	126,998	99,272
Diesel	lt farm^{-1} year^{-1}	18,000	16,048	28,018	32,181	19,021	19,752
LPG	lt farm^{-1} year^{-1}	539	1153	1670	6723	437	752
Methane	m^3 farm^{-1} year^{-1}	–	–	67	260	–	–
Water used on the farm	m^3 farm^{-1} year^{-1}	6401	6230	9827	10,462	5761	4283
Bedding materials							
Cereals straw	kg farm^{-1} year^{-1}	75,702	76,876	48,897	55,992	57,780	86,948
Calcium carbonate	kg farm^{-1} year^{-1}	2960	9949	36	188	578	2086
Sawdust	kg farm^{-1} year^{-1}	84	313	3803	10,050	3300	12,349
Woodchips	m^3 farm^{-1} year^{-1}	–	–	4783	22,211	5227	19,559
Outputs							
Liquid manure transfer	m^3 farm^{-1} year^{-1}	1414	2918	7149	29,726	355	966
Solid manure transfer	m^3 farm^{-1} year^{-1}	268	714	258	697	226	443

[a] Herds ranked according to the average milk yield (kg/cow/d): high-performing herds (> 32.6), mid-performing herds (25.4–32.6), low-performing herds (<25.4).
[b] Chemical fertilizers have been expressed as kg of Nitrogen.

The VS excretion was calculated (equation 10.24; IPCC, 2019) for each considered animal category. The GE, DE, and ash values were from the output of the formulation software. The CH_4 emission factor from enteric fermentation was obtained for each livestock category (equation 10.21; IPCC, 2019). The Y_m used was 0.0 for calves, 6.5 for young heifers, heifers, and dry cows, and 6.3 for lactating cows (IPCC, 2019).

The CH_4 emission factor for manure management (equation 10.23; IPCC, 2019) considered a maximum CH_4 production capacity of 0.24 m^3 CH_4 kg^{-1} of VS excreted, with a CH_4 conversion factor for the considered manure management system that accounted for the monthly temperature (°C) and the number of manure removals for the province in which the farm was located.

The IPCC (2019) was also used for direct and indirect N_2O emissions from manure storage, spreading and field fertilization (Table 3); the latter included an estimate for NO_3 emission. The direct and indirect N_2O from mineral fertilizers application and the NO_3 and CO_2 emissions were estimated according to IPCC (2006). The EEA (2013) was applied for NH_3, NO_x emissions from manure management, and $PM_{2.5}$ from animal housing. In contrast, the EEA (2016) was used for NMVOC related to manure spreading and silage. Prasuhn (2006) was the reference for PO_4^- and P from field fertilization, and Freiermuth (2006) was for heavy metals. Other specific references were involved concerning the requirements of the applied methods and formulae for calculating secondary data (Table 3). The impact method used was EF method version 2.0, and the datasets involved were contained in the EF 2.0 database. The processes associated with the activity data, such as emitted substances estimated with the respective methods (Table 3) and data collected (Table 1), were in the Quantis, Thinkstep, Blonck and Ecoinvent nodes.

Table 2
Descriptive characteristics of the analyzed dairy farms.

Characteristics	Units	[a]Herds					
		High-performing		Mid-performing		Low-performing	
		Mean	SD	Mean	SD	Mean	SD
Dairy farm management							
Farms	Number	14		27		14	
Dairy cows	Cows farm $^{-1}$ year $^{-1}$	142	79	177	192	103	71
Dry cows	Cows farm $^{-1}$ year $^{-1}$	23	15	26	28	15	11
Heifers	Cows farm $^{-1}$ year $^{-1}$	66	36	88	98	49	42
[b]Other cattle	Cows farm $^{-1}$ year $^{-1}$	70	36	89	89	51	40
Housing system (dairy cows)	-	Cubicles & full-floor		Cubicles & full- floor		Cubicles & tight stall	
Housing system (dry cows)	-	Cubicles & deep litter		Cubicles & deep litter		Cubicles, deep litter & tight stall	
Housing system (heifers)	-	Cubicles & deep litter		Cubicles, deep litter & slatted floor		Deep litter, slatted floor & tight stall	
[a]Housing system (other cattle)	-	Deep litter		Deep litter		Deep litter	
Holstein Friesian	%	96.0	6	92.4	18	96.2	6
Brown Swiss	%	0.7	3	4.9	17	0.1	1
Red Holstein Friesian	%	0.7	3	0.7	3	1.1	4
Crossbred Holstein Friesian	%	2.6	4	2.0	6	2.6	6
Age at first calving	Months	25	2	25	2	26	2
Average number of lactations	Number	2.3	0	2	0	2.4	2
Average milk production	t FPCM farm $^{-1}$ year $^{-1}$	1959.1	952	1913.6	2117	827.9	643
Average meat production	t meat farm $^{-1}$ year $^{-1}$	33.9	20	39.3	46	18.4	13
Farm arable land	ha	34.2	27	52.7	83	42.5	37
Permanent pastures and meadows	ha	15.6	27	16.5	33	7.4	11
Allocation							
Raw milk	%	90.0	3	88.0	3	85.0	5
Meat co-product	%	10.0	3	12.0	3	15.0	5

[a] Herds ranked according to the average milk yield (kg/cow/d): high-performing herds (> 32.6), mid-performing herds (25.4–32.6), low-performing herds (<25.4).
[b] The category "other cattle" referred to young heifers from weaning to 12 months of age and calves from birth until weaning.

2.4. Life cycle impact assessment

The life cycle impact assessment (LCIA) of on-farm and off-farm resource use and emissions, including enteric fermentation and manure management, was carried out using the commercial SimaPro® software v9.0.0.35 (PRé Consultants, 2019) to estimate the environmental impact on 19 impact indicators for the FU (Zampori and Pant, 2019).

The following impact categories were assessed: acidification (AP, mol H^+-eq), climate change (CC, kg CO_2-eq), climate change-biogenic (CC-biogenic, kg CO_2-eq), climate change fossil (CC-fossil, kg CO_2-eq), climate change - land use and transformation (CC-LTU, kg CO_2-eq), eutrophication - freshwater (F-EP, kg P-eq), ecotoxicity - freshwater (F-ETP, CTUe), resource use - fossils (F-RD, MJ), human toxicity - cancer (HTP-C, CTUh), human toxicity - non cancer (HTP-NC, CTUh), ionizing radiation - human health (IRP, kBq U^{235}-eq), land use (LOP, Pt), eutrophication – marine (M-EP, kg N-eq), resource use - mineral and metals (M-RD, kg Sb-eq), ozone depletion potential (ODP, kg CFC-11-eq), particulate matter formation (PMF, disease inc.), photochemical ozone formation - human health (POCP, kg NMVOC-eq), eutrophication – terrestrial (T-EP, mol N-eq), water scarcity (WRD, m3 deprivation).

2.5. Method for statistical analysis

Dairy farms were ranked based on the average milk yield/cow/d, and groups were created according to the quartile distribution:

- High-performing herds: average milk yield over the third quartile (> 32.6 kg milk/cow/d);
- Mid-performing herds: average milk yield between first and third quartile (25.4–32.6 kg milk/cow/d);
- Low-performing herds: average milk yield lower than the first quartile threshold (<25.4 kg milk/cow/d).

The objective of the ranking was to carry out a statistical analysis between groups of herds for considered impact indicators. To account for the family-wise error, the all pairwise comparison Tukey's honestly significant difference test was used for mean comparisons of normally distributed data. In contrast, the Steel-Dwass all pairs test was performed in a non-parametric analysis when the assumption for normality of data distribution was violated. The latter test allows for pairwise rankings in the presence of unequal samples sizes (Neuhäuser and Bretz, 2001). All statistical analyses were performed using JMP (JMP® Pro 15.2.0), and reported means were considered different for $P < 0.05$.

3. Results

3.1. Characteristics of the farms

The inventory of primary data is reported as average for the three considered groups of herds and allocated to the FU (Table 1). The LCI considered input and outputs. Among the inputs, five main categories were considered: off-farm feeds, on-farm feeds, energy, water used on farms, and bedding materials. The list of feeds within the off-farm feeds category, as well as the contributors of the on-farm feeds for chemical fertilizers, pesticides, and seeds, are the direct consequence of diets being fed to animals. Most of the time, diets included considerable amounts of silages, mainly corn, requiring important use of water for irrigation during the growing phase. The system's outputs were related to manure, either liquid or solid, moved to other farms or anaerobic digestion plants.

The main characteristics of the farms surveyed are reported in Table 2 as the average for the groups of herds. All farms were in a flat area, and animals were kept in open free-stall housing systems, either with cubicles and full-floor or with deep litter. In some farms of low-performing herds, animals were kept in tight stall systems or on a slatted floor. Farms were equipped with artificial ventilation and cooling

Table 3
Emissions estimated, methods used, and their references.

Emissions	Methodology used
Irrigation water	Mekonnen and Hoekstra, 2010; Chapagain and Hoekstra (2004); UNEP, 2016 (AWARE method)
Drinking and cooling water	CRPA (2005)
Cleaning water	Regional Legislative Decree IX/2208
Land occupation & transformation	Koellner et al. (2013)
CH_4 – enteric fermentation	Tier 2 (IPCC, 2019)
CH_4 – storages and pre-treatment	Tier 2 (IPCC, 2019); Regional Legislative Decree X/5171a; Regional Legislative Decree X/5418b; ISPRA, 2017
N_2O – direct – manure storage and fields fertilization[a]	Tier 1 (IPCC, 2019); Regional Legislative Decree X/5171a; Regional Legislative Decree X/5418b
N_2O – direct & indirect – mineral fertilizers application	Tier 1 (IPCC, 2006)
N_2O – indirect – manure spreading[b]	Tier 1 (IPCC, 2019)
N_2O – indirect – manure and fields fertilization[a,c]	Tier 1 (IPCC, 2019); Regional Legislative Decree X/5171a; Regional Legislative Decree X/5418b
NH_3 & NO_x – manure management[d]	Tier 2 (EEA, 2013); Regional Legislative Decree X/5171a; Regional Legislative Decree X/5418b
NH_3 & NO_x – mineral fertilizers application	Tier 2 (EEA, 2016); Ballabio et al. (2019); ISTAT, 2019
PO_4^- – fields fertilization[e]	SALCA-P (Prasuhn, 2006); Regional Legislative Decree X/5171a; Regional Legislative Decree X/5418b
P – fields fertilization[e]	SALCA-P (Prasuhn, 2006); RUSLE2015 method (EDA, 2018)
$PM_{2.5}$ – animal housing	Tier 2 (EEA, 2013); Regional Legislative Decree X/5171a; Regional Legislative Decree X/5418b
NMVOC – animal housing, manure storage & animal grazing	Tier 2 (EEA, 2016); Regional Legislative Decree X/5171a; Regional Legislative Decree X/5418b
NMVOC – manure spreading on fields	Tier 2 (EEA, 2016)
NMVOC – silage storage and usage	Tier 2 (EEA, 2016); Razio-Best v.560
NO_3 – fields fertilization[d]	Tier 1 (IPCC, 2019)
NO_3 – mineral fertilizers application	Tier 1 (IPCC, 2006)
CO_2 – urea fertilization	Tier 1 (IPCC, 2006a)
Cu–Cd–Pd–Zn–Ni–Cr–Hg leaching into groundwater	SALCA method (Freiermuth, 2006); Wolfensberger and Dinkel (1997)
Cu–Cd–Pd–Zn–Ni–Cr–Hg into surfaces water	SALCA method (Freiermuth, 2006); RUSLE2015 method (EDA, 2018)
Cu–Cd–Pd–Zn–Ni–Cr–Hg to agricultural soil	SALCA method (Freiermuth, 2006); Nemecek et al. (2014); Walther et al. (2001); Keller and Desaules (2001)
Pesticides – application to the soil	ISTAT, 2003; ISTAT, 2017; EDA, 2018
CO_2 – fuel combustion[f]	EF method version 2.0 - Thinkstep
Excluded[g]	
CO_2 – application of lime	Data not referring to the sample of dairy farms
CO_2 – peat drainage	Data not referring to the sample of dairy farms
CO_2 – carbon sequestration	Excluded, no land-use change
Refrigerants	Excluded, due to lack of data (EDA, 2018)

[a] Including emissions from pre-treatment and manure/urine excretion on the pasture.
[b] Including emissions from manure application on fields and pasture (due to N leaching).
[c] Emissions relating to N volatilization (NH_3 and NO_x).
[d] Including emissions from manure storage, pre-treatment, and manure/urine excretion on the pasture and fields.
[e] Including emissions from manure application on fields and pasture, artificial fertilizer application.
[f] The amount of fuel used is associated with a specific process of the EF method 2.0.
[g] Substances not affecting the farms involved in the study but whose quantification is foreseen by the PEF method.

systems to ensure animal welfare during the hot season, then avoid drops in the feed intake and milk yield due to body heat build-up. The cows were milked in dedicated milking parlors or on-site for tied stall barns, and the main breed was Holstein Friesian. The average number of lactating dairy cows was different among groups of herds, with the lower value for low-performing herds (103 ± 71), followed by high- (142 ± 79) and mid-performing (177 ± 192) herds. The low-performing herds also scored the lower milk production (827.9 t FPCM farm $^{-1}$ year $^{-1}$) compared to 1959.1 t for high- and 1913.6 t for mid-performing herds. Some farms with tied stall housing and/or farm size dictating some limitation in animal management solutions (i.e., lactating groups) could have contributed to the lower milk production observed for low-performing herds, which could also be a consequence of a lower milk efficiency. The mid-performing herds were from large-sized farms, on average, 52.7 ha of arable land and 16.5 ha of permanent meadows fields, compared to 34.2 and 15.6 ha for high- and 42.5 and 7.4 ha for low-performing herds, respectively. The allocation (milk/meat) was, on average, higher for high- (90% ± 3) compared with mid- (88% ± 3) and low-performing herds (85% ± 5).

3.2. Impact indicator: effect of animal performance in relation to milk yield

The results of the environmental impact assessment of milk production are shown in Table 4. Values were grouped by herd performance and reported as a total for the input of considered emission categories. The standard error of the means was not reported in the table when the normal assumption of the indicator was violated (AP, CC-Biogenic, CC-Fossil, CC-LTU, F-EP, F-ETP, F-RD, HTP-C, IRP, M-EP, M-RD, PMF). In our condition, except for F-ETP being higher ($P < 0.05$), the environmental impact in high-performing herds was lower ($P < 0.05$) compared with low-performing herds and lower ($P < 0.05$) for CC, CC-Biogenic, CC-Fossil, POCP, and T-EP when compared with mid-performing herds. Because of the distribution of impact indicators, a type II error for the test used for means comparison was observed in some conditions. Thus, the adopted test was unable to allocate mid-performing herds properly. Similar values of AP, IRP, and ODP indicators were observed among groups. According to analyzed indicators, results suggest high-performing herds generally had a better environmental performance. Indicator impact share above 50% among considered data categories and within different performing herds suggests environmental hotspots being in the order of importance off-farm feeds, on-farm feed, manure handling, enteric fermentation, and barn management (Fig. 2a, b, 2c). Independently of the different performing herds, the off-farm feed data category was a hotspot for AP, CC-LTU, F-ETP, F-RD, IRP, M-RD, and ODP. In contrast, high- and mid-performing herds also included CC-fossil, F-EP, HTP-C, LOP, M-EP, and PMF indicators.

The on-farm category was a hotspot for the HTP-NC and WRD indicators across the different performing herds, while F-EP and HTP-C were also critical for the low performing herds. The manure handling, the enteric fermentation, and the barn management categories also reported a share higher than 50% for T-EP, CC-Biogenic, and POCP, independently of the herds' performance.

The CH_4 (enteric fermentation, manure handling, processing of off-

Table 4
Characterization results for 1 kg of FPCM produced by farms for considered impact indicators.

Impact indicator	Unit	[a]Herds			SE
		High-performing	Mid-performing	Low-Performing	
(AP) [b]Acidification	mol H^+-eq.	5.30E-03	6.62E-03	6.61E-03	–
(CC) [c]Climate change	kg CO_2-eq.	1.45E+00^{c}	1.81E+00^{b}	2.15E+00^{a}	6.74E-02
(CC-Biogenic) [c]Climate change-biogenic	kg CO_2-eq.	7.89E-01^{c}	9.90E-01^{b}	1.19E+00^{a}	4.38E-02
(CC-Fossil) [b]Climate change fossil	kg CO_2-eq.	4.20E-01^{b}	5.31E-01^{a}	5.90E-01^{a}	–
(CC-LTU) [b]Climate change – land use and transformation	kg CO_2-eq.	2.39E-01^{b}	2.89E-01^{ab}	3.66E-01^{a}	–
(F-EP) [b]Eutrophication, freshwater	kg P-eq.	1.32E-04^{b}	1.67E-04^{ab}	2.12E-04^{a}	–
(F-ETP) [b]Ecotoxicity, freshwater	CTUe	1.05E+01^{a}	8.60E+00^{ab}	9.55E+00^{b}	–
(F-RD) [b]Resource use, fossils	MJ	3.24E+00^{b}	4.06E+00^{ab}	4.36E+00^{a}	–
(HTP-C) [b]Human heath toxicity, cancer effects	CTUh	2.17E-08^{c}	2.75E-08^{bc}	3.37E-08^{a}	–
(HTP-NC) [c]Human heath toxicity, non-cancer effects	CTUh	2.12E-06^{b}	2.68E-06^{b}	3.46E-06^{a}	2.14E-07
(IRP) [b]Ionizing radiation, human health	kBq U^{235}-eq.	1.28E-02	1.60E-02	1.52E-02	–
(LOP) [c]Land use	Pt	1.64E+02^{b}	2.03E+02^{ab}	2.38E+02^{a}	1.20E+01
(M-EP) [b]Eutrophication, marine	kg N-eq.	5.53E-03^{b}	7.03E-03^{ab}	7.28E-03^{a}	–
(M-RD) [b]Resource use, mineral and metals	kg Sb-eq.	2.37E-07^{b}	3.22E-07^{ab}	3.78E-07^{a}	–
(ODP) [c]Ozone depletion potential	kg CFC-11-eq.	6.23E-10	7.37E-10	8.68E-10	7.14E-11
(PMF) [b]Particulate matter formation	disease inc.	5.55E-08^{b}	7.00E-08^{ab}	7.74E-08^{a}	–
(POCP) [c]Photochemical ozone formation, human health	kg NMVOC-eq.	6.83E-03^{c}	8.61E-03^{b}	1.12E-02^{a}	3.03E-04
(T-EP) [c]Eutrophication, terrestrial	mol N-eq.	7.04E-02^{c}	8.96E-02^{b}	1.08E-01^{a}	2.99E-03
(WRD) [c]Water scarcity	m^3 depriv.	4.06E+00^{b}	5.40E+00^{b}	7.38E+00^{a}	4.84E-01

[abc]Means without a common superscript within a row differ ($P < 0.05$).
[a] Herds ranked according to the average milk yield (kg/cow/d): high-performing herds (> 32.6), mid-performing herds (25.4–32.6), low-performing herds (<25.4).
[b] Nonparametric analysis for non-normally distributed data: means comparisons according to Steel-Dwass all Pairs test.
[c] Parametric analysis for normally distributed data: means comparisons according to Tukey HSD test.

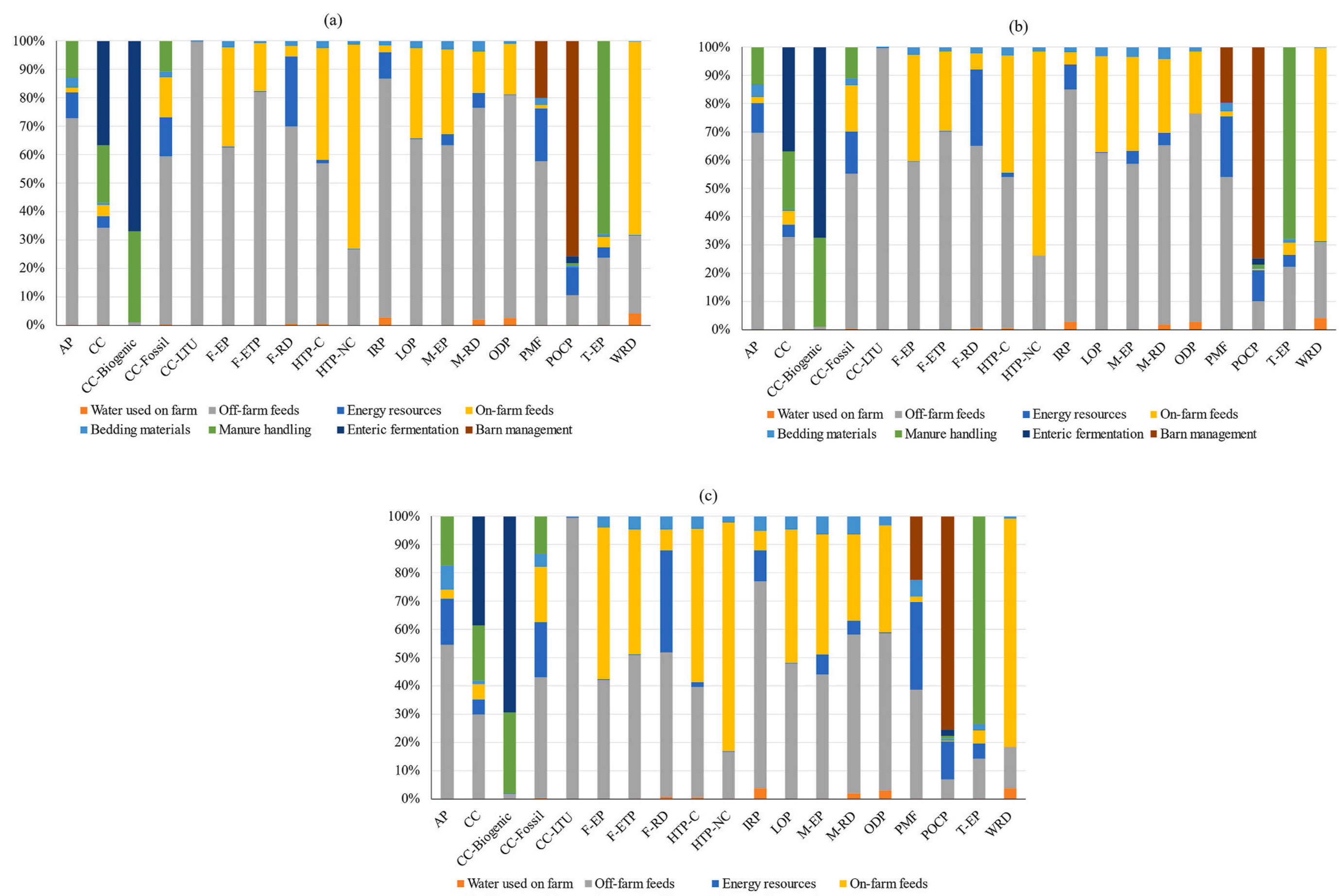

Fig. 2. Analysis of contribution for data categories considered in (a) high-, (b) mid- and (c) low-performing herds.

farm feeds), N_2O (manure management, fertilization of the off-farm feeds), and CO_2 (fossil fuels used for animal feeds production) contributed to CC. The enteric fermentation, off-farm feeds, and manure handling categories had a share of 36, 32, and 20%, respectively. The CH_4 from enteric fermentation (68%) and manure handling (31%) contributed to CC-Biogenic. In contrast, the off-farm feeds category affected CC-Fossil, with the contribution of CO_2 (the machine running on fossil fuels), N_2O (manure and chemical fertilizers spreading), and CH_4 (processing of feeds and compound feeds). Even though the share on CC-Fossil was lower for low-performing herds, because of the higher value of the indicator measured in this group, the absolute value of the off-farm feeds was the greatest. The same category contributed to more than 99% of the CC-LTU as CO_2 emissions from LUC.

The off-farm feeds and the energy resource categories had the higher share of the F-RD, contributing to emissions from energy use such as coal, natural gas, and oil. The resource use, as mineral and metals (M-RD), was mainly due to off-farm and on-farm feeds categories, the latter more pronounced in low-performing herds. Several substances contributed to the indicator, including heavy metals such as cadmium, chromium, copper, lead, and zinc, as well as the metals molybdenum and silver.

The impact indicators for freshwater and marine systems eutrophication behaved similarly. Categories having higher contributions were off-farm and on-farm feeds, the latter being more critical for low-performing herds. Substances affecting the indicators were phosphate (PO_4^{3-}) and phosphorus (P) emissions in freshwater. In contrast, marine eutrophication was mainly related to ammonia (NH_3), nitrate (NO_3), nitrogen dioxide (NO_2), and nitric oxides (NO_x) for off-farm feeds and NO_3 for on-farm feeds. On the other hand, the terrestrial eutrophication indicator (T-EP) was mainly due to emissions from manure handling (i.e., N_2O, CH_4, NO_2, NH_3, NO_x), with a higher share for low-performing herds.

The F-ETP impact indicator was addressed mainly by the off-farm (82% and 51%, respectively, in high- and low-performing herds) and on-farm feeds. The former mainly contributed with substances like alachlor, atrazine, chlorpyrifos, and cyfluthrin, whereas heavy metals such as chromium, copper, and zinc and pesticides such as herbicides, insecticides, and fungicides were related to the on-farm feeds.

The activity of agriculture and related sectors on land use and conversion is estimated by the impact indicator land use occupation (LOP). Off-farm and on-farm feeds explained almost entirely the LOP, with a higher share for off-farm feeds in high- and mid-performing herds and a similar contribution of the source of feeds in low-performing herds having a higher effect on local land use for crop and forage growing.

The PMF impact indicator considers the adverse effect on human health due to emissions of particulate matter (<2.5 μm) and its precursors (NO_x, SO_x, NH_3). Major contributors were off-farm feeds, barn management, and energy resources, the latter being more pronounced in low-performing herds.

The main contribution (>70%) to POCP was from the barn management category, and it was related to the emission of non-methane volatile organic compounds (NMVOC) and particulate matter (<2.5 μm).

In order of importance, the on-farm and off-farm feeds were significant contributors to the HTP-C impact indicator in low-performing herds. In contrast, the reverse was observed for high-performing herds. Heavy metals such as chromium and mercury were among the substances mainly affecting the indicator.

A similar pattern between low- and high-performing herds was also observed for the HTP-NC, an indicator measuring the non-cancer effects on human health. However, for HTP-NC the major contributor was the on-farm feeds category, with heavy metals such as lead, mercury, and zinc as the primary substances with impact.

The on-farm feeds category was also the main contributor to WRD (81%). The technology used for irrigation of crops and volumes of water use were significant factors affecting the impact indicator.

No differences among performing groups were observed for the AP, IRP, and ODP impact indicators, with the off-farm feeds category as the major contributor and a lower share for low-performing herds. The main substances associated with AP were NH_3, NO_2 and SO_2. The emission of Carbon-14 and Radon-22 were substances mainly affecting the IRP impact indicator. In contrast, substances emitted during the production of chemical fertilizers, pesticides, and fossil fuels such as bromotrifluoro-methane (Halon 1301), chlorodifluoro-methane (HCFC-22), dichlorodifluoro-methane (CFC-12), tetrachloro-methane (CFC-10) and trichlorodifluoro-methane (CFC-11) were related to the ODP.

4. Discussion

The LCA analysis carries out a quantitative assessment of impact indicators of a production process (Hauschild et al., 2018). The farm performance for milk production at the farm gate concerning environmental impacts was the focus of the LCA assessment in this study. The PEF method was used to model primary data for environmental assessment of resources usage and emissions in a Spanish (Egas et al., 2020) and an Italian (Famiglietti et al., 2019) dairy supply chain. Animal farming must rely on feeds for animal feeding, either on-farm produced or purchased from the market. Thus, the two main categories affecting impact indicators in our condition were off-farm and on-farm feeds. However, their contribution to indicators was different according to herds' performances. The increase in herd performance evaluated on milk yield/cow means a lower share of the environmental impact for the milk as FU in an LCA analysis. Thus, the more milk produced per cow will account for the decreased emission per FU, and it will improve the sustainability of the farming activity. Besides the amount of milk yield/cow, the herd performance also includes other activities in dairy farming, like management of the feed supply chain, the herd's fertility, and the available arable land for homegrown crops. The nutrient requirements of a producing dairy cow to support milk yield must be met in everyday feeding operations. Carbohydrates and the protein are among the most important nutrients requirements to be satisfied every day with the supplied diet for a lactating dairy cow, and their rate of degradation into the rumen and digestion in the intestine affect CH_4 emission and the nitrogen excreted into manure (Knapp et al., 2014). In conditions where farmers need to increase the supply of nutrients, solutions could be managing available land for second harvesting crops (Havet et al., 2014), improving the performance of homegrown crops, or relying on the market for feeds purchase (Fumagalli et al., 2011). In our conditions, second crops accounted for 31% of the available arable land, of which 77% was maize and 23% sorghum, both grown for silage making. The crop yields, water availability for irrigation, machinery, labor requirements, and general management of the farming activities from land to breeding are among the key factors prompting second crops (Gaudino et al., 2018).

Furthermore, the increased homegrown feeds could reduce inputs such as fossil fuels, pesticides, and chemical fertilizers (Batte, 2000) with improved use of livestock manure (UNECE, 2015). The current European Common Agricultural Policy (CAP) (Bartolini et al., 2020) aims the improvement of soil carbon conservation, ecological focus areas, and crop diversification (Gaudino et al., 2018). In this context, increasing homegrown feeds by the introduction of the second crop could be a valuable opportunity to the emissions related to the agricultural systems for preserving biodiversity in a sustainable agriculture practice (Thénard et al., 2016), and, in our condition, allowed by the PDO rules. Therefore, the need of the farm for forages can affect either the on-farm or the off-farm feed categories within the limitation of the production rules (i.e., source of feed within the boundary of PDO). The farms' available land was similar between high- and low-performing herds, whereas it was 39% higher in mid-performing herds. However, low-performing herds had less land dedicated to permanent grasses and more arable land dedicated to alfalfa. The farmer's choice to address different crops while managing the available land will ultimately affect the share of on-farm and off-farm contributions to feeds used in animal rearing, then on their importance in terms of the hotspot environmental impact indicators involved.

In front of a similar amount of arable land dedicated to annual crops when compared with high-performing herds, low-performing herds had a lower purchase of concentrate and soybean meal. Therefore, it justifies why LOP and CC-Fossil were not outlined as affecting the off-farm feeds category indicators as a hotspot. Moreover, the low milk yield of low-performing herds suggests poorer management of the quality of the feeds and diets being fed to animals leading to higher impacts on investigated indicators.

While the geographical area is important since it could affect some impact indicators differently, in addition to the number of dairy farms investigated and the assessment method being used, the comparison of our results with published work also considered other factors that could affect the values of impact indicators like the completeness and accuracy of the data collection as well as the implementation of a detailed LCI. Results of impact indicators from the analyzed dairy farms (55) partly disagree with previously reported outcomes (Famiglietti et al., 2019). Our results showed lower impact values for the indicators ODP, M-EP, F-ETP, PMF, M-RD, and AP, higher impact values for F-ETP and WRD indicators, and similar CC values (only in high-performing herds) when compared with results reported by Famiglietti et al. (2019). In our sample, higher CC was observed for the mid- and low-performing herds (Table 4). Differences were due to the approach used in modeling primary data when applying the IPCC guidelines method update (2019) to estimate CH_4 emissions from enteric fermentation and manure handling (Table 3).

While energy can be supplied to the animal with carbohydrates, either from forages or grains that, in our conditions, were produced or recruited from the local market, the animal's protein requirement is usually met with proteic feeds without the limitation of the PDO boundaries as the area of production. Less than 1% and 2% of arable land of the considered dairy farms was used for on-farm soybean production, respectively, for mid- and high-performing herds and none for low-performing herds. The affordability of soybean meal for farmers is a critical aspect, leading to the purchase of less costly soybean of non-European origin and grown on land affected by LUC, i.e., soybean meal coming from Argentina (70%), Paraguay (15.8%), and Brazil (6.8%) (Moschini et al., 2018). The use of this soybean in diets for a dairy cow, either directly or as part of concentrates, contributes to increasing the CC indicator (Lovarelli et al., 2019), with different weights of LUC according to the method used (Flysjö et al., 2012), as well as when using characterization factors proposed by EDA (2018). In our condition, the different values of CC-LTU observed among groups were primarily due to feeds purchases and the low milk yield of herds.

Based on our data, the soybean meal was included as input within the boundaries of the considered system, and in relation to its geographical origin (i.e., South America), it affected the LOP with a load of CO_2 emissions from crop production, as also reported in previous studies (Bava et al., 2018). In addition to the off-farm feeds category, our data also support the on-farm feeds as significantly affecting the LOP and the WRD. The latter from irrigation water, with corn as the most impacting on-farm produced feed. Different results for WRD were obtained by Famiglietti et al. (2019), where the bedding materials were the main category contributing to the indicator.

Other research in the dairy sector in Po Valley were conducted involving the cradle-to-grave supply chain approach for which the milk production phase was a fundamental step. Even though the PEF method was not adopted, a numerical comparison for a limited number of impact indicators is still possible. Compared to average data in our conditions, higher values were reported for POCP, AP, F-EP, M-EP, T-EP, and M-RD, whereas lower values were obtained for CC and LOP impact indicators (Lovarelli et al., 2019). Similar (CC, POCP, M-EP) or higher (ODP, PMF, AP, T-EP, F-EP, and M-RD) values were reported by Bava et al. (2018). Battini et al. (2016) and Guerci et al. (2013) investigated a lower number of impact indicators. The former reported values for F-EP, M-EP, and F-RD are similar to what was observed in our conditions, whereas Guerci et al. (2013) obtained a comparable result for the F-RD indicator. In both works, the CC was lower and AP higher than what was calculated in the three groups of herds in our condition.

Our data outlined the off-farm feeds, emissions from enteric fermentation, and manure handling as the most important data categories responsible for the CC, confirming results from a previous work of Lovarelli et al. (2019). A significant contribution was also observed for the energy resources, and on-farm feeds data categories. The substances involved are CH_4, CO_2, and N_2O (Rotz et al., 2010). The off-farm feeds affected CC-Fossil and LTU, as previously reported (Battini et al., 2016), while enteric fermentation and manure handling were involved in CC-Biogenic. The quality of feeds used and the digestibility of diets fed to animals contribute to CH_4 emissions expressed by the CC-Biogenic. The high-performing herds reported a low CO_2-eq per kg of FPCM compared to mid- and low-performing herds. The reduction of enteric CH_4 can be obtained with improved nutrient quality (Van Soest, 1994) and digestibility (Hristov et al., 2013) and increased feed intake (Mertens, 1994) and milk yield (Allen, 2000). As reported by Rotz et al. (2010), the emission of enteric CH_4 depends on feed composition and energy and, when balanced correctly in diet formulation, they maximize the feed intake and milk yield leading to a reduction of CH_4 emission (Hristov et al., 2013). The CH_4 emissions for the enteric fermentation and manure handling (Presumido et al., 2018), the barn management emissions (i.e., the use of silage feeds and bedding materials) (Derwent et al., 1998) also affected the POCP. In our condition, the manure handling in the context of applying manure to the field contributed to terrestrial eutrophication (Fig. 2a, b, 2c).

The nitrogen loss as leaching and P loss to the field from both manure handling practices (storage, manure treatment, and spreading to land) (Prasuhn, 2006) and chemical fertilizers application was responsible for eutrophication potential (IPCC, 2019). In our conditions, F-EP, M-EP, and the ecotoxicity impact indicator F-ETP were affected by the off-farm and on-farm feeds. In particular, the higher value of F-EP in low-performing herds due to on-farm feed might be explained by the management of crop fertilization: the usage of chemical fertilizer in place of manure which requires higher cost/equipment for distribution. The off-farm feeds also affected the AP indicator. Kim et al. (2019) reported that the ammonia emissions from slurry manure applied to the crop field are the major responsible. Indeed, ammonia loss in the atmosphere from livestock production systems leads to the eutrophication of natural ecosystems (Groenestein et al., 2019). The PMF was affected by the off-farm feeds (Baldini et al., 2018); however, the PMF was also affected by the barn management and energy resources in our condition. The animal feeding operations, silage feeds in diets, and straw as bedding material are responsible for air pollutants and contribute to the formation of fine particulate matter ($PM_{2.5}$) (Bava et al., 2018), considered a significant environmental risk to human health (Hristov, 2011).

The off-farm feeds were also the main contributor to M-RD and F-RD indicators. The production and use of fossil fuels in the energy and resource data category affected F-RD (Chobtang et al., 2018). The M-RD addresses non-renewable abiotic natural resources, i.e., minerals and metals (EDA, 2018). For the same indicators, Famiglietti et al. (2019) reported a significant contribution from water use for irrigation and livestock; however, in our conditions, we found similar values for the energy resources category and just a modest contribution of water.

The off-farm feeds also affected the ODP and IRP impact indicators in contrast to Chobtang et al. (2018), for which the largest contribution was due to on-farm feeds. Nevertheless, also our results suggest a substantial contribution of on-farm feeds linked to the usage of pesticides and fossil fuels for feed production and transport.

The HTP-C and HTPC-NC impact indicators were related to the use of chemical and organic fertilizers and pesticides in crop growing (Famiglietti et al., 2019), also supported by our results in which off-farm and on-farm feeds were the main contributors.

4.1. Sensitivity analysis

The methods used for environmental performance evaluation might have different sensitivities to the factors being considered. The IPCC

Table 5
Effect of different methane conversion factors (MCF) on climate change (CC) impact indicator for 1 kg of FPCM produced by farms.

Impact indicator	Unit	[a]Herds			SE
		High-performing	Mid-performing	Low-Performing	
MCF: IPCC 2019 – Tier 2					
(CC) Climate change	kg CO_2-eq.	1.45E+00[c]	1.81E+00[b]	2.15E+00[a]	6.74E-02
(CC-Biogenic) from manure	kg CO_2-eq.	2.51E-01	3.12E-01	3.41E-01	2.72E-02
MCF: IPCC 2019 – Tier 1					
(CC) Climate change	kg CO2-eq.	1.52E+00[c]	1.85E+00[b]	2.24E+00[a]	7.17E-02
(CC-Biogenic) from manure	kg CO_2-eq.	3.19E-01	3.87E-01	4.30E-01	3.13E-02
MCF: IPCC 2006					
(CC) Climate change	kg CO2-eq.	1.32E+00[c]	1.61E+00[b]	1.98E+00[a]	6.36E-02
(CC-Biogenic) from manure	kg CO_2-eq.	1.23E-01	1.49E-01	1.68E-01	1.16E-02

[abc]Means without a common superscript within a row differ ($P < 0.05$).
[a] Herds ranked according to the average milk yield (kg/cow/d): high-performing herds (> 32.6), mid-performing herds (25.4–32.6), low-performing herds (<25.4).

method considered in our work is no exception. Indeed, the MCF values considered did affect the CC indicator, particularly the CC-Biogenic from manure (Table 5). In our condition, the MCF considered detailed information about the number of manure storage emptying per year and the monthly temperature pattern for each dairy farm location. Thus, the MCF values were 2–4% for solid and 26–33% for liquid manure (Annex 10A3; IPCC, 2019). Since the detailed information required by the model are not always available, default values might be used. However, when this was the case, the applied MCF values (4 and 37% for solid and liquid manure, respectively, Table 10.17; IPCC, 2019) obtained, on average, a 25.9% higher value for the CC-biogenic from manure when referred to our modeling (Table 5).

On the contrary, a 51.3% lower CC-biogenic from manure was estimated when applying the previous IPCC guidelines (2006) (i.e., MCF values of 2 and 14% for solid and liquid manure, respectively, Table 10.17; IPCC, 2006). These findings show a higher contribution of manure to the CC impact indicator estimated according to the IPCC guidelines method update (2019) and suggest primary data should always be pursued for assessing this indicator because the contribution of manure handling might be relevant in differently performing herds. In addition to a careful estimation of CH_4 emission from manure, the CH_4 from enteric fermentation should also be modeled. There are no models considering different enteric CH_4 contributions from rumen fermentation kinetics related to the quality of diets fed to animals. A Y_m coefficient based on GE intake is applied for CC estimate, missing quantification of the CH_4 loss from the rumen. In our condition, on-farm feeds entering the diets were characterized for nutrient composition, and diets' digestibility was modeled accordingly for an accurate estimate of undigested organic matter voided with feces. Then, a neat estimate of CH_4 loss from manure was pursued based on the actual contribution of animal categories to manure VS.

5. Conclusion

The environmental impact of milk produced for PDO hard cheesemaking was investigated on farms in Northern Italy. Farms were stratified according to their performance on milk yield in high-, mid-, and low-performing herds, and the environmental impact was evaluated according to 19 impact indicators. The high-performing herds had a lower environmental impact than low-performing ones for 16 of the considered indicators and 5 when compared with mid-performing ones.

The off-farm and on-farm feeds were hotspots affecting most of the considered indicators. A significant contribution to the CC indicator was from enteric fermentation and manure management, while PMF and POCP were affected by barn management activities.

The low- and mid-performing herds seemed to rely more on the market for off-farm feeds and technical inputs related to agriculture, such as irrigation water and chemical fertilizers.

The high degree of specialization of the dairy farm and proper management allowed for high milk yield and reduced the environmental impact on the FU. Even though the environmental burden of some off-farm feeds used in high-performing herds, our results support the efficiency of livestock farming as an opportunity for food and environmental sustainability and for the growing consumer demands for environmental responsibility.

CRediT authorship contribution statement

Federico Froldi: Writing – original draft, preparation, Data curation, Visualization, Investigation. **Lucrezia Lamastra:** Writing – review & editing, Conceptualization, Methodology. **Marco Trevisan:** Visualization, Investigation. **Denise Mambretti:** Investigation, Data curation. **Maurizio Moschini:** Conceptualization, Methodology, Writing – review & editing, 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.

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Appendix A. Supplementary data

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