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LCA to Estimate the Environmental Impact of Dairy Farms: A Case Study

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Abstract: Intensive farming is responsible for extreme environmental impacts under different aspects, among which global warming represents a major reason of concern. This is a quantitative problem linked to the farm size and a qualitative one, depending on farming methods and land management. The dairy sector is particularly relevant in terms of environmental impact, and new approaches to meeting sustainability goals at a global scale while meeting society's needs are necessary. The present study was carried out to assess the environmental impact of dairy cattle farms based on a life cycle assessment (LCA) model applied to a case study. These preliminary results show the possibility of identifying the most relevant impacts in terms of supplied products, such as animal feed and plastic packaging, accounting for 19% and 15% of impacts, respectively, and processes, in terms of energy and fuel consumption, accounting for 53% of impacts overall. In particular, the local consumption of fossil fuels for operations within the farm represents the most relevant item of impact, with a small margin for improvement. On the other hand, remarkable opportunities to reduce the impact can be outlined from the perspective of stronger partnerships with suppliers to promote the circularity of packaging and the sourcing of animal feed. Future studies may include the impact of drug administration and the analysis of social aspects of LCA.

Keywords: LCA; climate change; agro-livestock sector; GHG emissions; dairy farming

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1. Introduction

Climate change, described as the long-term heating of our planet caused by human activities since the pre-industrial period, is among the main challenges on a global scale [1]. As it is well known, one of the main causes of increasing temperatures is greenhouse gas (GHG) emissions in the atmosphere.

GHG concentration affects the global temperature by absorbing strongly radiant electromagnetic energy at wavelengths capable of emitting quantities of elevated heat [2].

According to their global warming potential, the main gases responsible for the greenhouse effect are methane, carbon dioxide, used as a reference for the phenomenon, water vapor, and nitrous oxide, each with different global warming potential and specific sources. Methane, for example, is about 21 times more efficient in trapping heat in the atmosphere compared to CO_2, while nitrous oxide is 296 times more efficient, with persistence in the atmosphere for up to 114 years [3]).

The agro-livestock sector is responsible for a relevant share of these gases due to direct and indirect emissions, accounting for about 17% of the global GHG emissions in 2018 [4].

In addition to the release of GHG into the atmosphere, farming contributes in part to the worsening of air quality through the production of mainly nitrogen compounds from manure, particulates obtained from combustion, and volatile organic compounds other than methane (NMVOC), carbon black (BC), heavy metals (i.e., chromium, copper, nickel, selenium, zinc, lead, cadmium, mercury), dioxins, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), hexachlorobenzene (HCB), and of particulates, both less than 10 microns (PM_{10}) and 2.5 microns ($PM_{2.5}$), deriving from several farm-level operations [5].

Livestock production has a significant environmental impact as it affects several natural resources, including land and soil, water, air, and biodiversity. Nevertheless, growing populations and economics have led to increased demand for animal products and the consequent expansion of the livestock sector over the past decades. At the same time, in developed countries, consumers demand animal products that are both animal welfare- and environment-friendly [3].

In 2019, world milk production grew to about 852 Mt and was forecast to grow at 1.6% per year over the next decade, faster than most other main agricultural products [6]. Globally, cattle are the largest contributors to total livestock greenhouse gas (GHG) emissions, producing about 65% (4.6 Gt CO_2eq annually) of sector emissions, with milk production contributing 20% of total sector emissions [7]. Besides direct emissions, livestock systems are responsible for indirect emissions arising from land-use change, fertilizer use, energy, and transport emissions related to livestock operations and supply chains [8]. The three largest sources of GHG from milk production are emissions from manure management (CH_4 and N_2O), emissions from feed production, processing, and transport (CO_2 and N_2O), and emissions from enteric fermentation (CH_4), the latter accounting for more than half the total of emissions [9].

Although absolute emissions from the dairy sector have increased in the last decades due to production growth in response to the increasing demand, dairy farming is becoming more efficient considering that emissions per unit of product are decreasing [8].

Strategies to reduce GHG emissions include changes in feeding, breeding, and management practices, which essentially lead to the intensification of livestock farming. Strategies that aim to increase productivity are very promising ways to reduce environmental impact; however, in most cases, they are likely to negatively impact animal welfare. For example, intensive housing conditions increase the risk of social stress or hinder the expression of natural behavior [10].

The rising GHG emissions require shifting production systems toward carbon neutrality in order to take action to combat climate change and its impacts, which is one of the United Nations 2030 agenda for sustainable development goals (SDG 13). Moreover, sustainable food production systems and resilient agricultural practices are among the targets to achieve the "zero hunger" goal (SDG 2) and to promote new consumption and production models (SDG 12) by changing the way we produce and consume, mainly in the agri-food sector where these elements are so close, in the farm-to-fork perspective. At the same time, progress toward the sustainable use of natural resources is key to protecting biodiversity and ecosystems (SDG 15). Improving animal health and welfare and reducing GHG emissions through new farming techniques to meet societal demands on safe and sustainable food and contribute to climate change mitigation are among the nine key objectives of the 2023–2027 European common agricultural policy.

The relationship between livestock production and climate change is two-sided. Climate change, deriving from global warming, adversely impacts livestock production, with direct effects on animal health, reproductive efficiency, production performances, and behavior, but also indirect effects deriving from changes in the quality and quantity of feed, water availability, ecosystem alterations leading to changes in the biology and distribution of pathogens and vector-borne diseases [11]. An increase in temperatures negatively affects milk production, especially in cows with higher milk yield and milk quality, with a reduction in casein content [12].

Dairy cattle production systems need to adapt to climate change, but, on the other hand, they must commit to contributing to GHG reduction targets and minimize other negative environmental impacts while continuing to meet society's needs. Agriculture is estimated to generate 11% of all global emissions [13], and dairy farm contribution to the overall impact of milk products is almost as high as 72% [14]. A special focus on this production phase is required to meet the global goals.

The dairy sector is an extremely complex system with numerous interacting components; consequently, determining the best strategies to reduce GHG emissions will depend on each farm's local conditions and objectives. Therefore, a deeper understanding of the underlying driving factors of dairy cattle farming environmental impact is highly relevant to support strategies for limiting adverse effects on the environment and protecting the livestock sector [15].

Studies on the environmental impact assessment of dairy products have increased dramatically in the last decade and have been reviewed by several authors [16–21]. The main goals of these studies were either to assess the potential environmental impact of the product [22–25] or to compare different management systems [26–28]. However, very few of these have focused on Italian production systems [29–32] and even less on Italian Protected Designation of Origin (PDO) dairy products (e.g., Parmigiano Reggiano, Grana Padano) [33]. In Italy, milk production is concentrated in the northern plain regions, characterized by little rain during summer and a highly urbanized territory with low availability of agricultural land; cattle are kept mostly indoors, and maize silage is the main forage crop. Moreover, PDO product specifications impose restrictions on management strategies, sourcing, and type of animal feed.

Considering the peculiarity of the environmental conditions and farming practices, this study aimed to set up an LCA model specific for intensive dairy cattle farms involved in PDO production in Northern Italy. We aimed to evaluate the most relevant items of environmental impact triggered by this activity, considering its ability to impair animal health and welfare. To this end, a preliminary assessment was performed on a dairy cattle farm in the Emilia-Romagna region in Italy. The LCA model was realized using Simapro 8.5.1, including farm processes and main supplies, in terms of animal feed and end-of-life processes of the most relevant waste flows.

With the ultimate aim of integrating farm environmental impact and animal health and welfare, an interdisciplinary research approach combining engineering and veterinary expertise was carried out to evaluate farms operating conditions in terms of animal management and welfare, and specifically, to assess environmental impacts based on an LCA approach [34]. This approach offers grounds for future research and development of targeted sustainability strategies in the sector, specific to the studied geographical area, with a concrete possibility of application in the field.

2. Materials and Methods

The following sections report a detailed description of the site of the study (Section 2.1) and the conceptual model developed for the implementation of LCA (Section 2.2).

2.1. Site Description

The present study was carried out on an Italian dairy cattle farm producing Parmigiano Reggiano and soft cheeses in the Emilia Romagna Region.

Prior to the farm visit, a form for primary data collection was designed. During the farm visit (July 2020), data were collected on paper and subsequently transferred to Microsoft® Excel files. Data sources included the farm management software records, information collected by interviewing the farmer, and invoices.

For data that could not be collected on-farm, default values were defined based on processes available on Ecoinvent v.3.5 [35], with geographical reference to the European context, where possible, or Italian specific data, as in the case of the electricity production mix.

Information on farm size, number of animals, productivity, animal welfare, drug use, feed management, water consumption, fuel consumption, electric energy, manure management, and plastic waste were collected (as summarized in Table 1). It was not possible to quantify the use of chemical fertilizers and bedding material.

Table 1. Farm-specific primary data used to design the conceptual model for the assessment.

Category	Farm-Specific Information	Data
Farm size	Site A	2 ha
	Site B	0.5 ha
	Site C	1 ha
	Site D	1.9 ha
	Cropland	560 ha
Average number of animals	Milking cows	564
	Dry cows	84
	Replacements	622
	Calves	97
	Bulls	1
Animal turnover	Replacement rate	35%
	Longevity	2.5 deliveries
	Adult mortality	3%
	Calf mortality	1.87%
Productivity data	Annual milk production	66,000 quintals
Bought-in feed (source in brackets)	Sunflower seeds (Black Sea)	191,094 kg
	Soybean (Modena province)	9148 kg
	Maize (Modena province)	181,598 kg
	Protein feed (Cremona province)	22,042 kg
Water consumption (annual)	Drinking water	27,963,555.20 L
	Cooling water	72,000 L
Fuel consumption (annual)	Agricultural e livestock farming machines	181,995 L
Electric energy (annual)	Ventilation system	141,849 kWh
	Other operations	516,844 kWh
Manure management	Palatable slurry storage	6 tanks (12,667 m^3)
		3 cesspits (1001 m^3)
	Non-palatable slurry storage	9 open pits (12,229 m^3)
Plastic waste	Plastic wrapping and cleaning product containers	163,900 kg

The farm is structured in four sites, located between Bologna and Modena provinces. Site A hosted calves and replacements up to 5 months of age, pregnant heifers (from two months pregnancy to delivery), and dry cows. Replacements from 5 months of age to the first month of pregnancy were hosted in site B. Site C hosted mostly primiparous milking cows, and site D hosted mostly multiparous milking cows. Animals are moved from site A to site C or D twice a week and from site A to site B twice a month.

The most represented breed was Holstein Friesian, but Italian Red Pied, Jersey, and Montbéliarde x Swedish Red and White crossbreds were also present.

Average daily milk production amounts to 35.15 kg for multiparous cows and 30.15 kg for primiparous cows. The milk is destined to produce Parmigiano Reggiano.

Cows are loose housed on deep litter with straw bedding (dry cows and heifers) or in pens with cubicles covered with sand (milking cows). Dry cows and heifers have access to external exercise areas. The facilities are equipped with ventilation systems consisting of ceiling fans for the resting areas and horizontal flow fans for the feeding zones. The waiting parlor is equipped with a ceiling fan and water sprayers.

Calves up to one month of age are reared in individual pens and then moved to group pens. They are fed through an automatic calf feeder and weaned at 70 days of age.

Site C and site D scored 70.33/100 and 71.31/100, respectively, for animal welfare in 2018, as certified by the Italian National Reference Center for Animal Welfare (CReNBA).

The diet consists of 60% fodder and 40% concentrates. Fodder (alfa-alfa, grass hay) and part of sorghum are self-produced; the other feeds are bought in. Given the production requirements for Parmigiano Reggiano, corn silage is only fed to heifers (site B). Daily average dry matter intake is 25 kg for milking cows, 15 kg for dry cows and pregnant heifers, and 8 kg for replacements.

The water comes from the aqueduct. Site C was also supplied from a well, but it was not possible to quantify the water used. There is no water recycling system in place.

The slurry is spread on the farm's land intended for fodder production (470 ha). Figure 1 reports the data collection at the basis of the conceptual model definition.

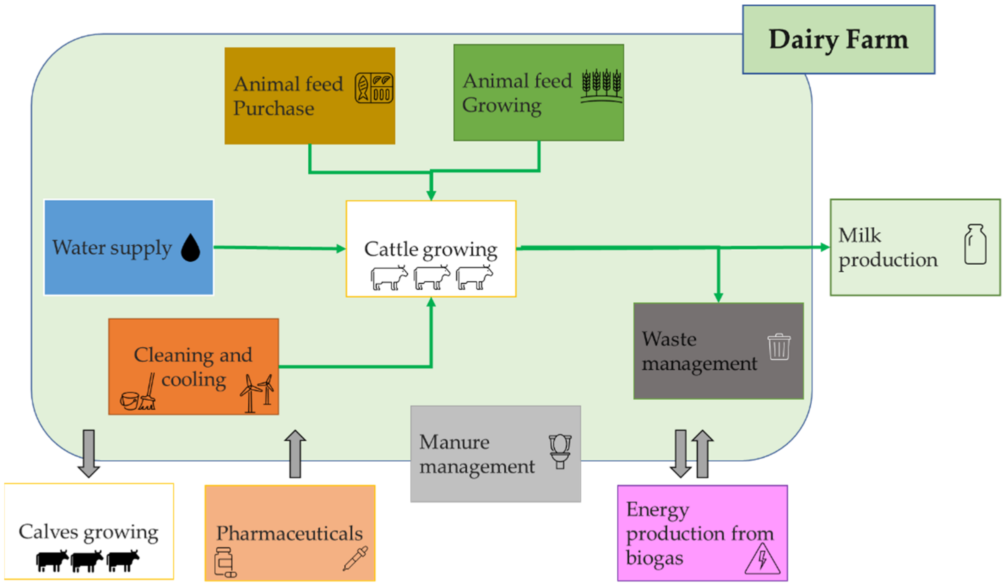

Figure 1. Conceptual model flowchart.

2.2. Conceptual Model for the Assessment

The conceptual model at the basis of the LCA has been defined based on a cradle to farm gate perspective over a calendar year. Considering the specificity of the farm analyses, the model has been developed based on primary data, whenever possible, and previous studies in the field (e.g., Grassauer et al., 2022 [28]).

Several assumptions have been introduced aimed at reducing the uncertainties of the results and at providing a preliminary assessment of the generated impacts, as presented below:

- Water for feeding and cleaning purposes was considered as deriving from the drinking water supply system;
- Electricity consumption was considered entirely covered by energy from the grid, as the biogas generation plant was inoperative at the time of the study. The Italian country mix for medium voltage supply included in the Ecoinvent library was selected as representative for the case;
- The processes related to calf growing were excluded from the model, as meat production, i.e., the co-production line, was out of the scope of the present study;
- As manure management consisted in storage and spreading in the farm fields, it was included exclusively in terms of machinery diesel consumption and equipment involved;
- The use of pharmaceuticals could not be included in the present model due to the lack of primary data about the impact of the specific drugs;
- Carcass disposal was excluded from the boundaries of the present study.

A specific focus was dedicated to animal feed, which has been represented in the following terms, considering each upstream process and relative impacts:

- The growing of sorghum and fodder in local sites was included in terms of machinery diesel consumption and equipment involved;
- Purchased animal feed was detailed by typology, source location, and transportation (mean and distance).

Figure 1 shows the conceptual model in the form of a flowchart. The system boundaries are marked in light blue. Each process included in the analysis is connected through green arrows to the main line of "cattle farming" and "milk-production". The excluded processes, either input (i.e., pharmaceuticals), outputs (i.e., calves growing), or both (i.e., energy production from biogas), are represented out of the system boundaries. Manure management, which lays on the system's boundaries, was included in the analysis exclusively in direct terms, as fuel consumed by the farm's machinery for spreading.

The LCA methodology was applied based on ISO 14040 [34] using the Simapro 8.5.1 software and the Ecoinvent 3.4. database [35]. The Functional Unit (FU) was set as 1 kg of Fat and Protein Corrected Milk (FPCM) produced in 2019, in accordance with similar studies in the field [24,25,33], and it is defined by [36] as

$$\text{FPCM (kg)} = \text{raw milk (kg)} \times (0.337 + 0.116 \times \text{fat content (\%)} + 0.06 \times \text{protein content (\%)})$$

The average Italian national fat and protein contents reported in the year prior to the visit (2019) were used as reference values; hence, all milk was converted to FPCM with 3.8% fat and 3.4% protein [37].

Details about the processes included are reported in Appendix A. Table A1 shows the overall model, Table A2 shows the details regarding animal feed production, and Table A3 shows the details regarding the transport of animal feed.

Considering the relevance of GHG emissions from farming and their impact on the global warming issue, the selected calculation method was IPCC100a, i.e., the method developed by the International Panel on Climate Change, which provides the carbon footprint developed over a time horizon of one hundred years [38,39], but still integrated into an LCA framework. Previous studies in the field have indicated this as the most conservative approach [27].

Uncertainty analysis was performed, applying Monte Carlo simulation with a 95% confidence interval.

3. Results and Discussion

In developed countries, since more and more citizens are concerned about health, environmental, ethical, and animal welfare issues, consumption of animal products has been showing a reduction trend [3].

Despite the negative effects on the environment, our planet faces the challenge of feeding a rapidly growing global population, which is projected to reach 9.73 billion by 2050 and 11.2 billion by 2100 [40], while fulfilling the obligation to reduce greenhouse gas emissions [17].

For these reasons, the involvement of milk and dairy producers at the local level and their commitment to sustainability is strategic to meet the global goals.

The farm included in this case study is part of the nearly 3000 farms active in the Parmigiano Reggiano production area. It uses the produced milk for making both Parmigiano Reggiano and soft cheeses [41]. The production of this PDO cheese follows a specification linked to the characteristics of the production area.

With its 1368 heads, the investigated farm was part of the 4.5% of dairy farms in Emilia-Romagna with a consistency greater than 500 heads, while most dairy cattle farms in this region (39.2%) own between 100 and 499 heads [42]. The farm covers an area of 5.4 ha used for animal rearing and 560 ha for agriculture, compared to the national average of 18 ha, ranking it among the larger farms [43]. In terms of productivity, the farm has an average milk production of 30–35 kg/cow/day, reaching 38 kg/cow/day in winter. These values are significantly higher than the national average, which is around 25 kg of milk per cow per day [42].

Considering the peculiarities of the farm, also within the framework of the Parmigiano Reggiano production area, and the high environmental pressure in the region, we developed a dedicated LCA model, able to valorize the primary data collected.

The LCA applied in this case study allowed us to identify the most relevant items of impact in dairy cattle farming in terms of products, such as animal feed and plastic packaging, and processes, such as machinery fuel consumption for local sourcing of supplements and standard operations of the farm. Table 2 shows the results obtained by LCA in terms of impact generated over a year, considering the farm total production and consumptions reported to the FU (1 kg of FPCM).

Table 2. Impact calculated for the yearly production of the farm and the functional unit, i.e., 1 kg of FPCM, expressed in terms of kg CO_2eq.

Process	Total Yearly Impact (kg CO_2eq)	Impact (kg CO_2eq/1 kg of FPCM)
Farm operating machines	822,797.95	19.97
Electricity consumption	61,470.30	1.49
Water consumption	10,678.27	0.26
Animal feed	244,051.51	5.92
Transport of animal feed	8903.68	0.22
Packaging film, low density polyethylene (LDPE)	443,183.57	10.76
Packaging, for fertilizers or pesticides, cleaning products (PE)	4234.03	0.10
PE recycling	−108,227.27	−2.63
Incineration of waste plastic	175,486.47	4.26
Landfilling of waste plastic	2337.88	0.06
Total	1,664,916.38	40.41

Uncertainty analysis was performed based on the Monte Carlo simulation. With a 95% confidence interval, the results range between 1,506,532.347 and 1,887,999.032 kg CO_2eq/year, with a standard deviation corresponding to about 6% of the mean value. Overall results of the simulation are available in Appendix B, Table A4.

The available literature shows high variability in the environmental impact of milk production due to the different assumptions and models used in the studies. Moreover, differences in the functional units, system boundaries, data sources, characterization factors, and allocation approaches add uncertainty to the comparisons [23,31]. For example, the study by Berton et al. [24] was based on data collected in different dairy farms of the Eastern Alps, therefore characterized by specific cattle breeds and farming and management systems. The tool proposed by Famiglietti et al. [33] outlines different system boundaries, including the cheese production phase and processes from different databases, to provide a comprehensive approach to the analysis.

However, the flows that mainly affect the results are the same, although their contribution to the total results differs due to the different assumptions and models used in each study. These include enteric fermentation, animal feed production, manure management, and spreading [44]. Nevertheless, it was evident that the case study presented discrepancies in terms of energy consumption, packaging, and animal feed compared to similar studies in the field. Consequently, the related impact results are higher than expected and suggest pathways for improvement.

As evident from the results, the diesel consumption for the farm operating machines is the most relevant item of impact, accounting for about 49% of the total impact, followed by the production of plastic packaging (27%) (Figure 2).

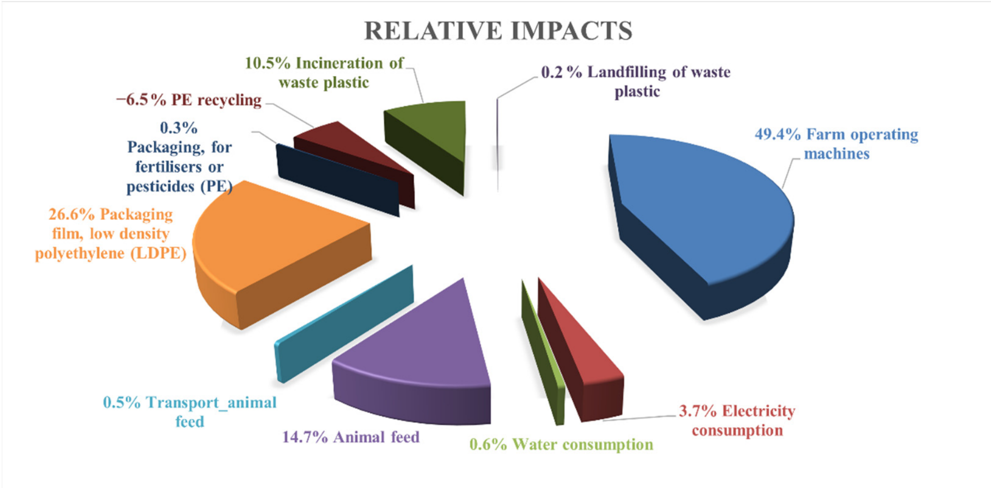

Figure 2. LCA results in terms of the relative impacts of each process.

Considering the possible solutions to tackle these specific issues, we recognized the necessity to involve the supply chain in both cases. The fuel used by the farm operating machines is a factor that is currently difficult to mitigate, as the technologies for the production of electric machines are not sufficiently advanced to ensure the necessary power for the vehicles used in livestock farming and agriculture.

Waste production and management evaluation, particularly in terms of plastic packaging coming from livestock management activities, such as the polyethylene wrapping of hay and straw bales, and cleaning product containers, represent another important item for assessing the overall environmental impact of the farm. A potential solution for reducing the production of plastic waste is almost ready at hand. Figure 2 shows that the disposal of plastic waste through recycling reduces the impact of this item by 7%. The thin polyethylene film, which represents 90% of the plastic present in the farm, can be replaced, for example, with recyclable plastic, thus significantly reducing the environmental impact and working in accordance with the Single-use Plastics Directive (SUPs) [45]. This would require a strong commitment to sustainable farming and partnership with suppliers toward the eco-design of animal feed packaging [46]. In addition to this, clear pathways to make plastic recycling the everyday standard are required to avoid the diffuse practice of incineration or, worse, landfilling [47–49]. Moreover, local initiatives may provide an opportunity for the integration of new business lines [50], as the implementation of sustainability-related practices may boost the overall performance of small and medium enterprises [51].

Animal feed production and the related logistics resulted responsible for about 16% of the total impact, considering only the sourcing from third-party suppliers, as the internal cultivation was accounted for in the consumption items for the site. Figure 3 shows in detail the impact triggered by each component of animal feed. The production phase is evidently the most impactful, and maize represents the main item of impact. The amount supplied each year is comparable with sunflower, which displays an overall impact that is almost 60% lower.

Considering only the transport of purchased animal feed (Figure 4), it is evident how the local sourcing supports limited impacts, while overseas supply triggers about 75% of the overall impact of animal feed transport.

In this regard, improvement actions that could reduce the potential environmental impact include increasing the consumption of grass silage instead of maize silage and lowering the use of concentrates or using locally produced concentrates instead of imported ones [26]. Therefore, a revision of the supply chain is strongly recommended to maintain cost control in case of fluctuating prices of international logistics [52] and to secure the consistency of supplies in uncertain international conditions, as we are experiencing in relationship with the COVID-19 crisis [53]. This would allow keeping the commitment to the SDGs by securing food supply chains (SDG 2) and improving working conditions (SDG 8) as well as the sustainability of production and consumption modes (SDG 9), with the overarching aim of reaching the climate goals (SDG 13), regardless of contingent factors [54].

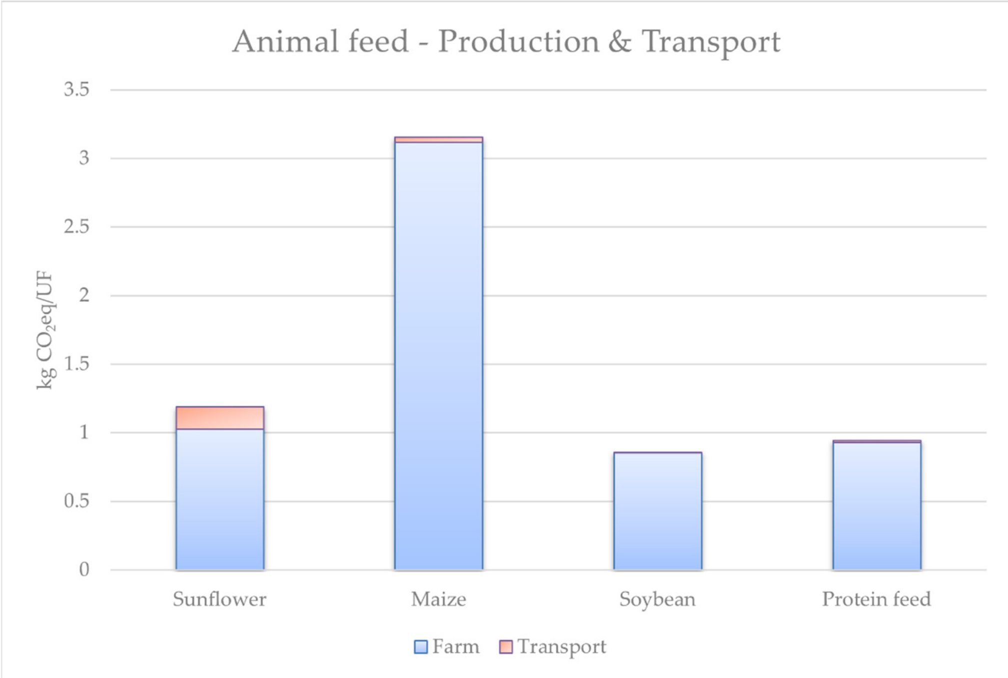

Figure 3. Impact results for external production and transport of animal feed, in terms of kgCO_2eq, referred to the FU.

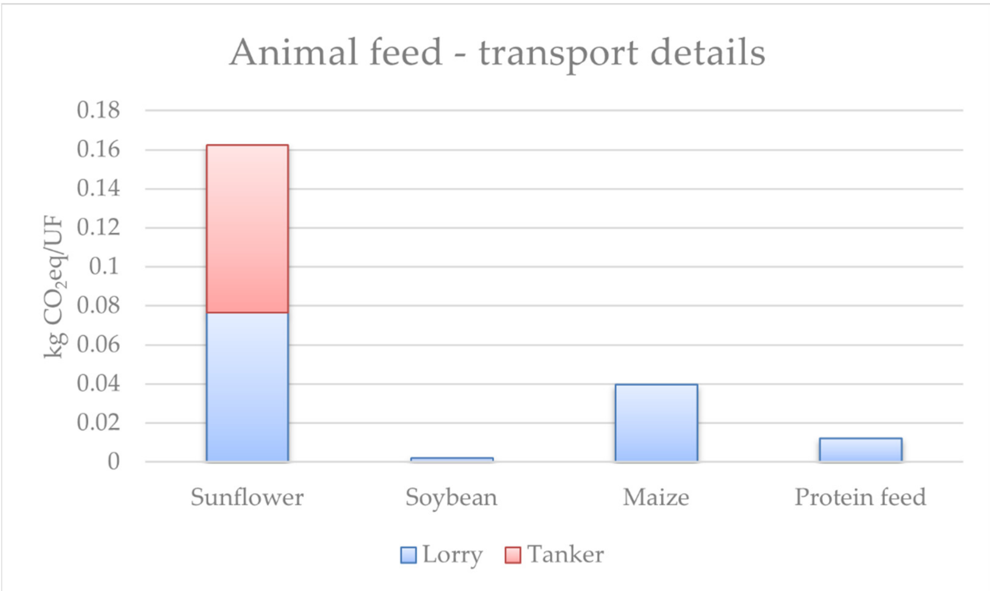

Figure 4. Impact results, in terms of kgCO_2eq, referred to the FU.

Table 3 summarizes the impact results for both animal feed production and transport.

Table 3. Impact calculated for the yearly supply of animal feed and the functional unit, i.e., 1 kg of FPCM, expressed in terms of kg CO_2eq.

Process	Total Yearly Impact (kg CO_2eq)	Impact (kg CO_2eq/1 kg of FPCM)
Production		
Sunflower	42,244.29	1.025
Maize	128,295.48	3.114
Soybean	35,211.73	0.855
Protein feed	38,300.00	0.930
Transport		
Sunflower	6686.42	0.162
Maize	1635.06	0.040
Soybean	82.37	0.002
Protein feed	499.83	0.012

As regards energy consumption, accounting for 4% of the total impact, according to the Institut de l'Elevage results [55], in the investigated farm, the following high-consumption areas could be identified: milk collection, refrigeration, and pumping; water heating for washing operations; overall lighting; cleaning and washing equipment.

Global warming is a major problem for livestock farming. It is particularly relevant in the Po Valley, where ensuring an adequate microclimate, which often requires putting in place air conditioning systems, is essential to reduce the risk of heat stress in cows [56]. In this case, about a quarter of the total energy consumed by the farm was related to the ventilation systems. Together with the consumption of water for summer cooling (72,000 L), this value reflects the robust farm commitment to ensuring a good welfare level for the cows.

Manure and sewage management is another fundamental issue for reducing GHG emissions, ensuring the environmental quality of rural areas, and protecting the aquifers and surrounding water basins. In this case, the lack of primary data on manure yearly production forced us to exclude the Tier 1 and Tier 2 emissions [38]. Therefore, the spreading, which the company carries out according to the guidelines of the Regional Agency for Prevention, Environment and Energy of Emilia-Romagna (Arpae), was the only treatment considered. In the modeled farm, sewage storage is carried out in uncovered basins and beds, trying to minimize the surface-volume ratio to avoid the transfer of dissolved organic carbon on the surface and reduce the related CO_2 emissions. Finally, the production of biogas from the anaerobic digestion of sludge represents an important sustainability strategy of the company, but bottom-line production data are still lacking.

4. Implications

The relationship between farm animal welfare and environmental sustainability is complex, and these two research topics have historically been addressed separately [57]. Their integrated study would help to better understand the synergies and antitheses between these two pillars of livestock farming sustainability and may facilitate the identification of coordinated actions for improvement.

The theoretical implications that would derive from such a multidisciplinary approach can be found at a systemic level since environmental impact assessment could be included in an integrated risk-based farm classification system, like the one developed in Italy, which already includes data on animal health and welfare, biosecurity, antimicrobial usage and related antimicrobial resistance [58].

Practical implications would include integrating environmental impacts and animal welfare items into control dashboards for farmers for the smart management of dairy farms. This would benefit livestock farmers as it would enable them to monitor their management strategies, both short-term, related, for instance, to animal feed purchase, and long-term, considering, for example, machinery purchasing or the implementation of infrastructures, in view of reducing the environmental impact of their farms. In perspective, the collection of summary and aggregated data from dairy farms may feed the policy-making process, supporting it with updated information about the state-of-the-art and the impact of sector-specific policies to meet the global goals.

5. Conclusions

Climate change is an established problem, and cattle farming actively contributes by emitting 14.5% of greenhouse gases from human activities [40]. Stricter environmental policies triggered by the diffuse awareness of the pressing urgency of global challenges could lead to innovative solutions that will improve the competitiveness of the livestock sector in the long term [6].

The investigation of the most relevant items of impact in the dairy farm management represents, in this sense, the first and fundamental step to building awareness and measuring the results of sustainability-oriented actions. Considering the variety of farms, management strategies and supply chains involved into the livestock industry, it is now crucial to create a solid benchmark of cases tailored to the specific milk production scenarios of different areas, thus avoiding the "one-size-fits-all" approach and allowing to identify the main items of impact based on the different production approaches.

The study presents some inherent limitations: firstly, the process of growing calves and the disposal of effluents and animal waste were excluded from the analysis; secondly, pharmaceuticals were not accounted for. In the first case, future research development may broaden the system boundaries, considering the multi-output process, i.e., meat production. In the second case, the main constraint is represented by the lack of information about these products regarding environmental impacts. However, drug use has been carefully mapped. It appears to be highly promising as a possible hotspot of impact, both in input (for the production) and output (for the contaminant load carried into animal urine and, consequently, wastewater). Considering the social dimension of sustainability, future studies may also evaluate the impacts of dairy production on workers, local communities, and society at large.

This study outlines pathways for future research at different levels despite its limitations. Firstly, it provides a preliminary LCA that can be extended to include elements so far neglected, evaluating, for example, the impact of different scenarios of drug administration. Secondly, considering the extensive data collection performed through an interdisciplinary approach. It represents the first step towards the integration of LCA with other frameworks for the performance assessment of dairy cattle farming, namely oriented to include animal health and welfare, with the final aim of evaluating livestock farms from both the environmental sustainability and social sustainability point of views.

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Informed Consent Statement: The farm manager signed an informed consent before the assessment started.

Data Availability Statement: All study data are presented in the article.

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Appendix A

Details on the processes included are reported in the following tables.

Table A1. Overall model, process details.

Process	Amount	Unit	Notes
Resources			
Water, well, in ground, IT	72,000	L	
	Materials/fuels		
Diesel burned in agricultural machinery	1,097,763.05	kWh	consumption for farm processes (both feed production and animal husbandry)
Tap water {Europe without Switzerland} ǀ market for ǀ APOS, U	28,035,555.2	kg	
Packaging film, low density polyethylene {GLO} ǀ market for ǀ APOS, U	147,510	kg	
Packaging, for fertilizers or pesticides {GLO} ǀ market for packaging, for fertilizers or pesticides ǀ APOS, U	16,390	kg	
Animal feed production	1	p	See Table A2
Electricity/heat			
Electricity, medium voltage {IT} ǀ market for ǀ APOS, U	141,840	kWh	
Animal feed transport	1	p	See Table A3
Final waste flows			
Polyethylene waste	163,900	kg	
Waste to treatment			
PE (waste treatment) {GLO} ǀ recycling of PE ǀ APOS, U	67,199	kg	41% of total waste, considering average regional waste disposal
Waste plastic, mixture {Europe without Switzerland} ǀ treatment of waste plastic, mixture, municipal incineration ǀ APOS, U	73,755	kg	45% of total waste, considering average regional waste disposal
Waste plastic, mixture {Europe without Switzerland} ǀ treatment of waste plastic, mixture, sanitary landfill ǀ APOS, U	22,946	kg	14% of total waste, considering average regional waste disposal

Table A2. Animal feed—production, process details.

Process Detail	**Amount**	**Unit**
Soybean, feed {GLO} ǀ market for ǀ APOS, U	9148	kg
Maize grain, feed {GLO} ǀ market for ǀ APOS, U	181,598	kg
Sunflower silage {GLO} ǀ market for ǀ APOS, U	191,094	kg
Protein feed, 100% crude {GLO} ǀ market for ǀ APOS, U	22,042	kg

Table A3. Animal feed—transport, process details.

Process Detail	Distance	Unit	Notes
Transport, freight, sea, transoceanic tanker {GLO} | market for | APOS, U	519,180.2	tkm	Sunflowers' transport—tanker, from Black Sea port (Ukraine) to Ravenna
Transport, freight, lorry 16–32 metric ton, EURO4 {GLO} | market for | APOS, U	21,211.43	tkm	Sunflower—road transport from Ravenna port
Transport, freight, lorry 16–32 metric ton, EURO4 {GLO} | market for | APOS, U	493.99	tkm	Soy—road transport from production site (Modena province)
Transport, freight, lorry 16–32 metric ton, EURO4 {GLO} | market for | APOS, U	9806.29	tkm	Maize—road transport from production site (Modena province)
Transport, freight, lorry 16–32 metric ton, EURO4 {GLO} | market for | APOS, U	2997.71	tkm	Protein feed—road transport from production site (Cremona province)

Appendix B

Results of the uncertainty analysis.

Table A4. Complete results of the Monte Carlo simulation for the overall process and for animal feed production and transport; other processes are integrated directly from Ecoinvent "SD".

	Unit	Mean	Median	Standard Deviation	Coefficient of Variation	2.5%	97.5%	Standard Error of the Mean
Total Yearly Impact	kg CO_2eq/year	1,669,074	1,661,037	102,232.5	6.125107	1,506,532	1,887,999	3232.877
Animal feed production	kg CO_2eq/year	243,847.2	242,761.9	16,982.24	6.964294	215,360.6	279,755.3	537.0255
Animal feed transport	kg CO_2eq/year	8883.801	8831.835	586.796	6.605236	7890.041	10,200.85	18.55612

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