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Carbon Footprint and Carbon Sink of a Local Italian Dairy Supply Chain

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Abstract: The dairy industry's contribution to global warming has been thoroughly examined. However, it is important to raise public awareness of emission hotspots and the possibility of mitigation in dairy supply chains. This study assessed the Carbon Footprint (CF) of five dairy products through a cradle-to-grave Life Cycle Assessment approach and evaluated the carbon sink potential of some practices. The functional units were 1 kg of fresh raw milk, yogurt, fresh cheese, mozzarella cheese, and aged cheese. The data collected were related to an extensive dairy farm, a cheese-factory, two markets, a delivery service, and a court of consumers. The CFs were 4.39, 5.10, 9.82, 8.40, and 15.34 kg CO_2 eq. for fresh raw milk, yogurt, mozzarella cheese, fresh cheese, and aged cheese, respectively. The hotspots of the dairy supply chain considered herein refer to farm activities and energy consumption, whereas conservative agriculture practices and rotational grazing sequestered 1.60 ± 0.80 kg CO_2 eq. per kg of dairy product consumed. The CF was reduced by 0.14 kg CO_2 eq. for 1 kg of dairy product delivered at home compared to direct purchasing at a market. The carbon sink capacity of dairy farms appeared as a primary mean for mitigating climate change in the dairy supply chain.

Keywords: life cycle assessment; farm to fork; dairy cattle; environmental sustainability; pasture system; conservative practices

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Citation: Rossi, C.; Grossi, G.; Lacetera, N.; Vitali, A. Carbon Footprint and Carbon Sink of a Local Italian Dairy Supply Chain. *Dairy* **2024**, *5*, 201–216. https://doi.org/10.3390/dairy5010017

Received: 12 January 2024
Revised: 10 February 2024
Accepted: 1 March 2024
Published: 5 March 2024

1. Introduction

In the last few years, several studies have investigated the environmental impact of animal-based products and the related supply chains.

Although livestock systems contribute to the emissions of several pollutants, the current spotlight is on the evaluation of greenhouse gas (GHG) emissions into the atmosphere, which continue to increase and affect many weather and climate extremes in every region across the globe [1]. Livestock contribution to GHG emissions is determined by methane (CH_4) from enteric fermentation, and CH_4 and nitrous oxide (N_2O) from manure, which account for 48.5% of the European emissions of the agricultural sector [2].

Nowadays, dairy cattle are responsible for half of the livestock environmental burden [2]. Additionally, milk production for the decade 2023–2032 is expected to grow faster than most of the other main agricultural products [3]. The production of dairy products (milk, cheese, and yogurt) involves the depletion of a wide amount of input such as water, crops, energy, and materials with, as a consequence, significant GHG emissions [4], which represents the 27% of the European emissions from food production [5].

Research on the environmental sustainability of dairy systems has focused on the Carbon Footprint (CF) [6], an indicator based on the Life Cycle Assessment methodology (LCA, [7]), to quantify the GHG emissions generated by all stages of the dairy supply chain and to evaluate the impact of mitigation strategies.

The CF, measured as kg of carbon dioxide equivalents (CO_2 eq.), was calculated to assess the environmental impact of a large number of products at the dairy plant with a wide variability in cheese characteristics and in manufacturing operations [8–10].

There are limited applications of a LCA analysis on dairy products from "local" supply chains. The definition of "local products" refers to the reduced distance between the place of production and that of sale, which determines the direct link between producers and consumers that is associated with environmental advantages deriving from the efficient exploitation of local resources and the reduction in energy costs due to the reduced distances of the products' distribution [11]. In Italy, most of the LCA studies of small-scale dairy systems refer to the typical Alpine farms and follow a "cradle-to-farm gate" [12,13] or "cradle-to-plant gate" approach [5]. The CF of local Italian dairy products, considering the entire life cycle up to the disposal stage, has not yet been evaluated.

Soil carbon stock in dairy systems has a wide variability and strongly depends on farm management. In grassland-based livestock systems, crop residues and manure released at field might provide a significant contribution to the carbon sequestration (C-sink) from soil, and thus represent an important mitigating strategy for GHG emissions. However, there are no standardized methods to account for soil C-sink, and the appropriate way to point out this mitigating effect on LCA analysis is still debated [14].

Few studies considered the contribution of C-sink in Italian dairy farms. [15] compared four dairy systems of the Po Valley for the production of PDO (Protected Designation of Origin) cheeses such as Parmigiano-Reggiano and Grana Padano and found a negligible contribution of C-sink in all of the investigated systems. Conversely, [16] investigated the C-sink in dairy Alpine farms and showed a reduction in emissions ranging from 12.2% to 21.2% of CO_2 eq. per kg of corrected milk.

The primary objective of the present study was to examine the CF of some Italian dairy products derived from a local supply chain using a cradle-to-grave LCA approach. The system investigated involved an extensive dairy farm practicing rotational grazing and minimum tillage operations that have the potential to enhance the soil's C-sink capacity [17,18]. Therefore, this study included the evaluation of the soil C-sink achieved through these practices.

In addition, the study also aimed to evaluate the contribution of GHG emissions from two purchasing systems of dairy products of the local supplied chain considered, directly at the market or through a delivery system.

2. Materials and Methods

2.1. Goal and Scope

According to [6,7], this study aimed to assess the CF of five dairy products from an Italian local supply chain: from raw milk production to consumption and waste disposal, and accounting for the conservative practices of C-sink related to pasture practices and conservative soil tillage. Finally, the direct purchasing by consumers from markets was compared with a delivery system using electric bikes, and the impact on the CF was evaluated.

2.2. Functional Units and System Boundaries

The functional units were 1 kg of fresh raw milk, 1 kg of yogurt, 1 kg of mozzarella cheese, 1 kg of fresh cheese, and 1 kg of aged-cheese (2–3 months ripened). The system boundaries determine which unit processes are included in the CF analysis, and in this study, they were defined by following the Product Category Rules (PCR) for dairy products of the Environmental Product Declaration [19]. PCR guidelines organize the dairy supply chain into three stages: upstream, core and downstream. The upstream stage considers the farm activities related to raw milk production such as crop production, animal management, and the related transport flows. The core stage refers to the milk processed at a dairy plant, and the operations of manufacturing and packaging of dairy products. The downstream stage involves the distribution of dairy products within a maximum radius of 50 km and the selling and consumption activities, which encompass the habits of purchasing, transports to home, and waste disposal.

Figure 1 resumes the system boundaries and represents the input and output unit flows and processes involved in this CF analysis.

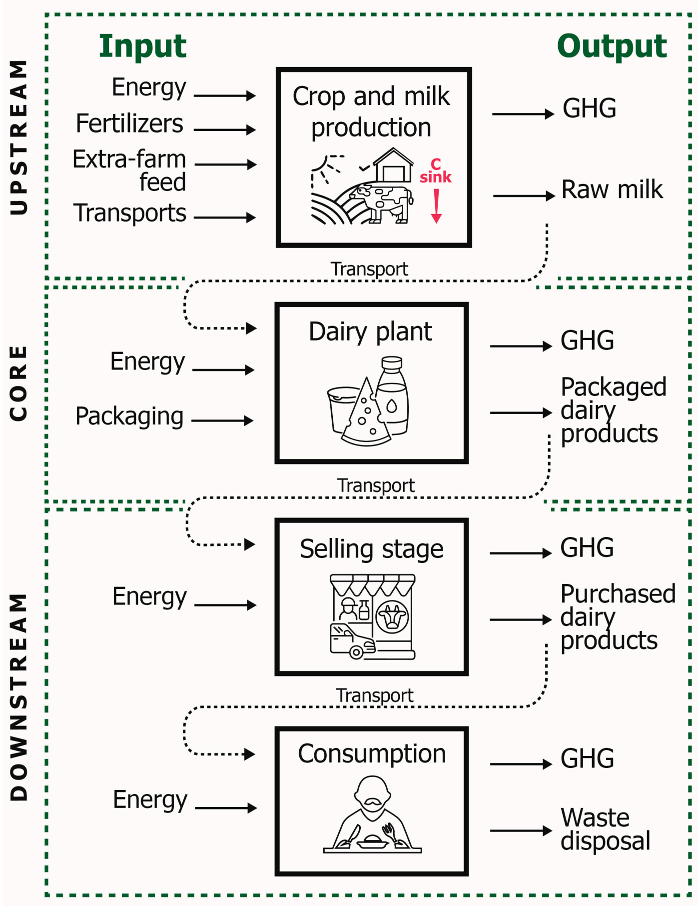

Figure 1. System boundaries considered for the local Italian dairy supply chain.

2.3. Significance Analysis

In accordance with the system boundaries, the unit processes that had a significant expected contribution to the CF analysis were defined. Although [6] allowed cut-off criteria, unit processes were removed only when the influence on the study was minimal. The significance analysis was performed through a consistent evaluation where all of the sources of emissions were characterized by combining four parameters: magnitude, influence, importance, and availability. Water-related flows, buildings, veterinary operations, energy for illumination, detergents, and waste disposal in upstream and core stages were not included in the examination.

The extended data of the significance analysis are reported in Supplementary Materials (Table S1).

2.4. Life Cycle Inventory

The approach employed for gathering and evaluating inventory data is in accordance with what is described in [20].

The study involved an extensive dairy farm, a cheese making plant, two markets, one delivery service, and 63 consumers. The data were collected throughout the year 2021.

Specific questionnaires were submitted to each actor of the local supply chain concerning upstream (herd composition, crops, soil tillage, milk yield and quality, manure management and grazing activities, and energy consumption), core (processed raw milk for each dairy product, energy consumed, and packaging materials), and downstream (distribution transports, amount of dairy product per market, refrigerated storage, consumers' transports and waste disposal). Secondary data from Ecoinvent v.3.2 database [21] and the literature [22] were collected when primary data were lacking or not adequate.

The uncertainty associated with the quantities of specific inputs or outputs is often challenging to determine from the available information [23]. In LCA studies, this is typically addressed using quality indicators derived from a pedigree matrix, as implemented in the Ecoinvent database [24]. Specifically, after obtaining the inventory data, the LCA practitioner evaluates its reliability, completeness, and its temporal, geographical, and technological relevance, rating each aspect on a scale from 1 to 5. These ratings are then converted into uncertainty factors, which are used to calculate the lognormal standard deviation in Ecoinvent [25]. The outcomes of the pedigree matrix assessment are detailed in the Supplementary Materials (Table S2).

2.4.1. Upstream—Dairy Farm

The commercial dairy farm was located in Sutri (Viterbo, Italy) and consisted of an extensive breeding of Pezzata Rossa cattle, an Italian genotype derived from Swiss Simmental. The farm had a total of 60 hectares, 12 of which were sited next to the barn and pastured, whereas the other hectares were finalized for forage production.

The herd was managed under rotational grazing, which consisted of a partition of the pasture area into smaller areas where cattle activity was concentrated in one section and monitored. This practice allowed cattle to graze only one portion of pasture at a time while the remainder of the grazing-area rested to rebuild the forage growth. Through this system, the fertilization of the fields was guaranteed from the excretes released during the pasture activities.

Animals were mainly fed by pasture, except for lactating cows and heifers. After milking, lactating cows were provided ad libitum self-produced hay; heifers were supplemented with a sunflower flour feed.

The cultivated forage was a dry annual crop of multi-essence that supported the nutritional needs of grazing animals. The fields were managed with minimum tillage operations, and organic fertilization was applied through surface spreading; inorganic fertilization was not employed.

Electricity consumption referred to the milking parlor and the refrigerant milk storage, while feeding machinery, sod seeding and crop harvesting were the main drivers of diesel consumption. Table 1 reports the key inventory information of the dairy cow farm.

Table 1. Key information of the extensive dairy cow farm.

Item	Value
Herd	
Dairy cow, no	30
Dry cow, no	7
Heifers, no	9
Beef calves, no	20
Milk, L/day/head	18
Fat, %	3.91
Protein, %	3.42
Feed	
Cultivated area, ha	48
Pasture area, ha	12
On-farm hay, q/y	3500
Extra-farm feed, q/y	25
Energy	
Electricity, kWh/y	12,491
Diesel, kg/y	7616

2.4.2. Core—Dairy Plant

The dairy was a farm-based plant sited next to the stall. The cheese-making plant produced several dairy products and the most representative were selected as the functional units of this study: fresh raw milk, mozzarella cheese, fresh cheese, yogurt, and mid-aged cheese (ageing from 2 to 3 months).

The commercialized fresh raw milk was not pasteurized and subjected to a maximum heating treatment of 40 °C.

Plastic materials were employed to package milk, mozzarella cheese, fresh cheese, and yogurt, whereas for mid-aged cheese, plasticized paper was used; all packaging was produced from virgin materials.

Energy consumption at the dairy plant referred to electricity and diesel usage for the manufacturing machineries and the refrigerant cells. Summary data of the dairy plant is reported in Table 2.

Table 2. Key information of the investigated dairy plant.

Item	Value
Production	
Processed raw milk, ton/y	119
Fresh raw milk, tons/y	11.9
Mozzarella cheese, tons/y	1.5
Fresh cheese, tons/y	2.7
Mid-aged cheese, ton/y	3.3
Yogurt, tons/y	16.1
Packaging	
PET, tons/y	0.2
PP, tons/y	1.7
LDPE, tons/y	0.17
Plastic-paper, tons/y	0.2
Energy	
Electricity, kWh/y	7608
Diesel, tons/y	884
Average Transports	
Packaging store, km/single trip	382 ± 250

2.4.3. Downstream—Selling and Consumption

In this stage two different purchasing habits were considered: direct selling through two markets, indicated as a and b in Table 3, and the delivery system based on an integrated service of refrigerated trucks and electric bicycles.

Table 3. Key information on consumers' habits.

Item		Mean Values	
		Consumers habits	
Markets		a [1]	b [1]
Purchased dairy products, kg		0.72 ± 0.67	0.56 ± 0.14
Total shopping expenditure, €		60 ± 29	33 ± 25
Dairy products on total expense, %		24 ± 23	44 ± 25
Transport type, km			
	On foot	1.4 ± 0.9	1.3 ± 0.7
	Bicycle	3.0	1.0
	Scooter	4.7 ± 2.9	-
	Hybrid car	6.4 ± 5.3	1.0
	Petrol car	5.4 ± 4.6	1.7 ± 1.0
	Diesel car	9.0 ± 6.9	2.0 ± 1.4
	Gas car	3.0	2.3 ± 1.2
	Bus/Metro	8.0 ± 0	-
Daily delivery transports			
Refrigerated trucks, km		19.4	
Electric bicycles, km		6	

[1] Data referred to two different markets, a and b, a supermarket and a neighborhood grocery store, respectively.

To account for the distribution of dairy products, the distance travelled and the amount of dairy products transported from the dairy plant to the two markets and the delivery center were considered. The distribution path was assessed by considering the kilometers travelled and the mass of the dairy products delivered in the selling sites. Less than 50 km separated the dairy plant from the markets and distribution center.

Energy consumption for the storage of dairy products during the retailing was evaluated according to [26], who indicated estimating the energy used in the refrigerant systems by considering a storage time of three days.

To define the survey sample size at market, the population size of customers was calculated by dividing the sold dairy products evaluated in the study in 2021 (6420 kg in milk solids) and the per capita annual amount of consumed dairy products (27 kg in milk solids) in the European Union, as reported in [27]. The population size resulted of 238 people, and then, the minimum sample size was calculated through Fisher's equation [28] with a 10% of margin error and 90% of confidence interval:

$$\text{Sample size} = \frac{\frac{z^2 \times p(1-p)}{e^2}}{1 + \left(\frac{z^2 \times p(1-p)}{e^2 N}\right)} \tag{1}$$

where N is the population size, e is the margin error, z is a critical value of the normal distribution at the required confidence level, and p is the sample proportion. According to Equation (1), 54 was the minimum consumers sample; however, in the study 63 customers were surveyed.

The data collected from the interviews referred to the amount and type of purchased dairy products, shopping expenditure, means of transport employed, distance travelled from home to market, amount of wasted dairy products, and packaging disposal [20]. The extended consumers' questionnaire is available in Table S3 of Supplementary Materials. However, survey information about the consumption behavior was also assumed as representative for the consumers served by delivery system.

Representative transportation from home to market was calculated by considering the total distance travelled by the 63 consumers surveyed and the incidence of self-reported vehicle of transportation. The total distance was found to be 204 km, and, for example, petrol cars travelled 57 km, corresponding to 28% of the total distance. This procedure provided shares for each vehicle, which were then used to weight each vehicle's contribution to the average distance travelled, which was found to be 3.24 km. Then, the 28% of 3.24 km was travelled by petrol car.

The transport system of the delivery service begins at the delivery center where the daily orders were arranged. Once the products were ready, refrigerated trucks transported the orders to the closest distribution hub, where they were distributed through electric bicycles to the home delivery place.

To estimate the transport of dairy products through the delivery service, the average daily distance travelled by trucks and electric bicycles was considered. Refrigerated trucks travelled this distance twice a day to place new orders, whereas bikers returned to the distribution hub five times per day to take the new delivery and transport eight packs of six kg each, for a total of 48 kg transported per trip.

Because of the lack of specific data about home refrigeration, it was esteemed an average fridge volume of 250 dm^3 where the purchased dairy products occupied 1 dm^3. The energy consumption of dairy products at home was calculated considering the energy consumption of the domestic fridge that was assumed as 56.1 $kWh/m^3/year$ [29] and a home cold storage of three days, as indicated by surveyed consumers.

Consumer habits showed that 86% of those interviewed used to dispose packaging with waste sorting, whereas the remaining part did not separate the wasted materials.

Table 3 summarizes the main information of selling and consumption stages.

2.5. Allocation Criteria

At the farm gate, the allocation factors (AF) for milk as a main product and meat as a co-product were calculated adopting the biophysical approach defined by the International Dairy Federation [30] as following:

$$AF_{milk} = 1 - 6.04 \times BMR \quad (2)$$

where the AF_{milk} is the allocation factor of milk and BMR (beef-to-milk ratio) is the ratio between the mass of live weights of animals leaving the farm per year (fattening calves and culled cows) and the mass of fat and protein corrected milk (FPCM) leaving the farm per year. Raw milk was corrected to the standard values of 4% of fat and 3.3% of protein as recommended by [31]. The allocation factors were 72% and 28% for raw milk and meat, respectively.

The dairy plant input flows, such as raw milk, energy, refrigerant gases, and organic carbon, were allocated considering the degree of total solids concentration on a final product. Because they are product specific, packaging materials were not allocated, but were individually assigned to the corresponding product [8]. The allocation factors were calculated following the method defined by [31], which is based on the total solid matter, as indicated in the following equation:

$$AF_i = (DM_i \times Q_i) / \sum_i^n = 1(DM_i \times Q_i) \quad (3)$$

where AF_i is the allocation factor of the dairy product (i); DM_i is the dry matter expressed as a percentage of the dairy product (i); Q_i is the quantity of dairy product (i) output at the production plant gate (kg of product i), divided by the total solid matter leaving the production site.

To account for the amount of processed dairy products and the relative dry matter content, the specific dairy yield of each product was considered, and laboratory analyses were performed to determine the percentage of dry matter content. The analyses were carried out by following the official methods of dairy analysis defined by the Italian Ministry of Agriculture and Forestry [32]. The dairy yield, dry matter content, and allocation factors of the examined dairy products are reported in Table 4.

Table 4. Dairy yield, dry matter (DM) and allocation factors (AF) of dairy products.

Product	Dairy Yield (%)	DM (%)	AF (%)
Fresh raw milk	100	12	18.5
Yogurt	90	14	29.1
Mozzarella cheese	12.5	30	5.8
Fresh cheese	15	25	8.7
Aged cheese	11	49	20.7
Other dairy products [a]	15	30	17.3

[a] This category refers to the other dairy products such as butter, kefir, Robiola, Stracchino, Stracciatella that are processed in the dairy plant, but they were not involved in the CF analysis because they are transformed seasonally or on request.

To define the AF related to the transport of purchased products from markets to homes, the economic approach was applied. Taking into account the outcomes of consumers' interviews, the total shopping expenditure at market with the expense for dairy products were combined, and it emerged the AF of 32%.

To calculate the AF to apply at the transport of dairy products by delivery services, the mass criterion was adopted. The AF was 2.1% corresponding to the number of dairy products on the total food delivery trip, including truck and electric bike.

2.6. Life Cycle Inventory Analysis

Enteric methane emitted by animals at the farm were calculated according to a Tier 2/3 methodology, as defined by [22]. For each animal category, the daily gross energy intake, the digestible energy, and the fraction of gross energy converted into CH_4 (Ym, conversion factor) were esteemed. The daily gross energy intake depends on the energy consumed for the animal maintenance, activity, milk production, pregnancy, and growth, as defined by [22]. The portion of gross energy not excreted in feces is the digestible energy, and it was assumed as 60% for lactating cows, fattening calves, and heifers.

Farm-based Ym factors were calculated by considering the forage content in the diets of different animal categories into a linear equation based on the values of Ym, related to forage content, as suggested in Table 10.12 by [22]. Further details about the developed linear equation are reported in [20].

The estimated Ym values were 7.89 for lactating cows and fattening calves and 7.70 for heifers.

The GHG emissions from solid and liquid manure produced in the barn and released by grazing were evaluated as follows. Volatile solids (VS) and excreted nitrogen per year were preliminarily calculated for each animal category [22,33]. Country-specific emission factors of 4.8 g and 15.3 g of CH_4 per kg of VS and 0.02 and 0.005 kg of N_2O-N per kg N were adopted for solid and liquid manure, respectively [34]. Emissions from dung released at pasture were determined by adopting the emissions factors of 0.8 g of CH_4 per kg of VS and 0.01 kg of N_2O-N per kg N [22].

In addition, the N_2O emissions from the soil were evaluated by accounting for the nitrogen released by crop residues and organic fertilization. The nitrogen content of above- and below-ground residues was calculated using equations defined by [22], whereas the nitrogen released in the field from manure spread and pasture activities was calculated as indicated elsewhere [22,33]. The emission factor used to assess N_2O from soil due to the nitrogen sources was 0.01 kg of N_2O-N per kg N [22] that was converted into N_2O considering the molecular weight.

Since the farm practiced both rotational grazing and minimum tillage practices, the amount of C-sink by the soil was calculated. The C-sink from above- and below-ground residuals and organic fertilizer (manure spread and pasture) was evaluated by the C/N ratio defined by the DeNitrification–DeComposition (DNDC) model [35]. From the total carbon input into the soil, the fraction that contributed to the C-sink formation and avoided the atmospheric release in a 100-year perspective was assumed to be 10%, according to [36].

The annual leakage of refrigerant gases from the dairy plant, markets, and home systems were evaluated through the equation defined by the Environmental Protection Agency [37], which combined for each cold storage the refrigerant capacity and the annual leak rate.

To model the emissions related to energy consumption (electricity and fuel), purchased feed, packaging materials, and transports along the supply chain, the Ecoinvent database [21] was employed. Computation was carried out by using SimaPro software v.9.1.1 (PRè Sustainability, Amersfoort (NL)). The emission factors of each accounted process in the study are reported in Table S4 in Supplementary Materials.

Emissions from waste disposal were evaluated according to the outcomes of consumer interviews, where it emerged that packaging was disposed through material recycling and landfilling. In both cases, transport of waste materials for 50 km by municipal trucks from consumers' home to the waste management site was assumed, as proposed by [38].

Recycling materials is a multi-functional process that includes the treatment of waste and the production of a new secondary product, simultaneously. To assess this practice, the recycled content approach (or cut-off approach) developed by [39] was adopted. This method allocates the environmental burden associated with recycling processes to the users of new secondary materials.

Emissions from the landfill disposal of plasticized paper and plastic packaging were modeled using the Ecoinvent database [21].

Impact Assessment

The CF of the five dairy products was assessed by considering the Global Warming Potential (GWP) of the GHG, converted into kg of CO_2 eq., over a 100-year time horizon. The GWP conversion was developed to standardize the impacts of different gases by taking CO_2 as a reference value of 1. According to the GHG assessed in this study, the GWP conversion factors of 1, 28, 265 per kg of CO_2, CH_4, and N_2O were employed, whereas to account for the leakage of refrigerant gases, the GWP of 3500, 1430, and 3922 kg CO_2 eq. per kg of HFC-125, R134a, and R404a [22] were applied.

3. Results

The CF of fresh raw milk, yogurt, mozzarella cheese, fresh cheese, and aged cheese evaluated from milk production to a consumers' disposal, considering the customers' purchase at market as a selling option, were 4.39, 5.10, 9.82, 8.40, and 15.34 kg CO_2 eq. kg^{-1}, respectively.

The GHG contribution of different stages along the supply chain was assessed for each product and reported in Figure 2.

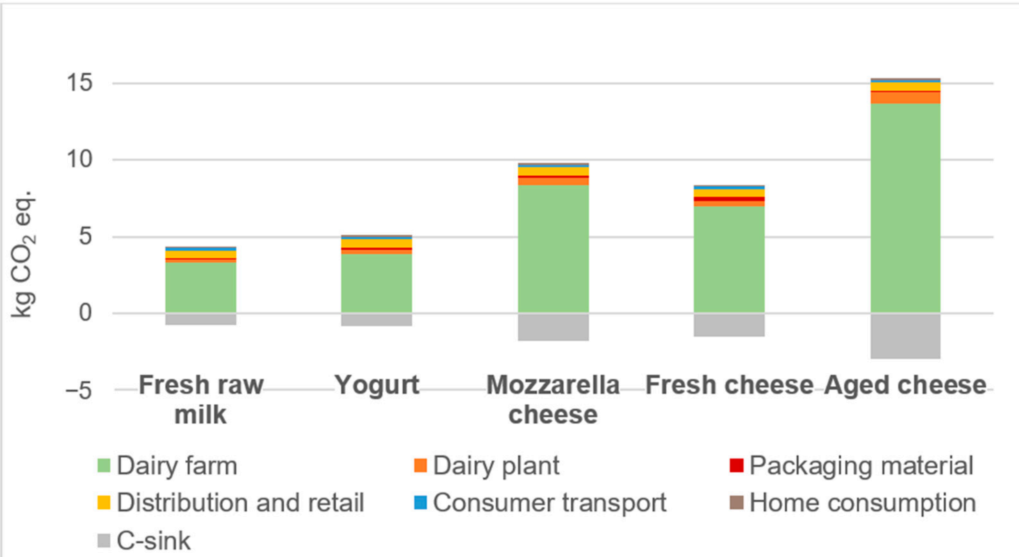

Figure 2. Contribution analysis of the GHG sources from cradle-to-grave CF of the investigated dairy products.

It is notable that dairy farm emissions contributed at least 75% of the CF of each dairy product considered and reached 89% for the production of 1 kg of aged cheese. CH_4 from enteric fermentation and CH_4 and N_2O from manure management and crop production were the main sources of GHG at the dairy farm and strongly affected the total GHG of milk at the farm gate.

The rotational pasture and minimum tillage practices, which were aimed at increasing the organic matter on soil, allowed an average C-sink of 1.60 ± 0.80 kg CO_2 eq. for each kg of dairy product, which corresponded to an average reduction of about 17% of farm emissions. The amount of C-sink in the soil was assessed for each dairy product, as reported in Figure 2, and showed a contribution of 0.72, 0.84, 1.80, 1.50, and 2.94 kg CO_2 eq. sequestered for the production of fresh raw milk, yogurt, mozzarella cheese, fresh cheese, and aged cheese, respectively.

Manufacturing and consumption stages accounted for about 24% of GHG emissions for the production of 1 kg of yogurt and fresh raw milk, whereas for mozzarella cheese, fresh cheese, and aged cheese, these stages had a contribution of 15, 17, and 11% on the corresponding CFs.

Since the management of dairy products at market and the consumer habits of transport and home consumption were assumed as equal for each product, the emission levels from the downstream phase were the same for all of the dairy products. However, within this stage, distribution and retail represented 65% of the downstream emissions.

Figure 3 shows the results of the environmental impact of the direct selling option compared with the emissions related to the delivery service of 1 kg of dairy product. The average distance travelled by consumers from home to the market was 3.24 km and the direct selling reported in Figure 3 represents the weighted contribution of consumers' transport type based on the distance travelled with each vehicle.

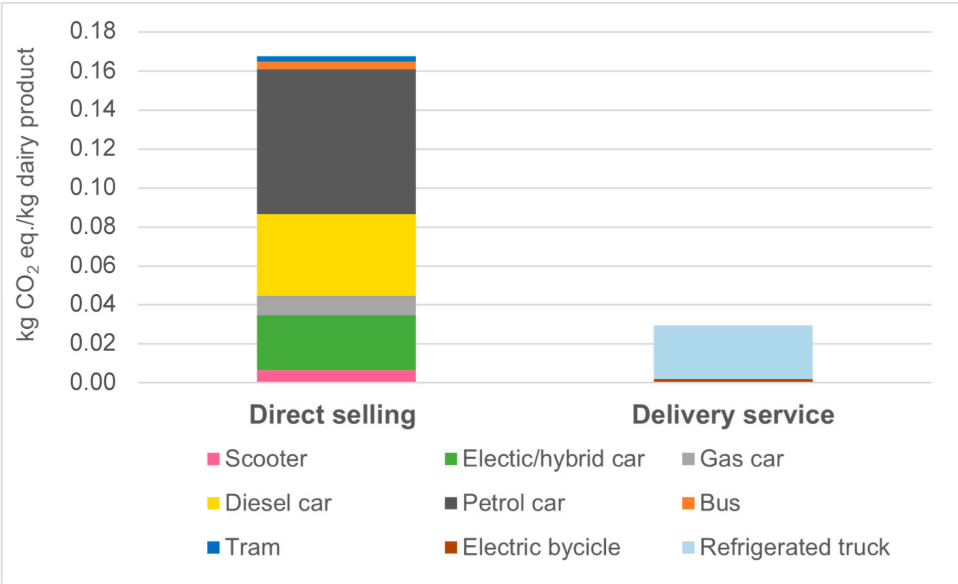

Figure 3. Comparison of emissions from the direct selling (consumers' transport) and the delivery system.

Although petrol and diesel cars had a greater incidence on the total distance travelled from home to market, most of the consumers (35%) chose to move on foot. The environmental impact of direct selling of 1 kg of dairy product was 0.17 kg CO_2 eq. The emissions related to the delivery service accounted for 0.03 kg CO_2 eq. per kg of dairy products transported and were mainly affected by the transport with refrigerated trucks from the delivery center to the distribution hub, whereas the emissions of the electric bicycle for the order distribution from the hub to consumers' home contributed to a lower extent.

Uncertainty Analysis

To determine the uncertainty of the CF, the results were subjected to a Monte Carlo analysis using the SimaPro software v.9.1.1. The Monte Carlo method is a statistical simulation based on a numerical calculation guided by probability statistical theory [40]. In the present study, 1000 simulations were run to form the uncertainty distribution of the results. To guarantee an accurate uncertainty analysis and to also consider the unavoidable errors in data collection, the uncertainty of the inventory dataset through the pedigree matrix was assessed previously. The Monte Carlo results are reported in Table 5.

Table 5. Results of 1000 Monte Carlo simulations of 1 kg of fresh milk, yogurt, mozzarella cheese, fresh cheese, and aged cheese from cradle to grave.

CF	Unit	Mean	CV, %	95% CI	
Fresh milk	kg CO_2 eq.	4.39	4.63	4.14	4.68
Yogurt	kg CO_2 eq.	5.10	5.95	4.81	5.45
Mozzarella cheese	kg CO_2 eq.	9.82	7.11	8.96	10.85
Fresh cheese	kg CO_2 eq.	8.40	7.22	7.60	9.37
Aged cheese	kg CO_2 eq.	15.34	7.29	13.97	16.95

CV = Coefficient of variation; CI = Confidence interval.

4. Discussion

The CF values of cow dairy products were already calculated in several studies and ranged from 1.2 to 12.7 kg CO_2 eq. [8,41,42]. Although the LCA methodology standardizes the environmental evaluation of a product, such wide variability mainly depends on the animal production system, manufacturing processes, dry matter in the product, and the allocation methods adopted.

In our study, the production of raw milk provided the greater contribution, mainly due to the CH_4 and N_2O emissions from enteric fermentation, manure management, and crop production. This trend has been already described in previous studies referring to yogurt [43] or cheese [44], which both reported that more than 60% of the CF was due to farm activities.

However, present data on GHG emission were higher than most of the baseline CF values of Italian cow milk evaluated at farm gate [45–47]. The rationale behind this difference likely stays on the lower production efficiency of the system analyzed herein (Italian Pezzata Rossa cattle raised under an extensive system) compared to the systems considered in the studies cited above (Holstein cows raised in intensive confined systems). Furthermore, animals involved in our study were fed diets based on high levels of forages that represented 100% of the ration for lactating cows and fattening calves, and the 85% for heifers' diet (the only category fed with a quote, 15%, of concentrate). It is well known that a high forage content in the ruminants' diets strongly affects the enteric methane emissions [48].

O'Brian et al. [49], compared the CF of cow milk coming from high-performing confinement systems or from grass-based dairy farms. These authors reported lower values of GHG emissions per unit of milk derived from confined systems and indicated a CF from 27% to 32% lower in top-performing herds.

Due to their low production efficiency, the CF may provide a misleading idea of the extensive pasture-based livestock systems when compared to intensive farming. We have to consider that the extensive systems may provide a wide range of ecosystem services with a positive impact on the environment, such as biodiversity and landscape conservation, soil protection, C-sink, agro-ecotourism, rural communities', and cultural heritage [50]. However, among these ecosystem services, only the C-sink is accountable in the CF scheme [6].

The conservative agriculture practices and grassland management considered in the present study have high C-sink potential [51] and may represent an important mitigation strategy to climate change [52]. The C-sink into the soil is a long-term process that represents a method of slow sequestration of atmospheric CO_2 by plants photosynthesis that is then directly stored into the soil throughout plant residuals and indirectly by organic carbon released at pasture through animal feces. As stated by [53], rotational grazing enhances the soil C storage capacity by keeping the pasture in a vegetative state and guarantying the continuous release of biomass on soil, whereas conservative practices, as minimum tillage, prevents the soil disturbance and the oxidation of the organic carbon.

Despite the practices for improving soil carbon, several factors can affect the amount and durability of carbon stored (e.g., climatic conditions and human activities). Therefore, carbon can either remain stored in soils for millennia, or be quickly released back into the atmosphere. The C-sink, calculated with the approach defined by [36], refers to a projection of 100-year time and considers the temporal aspects of soil carbon changes by combining the degradation and emissions of CO_2 from soil and the following decline in the atmosphere.

Although, there is no commonly accepted methodology to include contribution from soil C-sink in the CF, the approach proposed by Petersen and colleagues [36] seems to provide more precise and realistic results and allows for designing mitigation strategies with higher precision compared to other methods [14].

In the cheese-making plant, the primary factor driving over 50% of the GHG emissions at this stage of dairy-product processing was energy consumption. This high level of emissions is attributed to the use of electricity and diesel in manufacturing operations and for cold storage. The leakage of refrigerant gas provided a great contribution to GHG emissions at the dairy plant because the refrigerant gas R404a used in the cold storage had a relevant GWP. A reduction in environmental impact related to the transformation process is possible, especially by improving the machineries efficiency with new technologies that allow a low energy consumption and low request of refrigerant gases [54]. In addition, introducing blends of low-GWP gases, such as hydrofluoroolefins (HFOs) and hydrofluorocarbons (HFCs), may reduce the GWP of refrigerants [55].

Since the dairy plant is a multifunctional site aimed at transforming several co-products, the application of allocation criteria is necessary. However, different ways are suitable to allocate the dairy flows (mass, economic, physicochemical) and the choice of the allocation method may deeply influence the results of LCA studies [8].

Manufacturing plants show a wide variability of transformation processes involved in dairy production, and different dairy products LCAs used an economic allocation to evaluate them. However, the prices of products may depend on external factors not involved in the investigated system such as price fluctuation, demand, and industry subsidies. Therefore, the allocation method based on the total solids of dairy products (fat, protein, lactose, and minerals) may better weigh the intra-industry flows and permit a more effective resource allocation by reducing errors [56].

Each dairy product investigated in this study was evaluated by considering the relative packaging in terms of material type and weight per kg of product. The use of plastic materials (PET, PP, and HDPE) for fresh milk, yogurt, mozzarella cheese, and fresh cheese showed a higher GHG contribution compared with the plasticized paper used to pack the aged cheese. Nowadays, the most common packaging for dairy products employs plastic materials, glass, or paper combinations to provide and maintain the highest quality of the product after the processing stage. However, novel technologies offer several chances to increase the sustainability of packaging materials for dairy products without affecting their shelf life. These include the use of bioplastic, natural fibers containers made of completely biodegradable or recycled materials, and innovative packaging designed for higher distribution efficiency that saves space during storage and transportation [57].

From the retail and distribution stage, the greater contribution of GHG emissions came from the leakage of refrigerant gas from the cold storage cells. To account for these emissions, 5% of annual losses of refrigerant gas and an average storage duration of 3 days before the selling were considered. The distribution of dairy products and energy use at retail contributed less to GHG emissions. Therefore, the reduction in the environmental impact of the retail and distribution stages can be mainly achieved by monitoring the refrigerant systems with periodic checks, and by replacing the obsolete cold cells with sustainable and high-efficiency models. Additionally, the research in eco-friendly refrigerant systems showed promising alternatives in the use of low emissive gas mixtures, which may reduce the GWP without compromising the performance of the refrigerators [55].

To evaluate the emissions during the purchase phase, two selling options were considered: the direct selling at market and the delivery service at consumers' home. Direct selling involved the transport of customers from home to the market and was characterized by considering the vehicle used and the distance travelled. The weighted average between these two factors was calculated to assess the emissions, and the contribution of direct selling to the CF of the products studied was $4 \pm 3\%$. Among the consumer sample, 41% moved on foot, by bicycle, bus, or metro, which represent low or zero-emitting transports. A high incidence of these types of transport allowed the mitigation of the environmental burden of car emissions and reduced the overall GHG contribution of this stage for the local supply chain studied. Beyond the use of sustainable transport, the emissions of direct selling can be further reduced by purchasing different items/shopping trips, which would permit the allocation of the transport emissions to a larger number of products [58]. The comparison of direct selling and delivery service to purchase 1 kg of dairy products showed a relevant reduction in the environmental burden when the delivery service was chosen, and a total of 0.14 kg CO_2 eq. was avoided per kg of dairy product. The first explanation for the lower emissions refers to the shopping trip travelled by the delivery service, which involved the transport of different orders delivered along the daily path. Therefore, the environmental impact of 1 kg of dairy products was allocated considering the overall loading involved in the total delivery shipping. Additionally, the use of electric bicycles to transport the orders from the distribution hub to consumers' home contributed to lower GHG emissions compared to vehicles used by the customers.

Home consumption of dairy products, which included domestic cold storage and packaging disposal, provided a smaller contribution in the downstream stage compared to the emission from retail and purchasing. The transport of municipal waste and landfilling of packaging accounted for 0.002 kg CO_2 eq., whereas the emissions of a home refrigerator were 0.1 kg CO_2 eq. per kg of dairy product, which mostly referred to the energy consumption. It is notable that consumers' consumption of dairy products was the lower contributor to GHG emissions compared to the consumption phase of other food products because of the lack of the cooking process, which usually has a significant impact on this stage.

5. Conclusions

In the present study, GHG emissions were calculated to evaluate the CF of a local Italian dairy supply chain. The hotspot analysis showed that the greater emissions for each dairy product were due to on-farm activities, whereas the contribution of cheese making, selling, and consumption stages was significantly lower.

Several strategies were discussed that may reduce the GHG emissions over the entire life cycle of dairy products and increase their sustainability. However, since the major contributor to the CFs was identified at the farm level, the main improvement actions should take place during this phase. The rotational grazing and minimum tillage were examined and showed an important mitigating effect by soil C-sink capacity.

Consumers' transport can affect the environmental impact of dairy products during the purchasing stage, mostly by choosing fossil fuel vehicles. The environmental burden of direct selling strongly depends on consumers' behavior that can contribute to reducing the overall impact, preferring zero or low emissions transports.

A delivery system centered on distribution hubs and reliant on low-emission vehicle utilization might be more sustainable than making direct grocery shop purchases using fuel vehicles.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/dairy5010017/s1, Table S1: Significance analysis; Table S2: Pedigree matrix; Table S3: Consumers' questionnaire; Table S4: Emission factors of materials and energy used to assess the carbon footprint of dairy products.

Author Contributions: Conceptualization, A.V.; formal analysis, C.R. and G.G.; funding acquisition, N.L.; methodology, C.R., G.G. and A.V.; supervision, N.L. and A.V.; writing—original draft, C.R.; writing—review and editing, G.G., N.L. and A.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Union Next-GenerationEU grant number J83C22000830005 within the "National Research Centre for Agricultural Technologies" research programme. This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article/Supplementary Materials, further inquiries can be directed to the corresponding author.

Acknowledgments: The authors want to thank the dairy farm "Fattoria Faraoni", Sutri (VT, Italy), the consumers involved in this research and the delivery service "Zolle", Roma (RM, Italy), for the support in providing essential information through the surveys.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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