

Article

Efficiency and Emissions Performance in Latvian Dairy Farming: An LCA-Based Comparison Across Farm Sizes

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Abstract

The European Union's (EU's) climate neutrality agenda prioritises sustainable agriculture, within the scope of which the dairy sector is central to food security, rural life, and trade competitiveness. While Latvia's contribution to milk production in the EU is comparatively small, dairy farming constitutes a structurally important sector in the country that must reconcile economic sustainability with environmental concerns, including greenhouse gas (GHG) emissions and resource use. Therefore, this study's research aim is to identify key environmental hotspots and explore the relationship between productivity, economic performance, and sustainability using the life cycle assessment (LCA) approach in farms of different sizes in Latvia. This study applies an LCA methodology to evaluate environmental hotspots and investigate the relationships between the productivity, size, and economic performance of Latvian dairy farms; in addition, the GHG emissions of Latvian dairy farms are analysed. Small farms dominate by number in Latvia, while the largest farms have the highest yields and milk quality, and are more economically sensitive due to their high production costs. The LCA results show that large farms have the highest absolute environmental impacts—particularly milking and feed production—though the emission intensity per kilogram of milk is lower than that in small farms. These findings indicate productivity–profit trade-offs when considering environmental impacts, with milking and feed emerging as the key areas for enhancing sustainability.

Keywords: dairy farming; life cycle assessment; greenhouse gases; emissions; hotspots



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1. Introduction

In the EU, sustainability has become a core objective. Current EU strategies emphasise achieving climate neutrality by 2050, advancing the green transition, and ensuring that this transition is just and equitable [1]. Nonetheless, it is also considered important to ensure a high quality of life, particularly regarding agriculture, food security, water resources, and ecosystem health [2]. Milk production is the foundation of the agricultural economy in the EU, from which rural settlements derive their livelihoods, achieve trade balances, and ensure food security. The EU produced 165 million tons of milk in 2017, with Germany and France leading the way in milk production among EU countries. Although Latvia is recognised as one of the smallest milk producers in the EU [3], dairy farming remains a crucial sector in Latvia [4]. The EU is a significant player in the global dairy trade, accounting for approximately one-third of the world's dairy product exports and maintaining a substantial presence in overseas markets [5]. Milk production worldwide has been on the increase, stimulated by the rise in demand, dietary changes, and enterprises that supply farms with production factors [3]. However, studies have identified the dual dilemma of

dairy farming regarding the trade-off between profitability and environmental pressures, as a response to climate change and resource limitations [6]. Emerging trends, such as the geographic reallocation of milk production to nations in the Global South and mechanised intensification, are influencing both economic and ecological performance [7]. To address these demands, global eco-efficiency modelling systems integrating indicators derived from LCA with farm data enable the quantification of sectoral efficiency [8]. Increasing milk yield per cow reduces resources and emissions per unit of milk produced, making the entire system eco-efficient [9,10]. Increasing productivity can reduce inputs—such as animals, feed, land, and water—by 25–33% per million metric tons of energy-corrected milk, resulting in measurable environmental benefits [10]. However, regulatory circumstances can affect cost efficiency, with more stringent regulations having the effect of reducing economic efficiency through overcapitalisation and reliance on domestic feed [11]. Understanding the impacts of milk yield and farm size on environmental performance and profitability is crucial for developing sustainable dairy farming policies [6]. Bigger farms are more likely to have better yields and profitability but may have higher GHG emissions per hectare than smaller farms, requiring additional specialised policy instruments. Cluster analyses have revealed that farm size and environmental indicators respond differently across farm types [12]. It is necessary to utilise various multi-criteria tools that integrate economic, environmental, and social indicators, allowing for the identification of optimal configurations and trade-offs [10,13]. Italian farm studies and LCA results have suggested that farms can achieve high economic, environmental, and social performance simultaneously, indicating that conventional trade-offs between profitability and sustainability can be reduced [14]. Aiming to combine farm-level economic indicators, milk yield information, and cradle-to-gate life cycle assessment to identify key economic and environmental hotspots in dairy production, integrating LCA with life cycle costing and the Integrated Farm System Model, allows for robust quantification of performance, emissions, and resource use [15,16]. Previous livestock LCA studies have omitted some impact categories; thus, this study presents a broader set of indicators to better capture relevant trade-offs [16]. Cradle-to-gate approaches are most suitable for assessing GHG emissions, water use, and land use in dairy systems, even though more data are still needed throughout the value chain [17].

Global concerns regarding climate change, resource scarcity, and sustainable agriculture make it critical to evaluate both the economic and environmental performance of dairy farms. Despite extensive research globally, there is a lack of comprehensive data linking economic performance, milk yield, and environmental impacts across differently sized farms in Latvia. Therefore, this study's research aim is to identify key environmental hotspots and explore the relationships between productivity, economic performance, and sustainability using the LCA approach, considering differently sized farms in Latvia.

According to data from the Latvian Environmental Geology and Meteorology Centre, emissions from agricultural soil management accounted for the largest share (47.1%) of the sector's total emissions in 2023. Emissions from farm animal intestinal fermentation processes were the second-largest source of agricultural emissions, generating 41.6% of total agricultural emissions. Manure management contributed 7.6%, while liming and urea use together accounted for 3.7% of total agricultural emissions in 2023 [18].

The remainder of this paper is structured into five sections. Section 2 describes the research methods, as well as the data and materials used for calculations. Section 3 summarises the calculation results, comprehensively analysing the economic and environmental indicators of differently sized dairy farms in Latvia, using various methodologies, including LCA and the Intergovernmental Panel on Climate Change Guidelines (IPCC Guidelines). Section 4 presents a discussion of the main research results based on the scientific literature

and an analysis of empirical research studies. Section 5 summarises the main conclusions and future research priorities.

2. Materials and Methods

2.1. Initial Steps of the Methodological Framework

The step-by-step methodological framework of the study is shown in Figure 1. First, the scientific literature in the Scopus database and other sources was reviewed to identify different methodologies for GHG emission calculations. The literature review focused on LCA and the 2006 IPCC Guidelines [19], including studies focused on dairy farming in Latvia to determine the environmental impacts and GHG emissions associated with different farm size groups. Although studies typically report total emissions in a country or in the agricultural sector, more accurate information is needed—at the very least, at the level of different farm size groups—for policymakers to develop the necessary incentive measures to reduce such emissions.

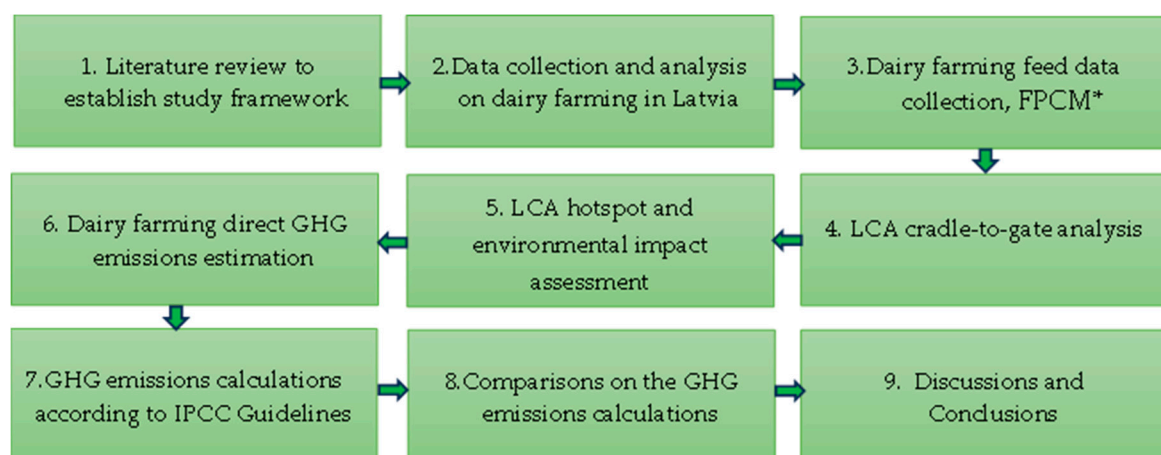


Figure 1. Step-by-step methodological framework of the study. * FPCM: fat- and protein-corrected milk.

In the second step, it was necessary to understand the economic characteristics of dairy farming. Therefore, Latvian data from the Farm Accounting Data Network (FADN) database for 2021–2023 were used for a detailed analysis of the economic income and cattle composition of dairy farms, broken down according to their economic size. The economic size of farms is one of the main categories used in the EU typology for classifying agricultural holdings, which is measured as the total Standard Output (SO) of the holding expressed in EUR. The SO is the average monetary value of the farm output according to the farm-gate price of each agricultural product (crop or livestock) in a particular area. In Latvia, only farms exceeding an economic size of 4000 EUR SO are defined as commercial and evaluated in the FADN database. Farms were divided into six groups based on their economic size in SO: 4–<15, 15–<25, 25–<50, 50–<100, 100–<500, and ≥ 500 thousand EUR [20].

As the FADN provides selected data for representative dairy farms in Latvia, it does not include all farms and data on milk quality indicators are not available. Consequently, in the third step, it was necessary to obtain dairy farming data regarding milk quality for the country. Therefore, the Rural Support Service (RSS) database, which contains farm statistics including the number of cows, herds, milk yields, and milk quality indicators (i.e., milk fat and protein content), was utilised [21]. Each herd was regarded as representing one farm. To ensure an in-depth analysis, all dairy farms were categorised into three sizes: small-sized dairy farms (1–50 dairy cows), medium-sized dairy farms (51–200 dairy cows), and large-sized dairy farms (201 dairy cows and larger). The data were compiled as of

the year up to 30 September 2024 (thus considered as data for 2024), and aggregated for each of the three groups, based on the total number of dairy cows, average milk yield per cow, and milk quality parameters. Data from the FADN was compiled for the 2021–2023 period, providing an overview of the dairy sector in Latvia. To compare the various milk quality and yield values per year, milk yield was recalculated to what is known as fat- and protein-corrected milk (FPCM; in kg), assuming a conversion to FPCM with 4.0% fat and 3.3% protein.

While approaches in the scientific literature for calculation of the FPCM differ, the prevailing approach is to use the following two formulas.

- (1) According to the International Dairy Federation, the FPCM should be calculated using Formula (1) [22]:

$$\text{FPCM}_{\text{IDF}} (\text{kg}/\text{year}) = \text{Production} (\text{kg}/\text{year}) \times (0.1226 \times \text{True Fat} (\%) + 0.0776 \times \text{True Protein} (\%) + 0.2534) \quad (1)$$

- (2) According to the United Nations Food and Agriculture Organization (FAO) (2007), the FPCM should be calculated using Formula (2) [23]:

$$\text{FPCM}_{\text{FAO}} (\text{kg}/\text{year}) = \text{Raw milk} (\text{kg}/\text{year}) \times (0.337 + 0.116 \times \text{Fat content} (\%) + 0.06 \times \text{Protein content} (\%)) \quad (2)$$

Both formulas for FPCM were calculated to obtain descriptive statistics and analyse the Latvian dairy sector. For LCA and per 1 kg of emissions, the FPCM_{FAO} formula was used.

In the LCA model, the functional unit was set for FPCM, with the output being the per cow annually generated FPCM_{FAO} amount, while the input was the respective feed amount per cow annually. The average dairy cow's active milking lifespan is 3–4.5 years in high-income countries [24]. As LCA was performed for comparison of the three dairy farm size groups, the annual data were not multiplied.

According to the International Organization for Standardization (ISO) standards [25], it is recommended to avoid allocation whenever possible. However, in this study, allocation was necessary due to the significance of the animals as a co-product of milk. According to the EU Commission, the default allocation factor for cattle farming is based on mass for animals (for live weight, 12%, and for milk, 88%) [26]. This allocation was also used in the LCA research conducted in SimaPro (see Section 2.2), which was applied to all farms, and served as the basis for the obtained results.

2.2. Environmental Impact Assessment Through the Cradle-to-Gate LCA Technique

LCA was performed according to the study's overall framework (Steps 5 and 6). To further evaluate the hotspots of environmental damage and assess whether the feed and size of dairy farming operations differ, LCA was performed with the use of SimaPro 10.2.0.2 and the Ecoinvent 3.0 database. Cut-offs were determined via a classification system, using ReCiPe 2016 Endpoint (H) V1.11/World (2010) H/A [27]. The research focused on emissions linked to milk production until the farm gate. The SimaPro software 10.2.0.2 (PRé Sustainability B.V., Amersfoort, The Netherlands) (further in text SimaPro), along with the Ecoinvent database, offers detailed life cycle inventories for various agricultural inputs. The constructed model encompassed upstream operations such as the manufacture and transport of feed, fertilisers, and other consumables, which are usually considered as Scope 3 emissions according to the GHG Protocol. While other Scope 3 emissions from post-farm activities (e.g., milk processing, packaging, distribution, and consumption) were not taken into consideration, the addition of these upstream inputs would provide a less fragmented view of the indirect environmental impacts within a cradle-to-farm boundary; however, the carbon footprint results would differ if a cradle-to-grave approach were used.

For LCA, there are two general approaches: bottom-up or top-down. As identified in ISO 14072:2024 [28], the bottom-up approach involves compiling various Life Cycle Inventories (LCIs) of an organisation's products, which are weighted by the quantity of products produced during the specified period, including associated utilities. In the top-down approach, it is essential to consider the organisation as a whole, and adding upstream models (known as “cradle-to-gate”) for all outputs is crucial. LCA enables the identification of key environmental hotspots and opportunities for improvement. Buxel et al. (2014) noted that “while LCA was originally designed to support decisions in the environmental engineering area, it is a tool that can also be used managerially to develop valuable and fact-based sustainability strategies within the company regarding its products and services” [29]. Therefore, the LCI process of LCA involves collecting data on resource inputs, energy consumption, and emissions to air, water, and land throughout a product's life cycle [30]. The life cycle impact assessment step should enable description and assessment of the environmental impacts of the inventory components. The LCA technique was applied in a cradle-to-gate manner, which involves analyses from raw materials through to manufacturing, including at the factory/farm level [30]. This required defining the functional unit and allocation method, as well as data collection for LCI—including feed data and milk output for each farm size according to the RSS data (see Figure 2).

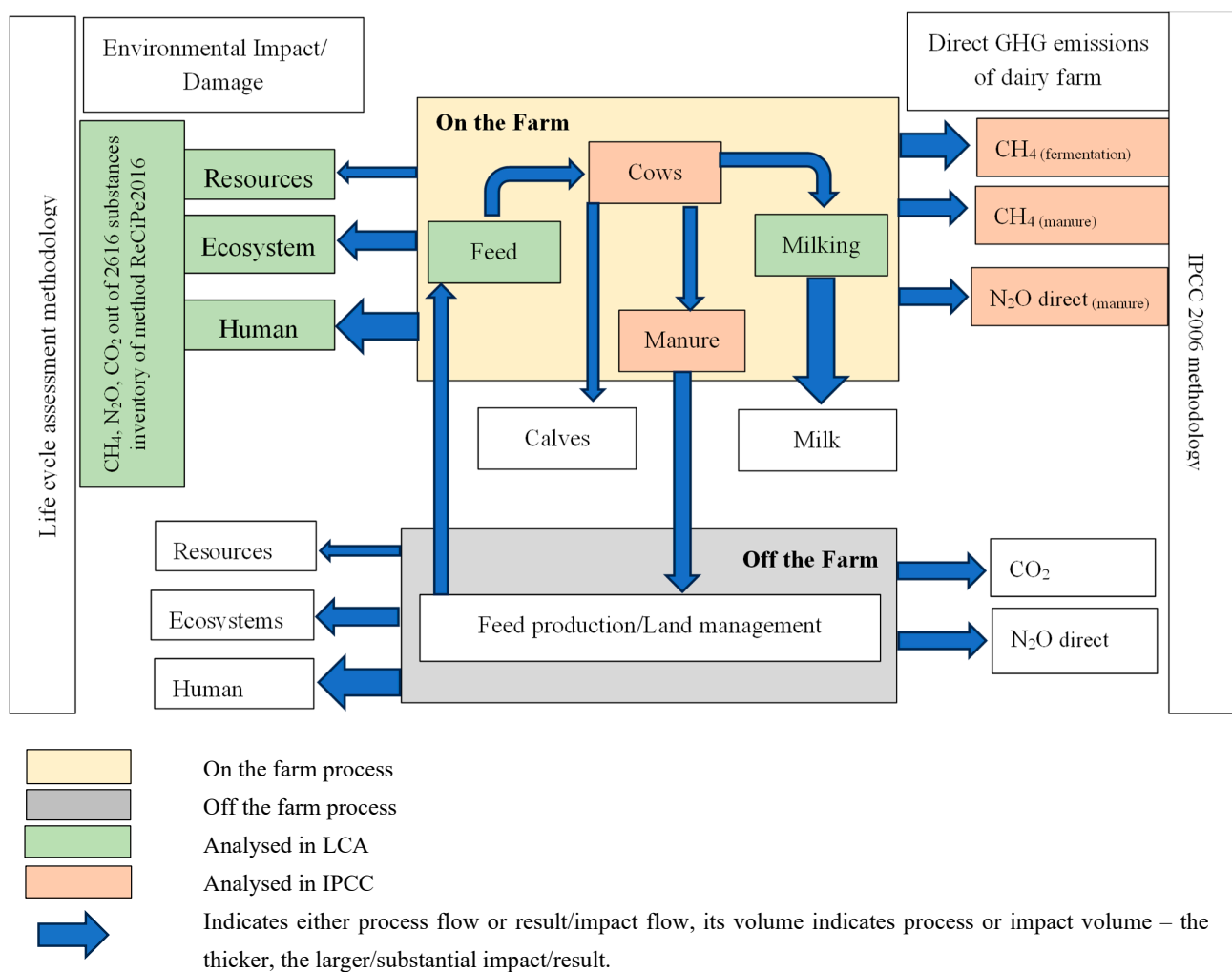


Figure 2. Schematic overview of the milk production system and analysis components.

The dairy farming feed structure and components for Latvia were compiled from various sources: research articles, farmer advisory and consulting articles, and a hand-

book [31–33]. The types of fodder and rations in small, medium, and large farms (in kg dry matter per day) are listed in Table A1 in Appendix A. It can be observed that for large-sized farms, more emphasis is placed on the total mixed ratio of feed. For dairy farms with 1–50 dairy cows, significant focus is placed on the combination of legumes with grass silage, hay, and grass silage/haylage, with the addition of roots in the feed mixture also observed.

A total mixed ratio (TMR) was created in SimaPro based on inputs derived from Latvian Rural Advisory and Training Centre (LLKC) data [33], which are presented in Table A2 in Appendix A. TMR—well-balanced feed which is already premixed before feeding—is typically administered in medium- and large-sized farms to ensure homogeneity of feed and consistency in milk output and quality, but is less commonly used in small farms. While the TMR formulation varies with each farm, as a farm typically works in collaboration with feed sellers to optimise the formula for their own farm, the average recommendation from the LLKC was adopted in this study.

Averages per group, especially for medium- to large-sized farms, were used as assumptions for lactation phases. According to Degola et al. (2016) [31], lactation is distinguished as lasting for 150 days. According to the notes, the period from the beginning to the end of lactation lasts 305 days, with the lactation end phase lasting 155 days, while the dry period averages 40–65 days. To approximate the calendar year, the latter period was assumed to last 60 days. To calculate the average feed for medium- and large-sized farms, these period estimates were used for proportional estimation of the feed intake according to the following formula:

$$\text{Feed amount} = 150/365 \times \text{feed amount} + 155/365 \times \text{feed amount} + 60/365 \times \text{feed amount} \quad (3)$$

The nutrient composition in feed rations is summarised in Table A3 in Appendix A.

ISO standards (especially 14040:2006 [30] and 14044:2006 [25]) standardise the LCA process and are widely used globally [34], including in the life cycle inventory stage of the SimaPro software. For impact analysis in the SimaPro software, global ReCiPe2016 endpoint data were used, allowing the environmental impact assessment to be aggregated into a single score and compared between dairy farms of different sizes. The single score (Pt) was calculated by applying a weighting factor to each impact category to normalise the score in the damage assessment [35].

2.3. Calculation and Analysis of GHG Emissions

GHG analysis was performed according to the study's overall framework (Steps 6, 7, and 8).

According to the FAO (2007), GHG emissions from dairy farming are quantified as carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) emissions, including those from milked cows, animals for replacement in the herd, and surplus calves for meat. However, factors such as land use, capital goods, the retail stage, and disposal of packaging are excluded [23]. The GHG emission calculation was performed using LCA and the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [19].

To calculate the environmental impacts for the dairy sector—especially its contribution to GHG emissions—using the 2006 IPCC Guidelines, the results were based on calculations according to Formulas (4)–(8).

For CH₄ intestinal fermentation and manure, an annual, per country formula is used, as shown in Formulas (4) and (5) [19].

$$CH_4 (\text{intestinal fermentation}) = EF_{1(\text{Dairy cows})} \times N \quad (4)$$

where CH₄ intestinal fermentation denotes CH₄ emissions from feed intestinal fermentation in a country, expressed in kg of CH₄ annually; and EF_{1(Dairy cows)} is the CH₄ emission

factor/multiplier for dairy cows, which varies according to the 2006 IPCC Guidelines; for Western Europe, it is 117, and for Eastern Europe, it is 99 [19], while Popluga et al. (2019) calculated a specific value for Latvia, and obtained 141.2 kg of CH₄ emissions per dairy cow annually [36]—thus, this value was used for Latvia. Furthermore, N denotes the number of dairy cows in Latvia.

$$CH_4(\text{manure}) = EF_{2(\text{manure})} \times N \quad (5)$$

where CH₄_{manure} denotes CH₄ emissions from dairy cow manure in the country, expressed in kg of CH₄ annually; and EF_{2(manure)} is the CH₄(manure) emission factor/multiplier for dairy cows. For Latvia, Popluga et al. determined the value of this multiplier to be 17.28 [36]; however, according to the 2006 IPCC Guidelines, the coefficient is dependent on the temperature. According to Tradingeconomics, in 2024, the average temperature in Latvia was 8.51 degrees Celsius, which is below 10 degrees and, thus, corresponds to a coefficient of 11 according to the 2006 IPCC Guidelines [37]. As the indicator for Latvia has been calculated, it will be used.

For N₂O, an annual, per country formula is also used, as shown in Formula (6) [19].

$$N_2O_{Dmm} = N \times N_{ex} \times MS \times EF_3 \times 44/28 \quad (6)$$

where N₂O_{Dmm} denotes direct N₂O emissions from manure management (mm) in the country, kg N₂O annually; N is the number of dairy cows in Latvia; N_{ex} is the annual average N excretion per dairy cow in the country, kg N per animal annually (as of 2021, this is 119.90 according to Latvia's National Inventory Report 1990–2021 [38]); MS is the fraction of total annual nitrogen excretion for each dairy cow that is managed in a manure management system in the country, dimensionless (for Eastern Europe, this indicator is 0.35, according to the 2006 IPCC Guidelines); EF₃ is an emission factor for direct N₂O emissions from the manure management system in the country, kg N₂O-N/kg N in manure management system (for Latvia, the value of this factor is 0.005) (Popluga et al., 2019) [36]; and 44/28 is the value for conversion of (N₂O-N)_(mm) emissions into N₂O_(mm) emissions.

According to ISO 14067/2018 [39], GHG emissions other than CO₂ are expressed in CO₂eq by multiplying the respective GHG emissions using conversion coefficients for CH₄ and N₂O to CO₂eq (Formulas (7) and (8)). New conversion rates have been developed, according to Statistics Netherlands. Since September 2022, due to the IPCC's rules, the conversion factor for methane (CH₄) has been increased (from 25 to 28), while that for nitrous oxide (N₂O) has decreased (298 instead of 265) [40].

$$CO_2eq(1) = 28 \times CH_4 \quad (7)$$

where CO₂eq(1) denotes CH₄ emissions converted into CO₂ equivalent global warming units, methane kg per animal per year, and CH₄ is the methane emissions derived from fermentation and manure, summed together per dairy cow, in kg annually.

$$CO_2eq(2) = 265 \times N_2O \quad (8)$$

where CO₂eq(2) denotes the direct N₂O emissions converted into CO₂eq global warming units, nitrogen oxide kg per dairy cow annually; and N₂O is the direct nitrogen oxide emissions from dairy cows' manure per dairy cow, in kg annually.

Figure 2 illustrates the connections, commonalities, and differences between the LCA and 2006 IPCC Guidelines methodologies for calculating GHG emissions.

Figure 2 illustrates the separation and analysis components for on- and off-farm processes. On-farm refers to data and processes that take place on the dairy farm, including feed provided to cows and the milking process, as well as manure from cows; meanwhile,

the feed is prepared off-farm, and milk and calves/meat are also sold outside the farm (if the dairy farm itself does not process milk). Cradle-to-gate LCA analysis was performed for the on-farm processes from feed to milking (inclusive), thereby enabling estimation of the environmental impacts and their components. The separately analysed GHG emissions of CO₂, CH₄, and N₂O were also considered. These emissions were compared with the direct emissions—which result from cows and manure, according to the 2006 IPCC Guidelines methodology—and then the results were compared.

Research limitations: (1) Only direct on-farm GHG emissions for the dairy sector were calculated using IPCC Guidelines; (2) cradle-to-gate LCA was chosen for hotspot detection from annual data; and (3) off-farm processes were considered outside of the study's scope.

3. Results

The outcomes in this section are presented in three subsections. The first involves a comparison of dairy farms of different sizes, based on several sources of information. The second involves the evaluation and comparison of these farms by means of LCA. The third evaluates GHG emissions, which were estimated by employing different methodological strategies.

3.1. Characteristics of Dairy Farms in Latvia

According to statistical data, there were 113,000 dairy cows in Latvia at the end of 2024 [41], with an average milk yield per cow of 8239 kg, representing a 15% increase compared with 2020 [42]. The number of cattle and cows has shown a declining annual trend over the period 2020–2024, with 12%, 11%, and 17% reductions in total cattle, the number of cows, and dairy cows in 2024 compared with 2020 [43]. There were 58.6 thousand farms in Latvia at the end of 2024; of these, only 7194 farms (or 12%) were engaged in dairy farming [44].

An overview of the composition of dairy farms in Latvia in 2023, based on the FADN data, is presented in Table 1. While the FADN included 270 farms (or 4% of the total), these farms are representative of 74% of the total dairy farms in Latvia.

In Latvia, when a dairy farm's size exceeds 100 cows, its annual milk yield tends to increase significantly; the reason for this is that larger farms are typically commercial, large-scale operations and, thus, they are very focused on optimising the milk output amount. Therefore, they are also constantly adjusting and looking for the right feed mixture for yield optimisation. Most dairy farms, according to their economic size, are in the range of 15–50 thousand EUR SO.

An economic analysis indicated that the gross and net income per farm varies significantly. While the total net income in 2023 was negative, large farms represented the overall losses, despite having significantly—from 8 up to 90 times—higher gross income compared with other dairy farms. This outcome indicates the pressures that such dairy farms are experiencing despite their large size and possibility of economies of scale, with the cost of milk production in 2023 impacting the bottom line of the largest farms the most. The highest net and gross income were observed for farms with SO from 15 up to 100 thousand EUR, which also had the lowest milk yield per cow—from 5.10 to 5.66 tons per year. Meanwhile, larger farms with higher income, namely those with 100–500 and >500 thousand EUR SO—had lower profit or loss, respectively, but the highest yields. As such, high yields for the year 2023 came with additional pressure on net income for the largest dairy farms in Latvia. Therefore, to assess the differences and potential for environmental impact hotspots, a detailed LCA was carried out. As the six SO groups detailed above were too fragmented for analysis, the dairy farms were further aggregated

into three categories: small, those with 1–50 dairy cows; medium, with 51–200 dairy cows; and large, with 201 or more dairy cows.

Table 1. Characteristics of dairy farms by size groups in Latvia in 2021–2023 based on the FADN data [20].

Size Groups, 000 EUR/Indicators	Average per Farm	4–<15	15–<25	25–<50	50–<100	100–<500	≥500
Number of farms 2023	270	7	42	63	61	84	13
Number of farms 2022	276	29	47	64	59	67	10
Number of farms 2021	278	25	46	71	59	69	8
Farms represented 2023	5347	350	2085	1387	817	601	107
Farms represented 2022	5484	2101	1434	966	462	441	80
Farms represented 2021	5547	1974	1522	1068	460	454	69
Dairy farms as % of the total in the dairy farm sector 2023	5%	2%	2%	5%	7%	14%	12%
Dairy farms as % total farms 2023	24%	5%	39%	34%	32%	23%	18%
Average gross income per farm, EUR 2023	33,824	–14	8439	10,761	25,973	84,605	713,972
Average gross income per farm, EUR 2022	44,169	5876	10,360	21,362	48,764	159,853	1,266,762
Average gross income per farm, EUR 2021	30,731	5654	8041	15,575	33,159	125,697	843,218
Average farm net income per farm, EUR 2023	9586	–939	6959	7664	16,627	23,877	–13,976
Average farm net income per farm, EUR 2022	26,470	7473	10,687	17,696	32,326	82,687	570,454
Average farm net income per farm, EUR 2021	13,035	4396	6438	11,359	16,338	43,052	212,423
Average farm net income to gross income 2023	28%	n.a.	83%	71%	64%	28%	–2%
Average number of dairy cows 2023	20	3	5	9	18	54	344
Average number of dairy cows 2022	21	5	7	14	27	75	422
Average number of dairy cows 2021	21	5	7	13	28	78	455
Milk yield per cow, tons per year 2023	7.37	5.34	5.10	5.21	5.66	6.60	10.24
Milk yield per cow, tons per year 2022	7.26	5.22	4.84	5.45	6.03	7.22	9.79
Milk yield per cow, tons per year 2021	7.14	5.64	4.61	5.27	5.87	7.34	9.58

Compiling and analysing RSS data for dairy farms in Latvia, Table 2 shows that there are only 2794 farms (or 39% of the total in the country) under the milk monitoring system; however, these farms include 101,000 cows, accounting for 89% of the total number of cows in Latvia. The most significant number of herds in Latvia is attributed to small-sized dairy farms, with 1–50 cows per herd. It is important to note, as mentioned for the FADN data in Table 1, that very small but economically significant farms are not covered; however, by herd number, they are substantial, and a part of this group would not be covered in the FADN data. Small-sized farms also yield 21% fewer kg of milk per cow per year (p.a.) on average compared with medium-sized dairy farms, and 38% fewer kg of milk per cow p.a. compared with large-sized dairy farms. When breaking down the data for the small farm size category in more detail, it can be observed that the majority of herds are in the category with more than 4 to less than 15 cows per herd, comprising 1350 herds (or 48% of herds in the RSS milk monitoring system), while very small farms with 1 to 4 cows comprise 302 herds (or 11%). Together, farms with 1–15 dairy cows comprise over half (59%) of the dairy herds in Latvia, while producing only 9% of the total milk output in 2024 [43]. The medium-sized dairy farm group comprises farms with herds ranging from 51 to 200 dairy cows, generating 29% of total annual milk output in Latvia. In contrast, small farms generate only 24% of the yearly milk output despite having 9% more dairy cows compared with medium-sized farms. The majority (47%, or almost half) of Latvia’s annual milk output is generated by large-sized farms; that is, those with 201 or more cows per herd. Although there are only 79 such dairy farms, this group achieved the highest milk yield per cow, at 11,200 kg per year. The farms also differ regarding the quality of the milk they produce based on their size. When measured in terms of fat and protein components,

the highest fat content (4.17%) was found in milk from small farms, while medium farms had a lower average fat content (at 4.07%) and the lowest value of this indicator was found in milk from large farms (3.9%). The most significant variations from the average between herds regarding milk fat content were observed in the small farm group, ranging from 2.27% to 6.04%. In contrast, more consistent results were found among large farms, with fat content ranging between 3.04% and 4.74%. To compare milk yields when their quality indicators vary, FPCM has been used globally to recalculate and convert milk yields to a fat content of 4% and a protein content of 3.3%. Widely used approaches to calculating FPCM derive from two sources: the FAO and IDF formulas. However, it should be noted that these formulas can generate different results. For example, with the Latvian farm data, the FAO formula generated a lower amount of kg FPCM when compared with unadjusted milk yields per year. In contrast, the IDF formula yielded 24–26% higher FPCM kg milk per cow compared with the FAO formula, resulting in a higher average milk yield per cow in Latvia compared with the non-adjusted average milk yield in kg per cow (except for large-sized farms). Therefore, for LCA analysis, comparability was ensured by using the FPCM kg of milk yield per cow per year calculated via the FAO formula, which provides more conservative values.

Table 2. Breakdown of dairy production indicators and FPCM in Latvia by herd size for the year up to 30.09.2024 based on RSS data [20–23].

Indicators/Number of Cows per Herd	1–50	51–200	≥201	Total/Overall Average
Total number of herds (365-day average)	2404	311	79	2794
Average milk yield kg/per cow/per year	6990	8826	11,220	7314
Total number of cows	32,776	30,021	38,308	101,105
Total milk output, tons per year	231,060	273,248	441,392	945,701
% of total milk	24%	29%	47%	100%
Average fat content, %	4.17	4.07	3.90	4.15
Minimum fat content, %	2.27	2.74	3.04	2.27
Maximum fat content, %	6.04	5.63	4.74	6.04
Average protein content, %	3.34	3.38	3.43	3.34
Minimum protein content, %	2.84	2.90	3.13	2.84
Maximum protein content, %	4.49	3.85	3.70	4.49
Fat- and protein-corrected milk FPCM (kg/per cow/per year) (FAO formula)	5748	7164	8875	5999
Fat- and protein-corrected milk FPCM (kg/per cow/per year) (IDF formula)	7150	8962	11,185	7470
Deviation IDF/FAO formula	124%	125%	126%	125%

3.2. LCA Calculation Results for Dairy Farms in Latvia

The life cycle impact assessment (cradle-to-gate) results are shown in Table 3.

As can be seen from the impact data in Table 3, the most significant impacts are those related to fossil and mineral resource scarcity, fine particulate matter formation (leading to human non-carcinogenic toxicity), and the impacts on human health due to global warming. When comparing the three dairy farm size groups, the impacts were found to differ, especially between small- and medium-sized farms (with a difference of 2% to 58% in the presented indicators, being larger in the medium group compared with the small group), as well as between small- and large-sized farms (differences between 0% and 66%, with higher impact factors observed for large-sized dairy farms). Less deviation was observed between medium- and large-sized dairy farms (difference between 1 and 14%, with the exception of significantly lower terrestrial acidification in large-sized farms). Therefore, significant differences were observed when comparing the three groups of dairy farms regarding the environmental impact/damage categories. When expressed

in relative terms—that is, where 100% indicates the farm size with the most significant indicator and the respective values for farms of other sizes are expressed as a percentage of that main factor—it was found that for all 22 midpoint impact categories, large-sized farms were the main contributor, with exception of the terrestrial acidification category, where the main contributors was medium-sized farms, with an assigned value of 100% [43].

Table 3. Life cycle impact assessment (cradle-to-gate) midpoint comparison between Latvian dairy farms of three different sizes in 2024 [21,23,27,31–33].

Impact Category/Indicators	Unit	Life Cycle Impact Assessment of			Deviation		
		Small Farms (1–50 Cows)	Medium Farms (51–200 Cows)	Large Farms (≥ 201 Cows)	Medium—Small Farms	Large—Medium Farms	Large—Small Farms
Water consumption, Aquatic ecosystems	species.yr *	5.44×10^{-12}	8.00×10^{-12}	9.01×10^{-12}	47%	13%	66%
Water consumption, Terrestrial ecosystems	species. yr	4.06×10^{-8}	5.81×10^{-8}	6.31×10^{-8}	43%	9%	55%
Water consumption, Human health	DALY *	5.38×10^{-6}	7.60×10^{-6}	8.35×10^{-6}	41%	10%	55%
Fossil resource scarcity	USD2013	41.47	54.28877	57.91831	31%	7%	40%
Mineral resource scarcity	USD2013	0.86	1.085099	1.137804	26%	5%	32%
Land use	species.yr	1.05×10^{-5}	1.66×10^{-5}	1.73×10^{-5}	58%	4%	65%
Human non-carcinogenic toxicity	DALY	0.000206	0.00021	0.000211	2%	0%	2%
Human carcinogenic toxicity	DALY	0.000511	0.000634	0.0007	24%	10%	37%
Marine ecotoxicity	species.yr	5.48×10^{-9}	6.59×10^{-9}	7.19×10^{-9}	20%	9%	31%
Freshwater ecotoxicity	species.yr	2.80×10^{-8}	3.38×10^{-8}	3.69×10^{-8}	20%	9%	32%
Terrestrial ecotoxicity	species.yr	2.08×10^{-8}	2.71×10^{-8}	2.84×10^{-8}	30%	5%	36%
Marine eutrophication	species.yr	3.71×10^{-9}	6.58×10^{-9}	6.99×10^{-9}	77%	6%	88%
Freshwater eutrophication	species.yr	2.36×10^{-7}	3.03×10^{-7}	3.37×10^{-7}	28%	11%	43%
Terrestrial acidification	species.yr	1.92×10^{-6}	2.08×10^{-6}	1.92×10^{-6}	8%	−8%	0%
Ozone formation, Terrestrial ecosystems	species.yr	2.60×10^{-7}	3.45×10^{-7}	3.58×10^{-7}	33%	4%	38%
Fine particulate matter formation	DALY	0.001186	0.001397	0.001415	18%	1%	19%
Ozone formation, Human health	DALY	1.78×10^{-6}	2.35×10^{-6}	2.44×10^{-6}	32%	4%	38%
Ionising radiation	DALY	3.21×10^{-7}	3.69×10^{-7}	4.21×10^{-7}	15%	14%	31%
Stratospheric ozone depletion	DALY	3.55×10^{-6}	5.24×10^{-6}	5.27×10^{-6}	48%	1%	48%
Global warming, Freshwater ecosystems	species.yr	5.31×10^{-11}	7.51×10^{-11}	8.10×10^{-11}	41%	8%	52%
Global warming, Terrestrial ecosystems	species.yr	1.95×10^{-6}	2.75×10^{-6}	2.96×10^{-6}	41%	8%	52%
Global warming, Human health	DALY	0.000645	0.000911	0.000983	41%	8%	52%

* species.yr: ecosystem impact, expressed as the loss of species over a specific area, during a particular time in years. DALY: disability-adjusted life years, a measure of human health, described as the number of years of life lost and the number of years lived with disability combined, expressed in years [45].

How the midpoint impact categories detailed in Table 3 translate into three aggregated endpoint areas of production/categories—namely damage to human health, damage to ecosystems, and damage to resource availability—and the associated damage pathways are shown in Figure 3.

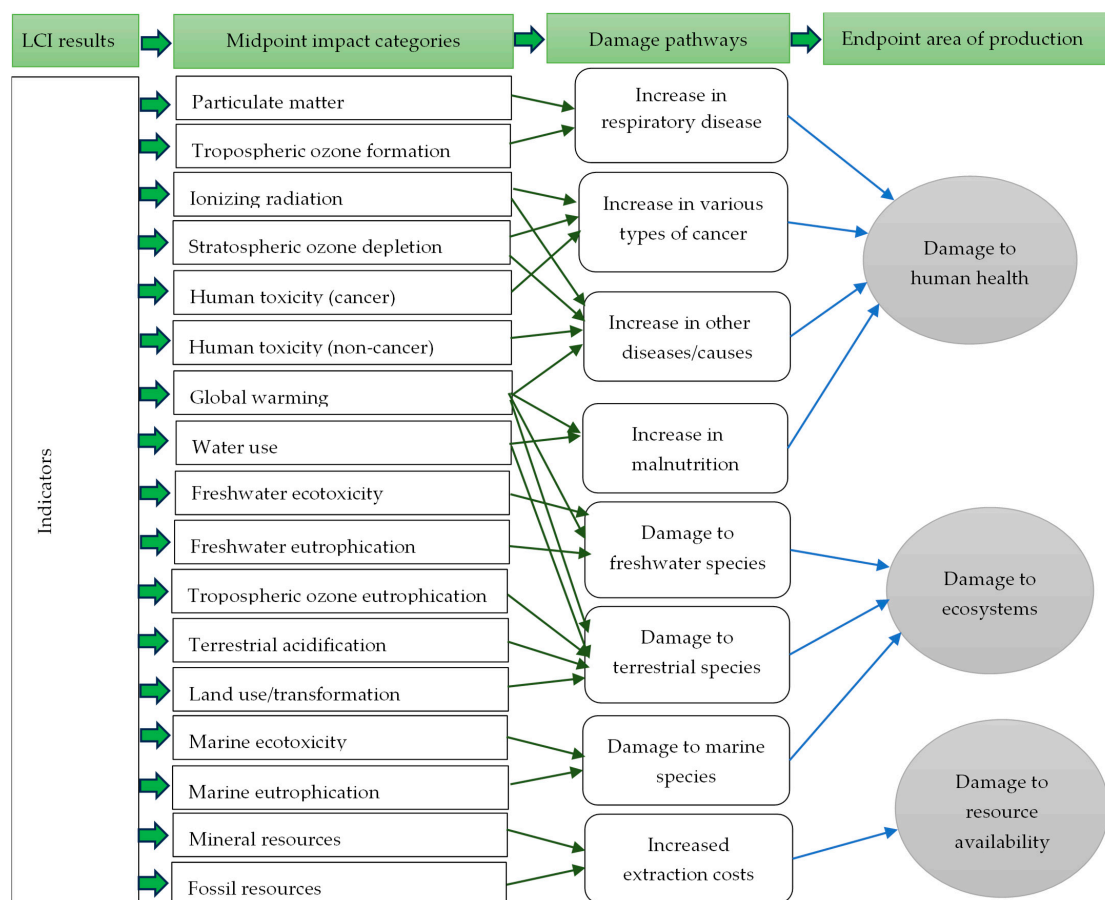


Figure 3. Presentation of the relationships between impact categories, midpoints, and endpoints in ReCiPe 2016 (SimaPro database manual—methods library) [45].

In Table 3, the results of an analysis performed for each damage impact factor are shown. To assess which of the three significant factors was the most impactful on the environment, Figure 4 represents the results as a unified single score.

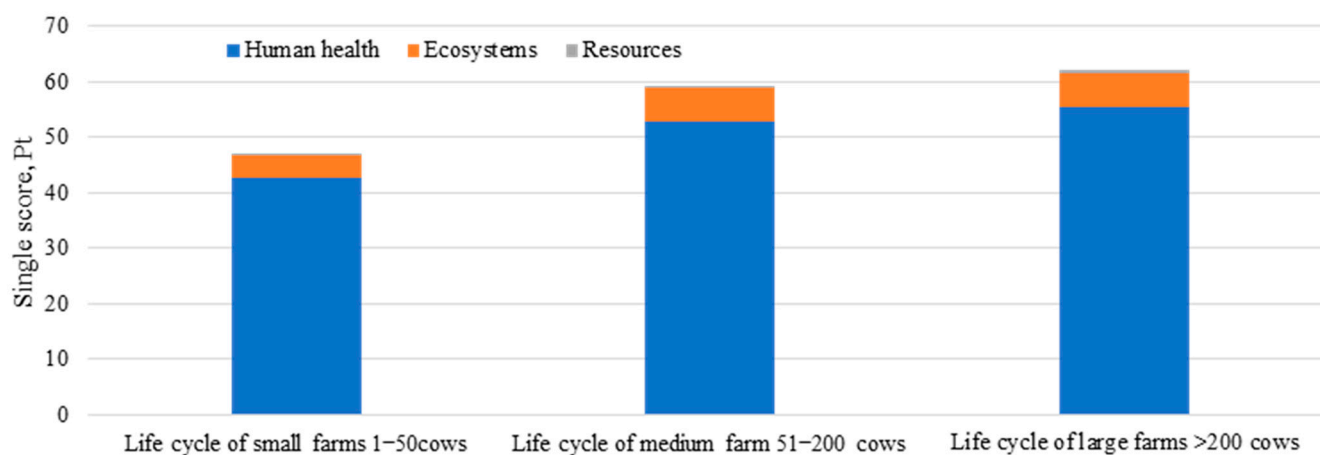


Figure 4. Damage assessment (cradle-to-gate) by farm size, and single-score impact grouped by environmental endpoint impact category in Latvia for 2024 [21,23,27,31–33].

Figure 4 shows that the most significant impact of dairy farming is on human health aspects, followed by a significantly lower impact on ecosystems and a minimal impact on resource scarcity. The hotspot affecting human health, as shown in the figure above, results from factors such as ozone depletion and particulate matter generation. The difference in impact is most obvious between small-scale dairy farms and medium- to large-scale dairy farms in Latvia.

The cradle-to-gate environmental impact (Table 4)—that is, covering from feed to milking—is a significant influencing factor that can be expressed as a single score, Pt, in ReCiPe. The most important factor, according to this score, is the milking process—comprising 34% of the impact of all processes analysed in small and medium farms, and 40% in large farms. This suggests an area for more in-depth exploration, potentially helping in the search for damage reduction possibilities. At the same time, differences can be observed between small farms and medium- to large-scale farms, with alfalfa silage serving as the second-greatest contributor in the latter (18% in large farms and medium farms) according to the overall damage assessment normalised score, while the contributor in second position for small farms is hay.

Table 4. Life cycle impact assessment (cradle-to-gate) comparison between different-sized dairy farms in Latvia, expressed as a single score (Pt), and its structure in 2024 [21,23,27,31–33].

Indicators and Sources	Small Farms (1–50 Cows)		Medium Farms (51–200 Cows)		Large Farms (≥201 Cows)	
	Pt	% of Total	Pt	% of Total	Pt	% of Total
Total of all processes	47	100%	59.2	100%	62.1	100%
Alfalfa–grass mixture, Swiss integrated	3.10	7%	2.88	5%	1.38	2%
Alfalfa silage, Global	4.59	10%	9.98	17%	11.4	18%
Barley grain, feed, Swiss production	3.38	7%	4.44	8%	4.15	7%
Fodder beet, Swiss	0.11	0%	0	0%	0	0%
Grass silage, Swiss	5.34	11%	6.04	10%	4.99	8%
Hay, Swiss	6.90	15%	2.99	5%	2.65	4%
Maize chop, Rest of the world	0.20	0%	0.433	1%	0.494	1%
Maize silage Swiss	0.14	0%	0.356	1%	0.453	1%
Milking process	16.20	34%	20.2	34%	25	40%
Mineral supplement, Global	0.54	1%	0.641	1%	0.624	1%
Molasses, Global	0.08	0%	0.0984	0%	0.125	0%
Rape meal, Global	1.06	2%	2.6	4%	2.09	3%
Soybean feed, Global	1.70	4%	3.69	6%	4.2	7%
Straw, Europe	0.12	0%	0.0999	0%	0.0777	0%
Total mixed ratio	0.00	0%	0.00151	0%	0.00172	0%
Wheat grain, feed, Swiss	3.63	8%	4.77	8%	4.45	7%

3.3. Comparisons of the Calculation of Direct GHG Emissions in Different Sizes of Dairy Farms in Latvia

The GHG emission calculation results obtained using the 2006 IPCC Guidelines methodology are shown in Table 5, while those using the LCA methodology are presented in Table 6.

Table 5. Calculation results of direct GHG emissions in 2024 for the dairy sector in Latvia, broken down by farm size group, according to the 2006 IPCC Guidelines methodology [19,21,23,36,38,40].

Indicators/Number of Dairy Cows	Unit	1–50	51–200	≥201	Total
Total number of cows in the size group	cows	32,776	30,021	38,308	101,105
CH ₄ (fermentation)	kg	4,627,999	4,238,979	5,409,090	14,276,068
CH ₄ (manure)	kg	566,373	518,765	661,962	1,747,100
CH ₄ to CO _{2eq}	kg	145,442,421	133,216,830	169,989,452	448,648,702
N ₂ O _{Dmm} (direct manure)	kg	10,807	9899	12,631	33,337
N ₂ O to CO _{2eq}	kg	2,766,626	2,534,069	3,233,563	8,534,258
Total CO _{2eq} , by size groups	tons	148,209	135,751	173,223	457,183
FPCM kg per cow, per year (FAO formula)	kg	5748	7164	8875	5999
CO _{2eq} per 1 kg of milk	kg	0.79	0.63	0.51	0.75

The main difference is that the number of dairy cows changes the emissions (Table 6). The deviation between groups regarding the number of cows would lead to the same deviation in the total direct emissions from the dairy sector. Notably, this gives rather simplistic and overall GHG emission results for the sector; as such, additional benefits can be gained through LCA to determine hotspots.

Table 6. Calculation results of direct GHG emissions in 2024 for the dairy sector in Latvia, broken down by farm size group, according to the LCA (cradle-to-gate) methodology [21,23,27,31–33].

Indicators/Number of Dairy Cows	Unit	1–50	51–200	≥201
Total number of cows	cows	32,776	30,021	38,308
Carbon dioxide, biogenic, per cow	kg	35.6	53.2	50.3
Carbon dioxide, fossil, per cow	kg	414	541	596
Carbon dioxide in the air, per cow	kg	2610	3290	3000
Carbon dioxide, land transformation, per cow	kg	49.7	107	122
Carbon dioxide non-fossil resource correction, per cow	kg	−96.9	−114	−155
Total carbon dioxide, per cow	kg	3012	3877	3613
Total carbon dioxide per whole group	tons	987,350	1,163,978	1,384,183
Nitrogen oxide N ₂ O per cow	kg	1.84	2.44	2.53
Nitrogen oxide per group	tons	60	73	97
Nitrogen in CO _{2eq}	tons	15,982	19,412	25,684
Methane biogenic, per cow	kg	0.0482	0.0608	0.0733
Methane fossil, per cow	kg	1.27	1.66	1.8
Methane total per cow	kg	1.3182	1.7208	1.8733
Methane per group	tons	43	52	72
Methane in CO _{2eq}	tons	1210	1446	2009
Total CO ₂ in CO _{2eq} , p.a.	tons	1,004,542	1,184,836	1,411,876
Deviation from the previous group	%	N/A	18%	19%
FPCM kg per cow, per year (FAO formula)	kg	5748	7164	8875
CO _{2eq} per 1 kg of FPCM milk	kg	5.33	5.51	4.15

As can be seen in this stage of the cradle-to-gate process, the primary emissions are attributable to the feed and milking processes. Therefore, these emissions should be calculated separately when comparing the three groups to obtain a more in-depth picture. Notably, the LCA results were 4–5 times higher than those obtained when using the 2006 IPCC Guidelines methodology. A reason for this could be that in the IPCC calculations, only the number of cows is taken into account, and the agricultural feed production side is

calculated separately. When evaluating the overall CO₂eq, it is evident that larger farms contribute more emissions; however, when recalculating per 1 kg of milk, it becomes clear that large farms actually generate the least emissions between the three groups per 1 kg of FPCM, making them more efficient. A similar result was also obtained when performing the evaluation using the 2006 IPCC Guidelines methodology; that is, the large-sized dairy farms generate the most emissions in CO₂eq, but when recalculating not per cow but per 1 kg of FPCM, large dairy farms were again found to generate the least emissions per kilogram of milk.

4. Discussion

4.1. Productivity and Economic Performance

This analysis examines the relationship between farm scale and several economic indicators, including gross and net income, as well as production-based indicators of farming sustainability such as productivity. This study considers the effects of herd size on milk yield, yield components, fat content, and protein content. It is worthwhile to address the reasons why larger agricultural operations produced negative net incomes when their gross revenues can be in the millions of dollars [6]. The economic resilience of small- and medium-sized farms was compared with that of larger farms, indicating vulnerability and economic adaptability in the dairy sector.

The analysis of various-sized dairy farms provides insights into their operational differences, as previously noted by Brkic et al. (2024), which can enable a comprehensive understanding of sustainable dairy production [6]. Additionally, it has been indicated that herd size does influence milk yield and quality, specifically, the fat and protein content, which is a critical area for optimising dairy farm productivity [46]. It was also observed in this study that larger herds yield significantly more milk per cow when compared with those in smaller-sized dairy farms. It can also be assumed that larger herds should benefit from economies of scale regarding infrastructure and bulk purchasing, which could lead to lower per-unit production costs [47]. However, the study of FADN data for Latvia in 2023 indicated that the largest farms (i.e., those with SO > 500 thousand EUR on average) experienced losses per year, when compared with smaller farms.

However, the relationship between herd size and milk quality varies; in particular, smaller farms tend to have higher fat indicators but a more significant deviation from the mean value. In comparison, larger farms have lower fat content with less variation, as shown in this study. Large farms may struggle to maintain consistent feed quality and individual animal health, which can influence the stability of fat and protein content in milk; for example, they try to focus on reducing feed purchase costs while optimising nutrient management. As noted by Holly et al. (2018), feed costs can make up a substantial part of total operating expenses [48]. Notably, feed costs typically represent the most significant single expense for dairy farms, often exceeding 50% of total operating costs; thus, it is essential—regardless of the size of the dairy farm—to maintain efficient feed management [49]. It has been established that the success of dairy farms largely depends on the breeds and productivity of cows, the farming conditions and technologies applied, as well as the quality of feeding and milking practices [50].

4.2. Environmental Impact and Sustainability

As yields and efficiency are crucial for a farm's survival, it is equally important to evaluate the primary sources of environmental impacts in dairy production, with a particular focus on the milking process and feed production; that is, the processes that contribute most to the environmental footprint of the dairy industry [51]. In this study, how the impacts vary based on the size of farms was investigated. The results indicated

a certain level of variability, with larger farms overall having a greater impact on the environment; however, contrasting results were obtained when the impact values were recalculated not per cow but per kilogram of milk, demonstrating that per kilogram of milk, large farms contribute least to environmental impacts. The decrease in the environmental effect per kilogram of milk is associated with the implementation of technologies and the increased efficiency of the system. At the same time, we also need to bear in mind that the lower the emissions, the more resources are used per hectare, which means the reductions are offset by the increases in productivity [52]. Accepting the specifics of the farms—including the strategies and the whole chain connected with the livestock industry—there is a need to generate a clear benchmark, which is developed to fit the different milk production scenarios of various regions, thus rejecting the “one-size-fits-all” approach and allowing for identification of the main impacts based on different production methods [53]. As previously noted, it is necessary to establish the size-specific contributions of farms to human health, ecosystem damage, and resource scarcity impacts [54], which was achieved in this research through an LCA based on the comparison of farms of various sizes. The analysis highlighted the primary areas of environmental impact and illustrated opportunities for targeted efforts to mitigate these impacts, enabling sustainable dairy farming [6]. Furthermore, CO₂eq emissions were specifically calculated according to LCA and 2006 IPCC Guidelines methodologies, further comparing the three different sizes of dairy farm. Additionally, total direct GHG emissions were assessed, as well as emissions per kilogram of FPCM, to investigate the variations in efficiency between small, medium, and large dairy operations regarding their environmental performance. This type of analysis regarding the interactions between dairy farming practices and environmental outcomes provides a framework for informed decision-making, supporting the pursuit of more sustainable dairy agriculture [10].

The overall purpose of such framework is to identify potential interventions that could minimise environmental burdens while maintaining economic viability and the social acceptability of dairy production [55]. The quality and nutritional value of the feed given to dairy cattle have a very significant influence on the total environmental impact of a milk production farm. If the feed is of low quality or poorly digestible, the methane emissions from enteric fermentation will increase, as the cows will have to use more energy to digest the fibre. Besides alterations in the composition and proportion of feed or concentrate, fats can also be used as additives in dairy diets to decrease the emission of gases from the respiratory tract. On the other hand, a high-quality, high-energy feed will enhance digestion efficiency and lower methane emissions per litre of milk [10]. Additionally, high-protein diets increase nitrogen excretion, which is the primary source of ammonia and N₂O emissions from manure. Precision feeding—that is, providing the right amount and type of feed according to animal’s nutritional needs—has been demonstrated to lower nitrogen emissions and to be beneficial from both environmental and economic perspectives [56]. An LCA-based study of an organic farm in Central Germany revealed that a diet based on grassland for cows with a low-input feeding regime—without maize silage and with limited concentrates—resulted in about 20% lower milk production, thus increasing emissions per kg of milk [57]. Therefore, the exploration of advanced feed practices, such as the use of different feed formulations, may significantly reduce the environmental impact per unit of milk produced, moving towards a more circular agricultural economy [58]. The dairy sector is recognised as a significant contributor to greenhouse gas emissions; therefore, it is necessary to examine the factors contributing to these emissions [59].

4.3. Balancing Productivity, Profitability, and Environmental Performance

The trade-offs between achieving high milk yields, economic viability, and lower environmental impact in the dairy industry are complex. In Latvia, it was observed that the highest milk yields per cow were achieved in large farms, which produce 47% of total milk in Latvia. Simultaneously, these farms had the lowest environmental impact and emissions per 1 kg of produced milk; however, the absolute largest farms experienced economic losses in 2023. While dairy production is essential for global nutrition, it faces significant environmental scrutiny [6]. Growing consumer demands, climate change, and global food security concerns necessitate a re-evaluation of traditional dairy management practices to enhance profitability and sustainability [60]. This re-evaluation should involve searching for strategies through which large farms may boost financial returns while reducing their ecological footprint. The policy and management implications for achieving sustainable intensification should also be examined [61]. Historically, improving productivity in ruminant systems, including dairy, has led to lower resource use and greenhouse gas emissions per unit product, mainly by diluting maintenance effects [9]. With respect to dairy production, high feed efficiency is key to minimising both feed costs and the negative impacts of milk production on the climate and environment. However, understanding of the relationships between feed efficiency, eating behaviour, and activity [62] remains limited. Achieving a balance between these factors is difficult, requiring the careful use of technology and management practices that maximise resource use without compromising animal welfare or economic stability [63]. Genomic selection and precise ration formulation can significantly improve the efficiency of high-performing herds, thus contributing to a lower environmental impact per unit of milk produced [64]. Nevertheless, despite these improvements, dairy systems continue to create environmental pressures, including direct GHG emissions from enteric fermentation, manure management, and feed production, as well as significant water and land usage [10]. On one hand, Salari et al. (2025) [55] argued that due to methodological variability and the much broader range of environmental impacts, the diversity of LCA studies rarely allows for direct comparisons. This level of complexity precludes any reasonable expectation of general conclusions across systems of production in a globally transferable way. Nonetheless, research confirms the importance of milk production in conventional and organic systems, being sustainable and decreasing the ecological burden, which is still possible if appropriate measures of productivity—especially best management practices and specific mitigation strategies—are applied.

The dimensions of a previous study focused on the carbon footprint in different parts of the world, such as the United Kingdom and Italy, were characterised by the researchers as broad. They noted that a broader LCA framework would drive the sustainability of environmental analysis, mainly given the resulting variation stemming from different farm management practices, reflected by factors such as feed digestibility, crude protein content, and environmental conditions [65,66]. Furthermore, farm efficiency causing environmental sustainability was the overall message of the study by Lovarelli et al. (2019) [67], who observed that the most efficient farms are not only the greenest, but also generate more revenue.

O'Brien et al. (2014) suggested that future surveys in Ireland should be conducted as broad-scale studies on larger, more diverse samples of commercial farms, with the purpose of assessing the performance of the full range of production systems and their environmental impacts [68]. On the other hand, researchers in Malta seem to think that alternative feeding strategies remain the only practical solutions if issues relating to energy requirements in processing and transportation are taken into account; they mainly referred to the replacement of protein sources, such as soybeans, due to the low energy cost of processing and the environmental consequences of transportation, making practical

recommendations. It seems reasonable for most European countries to follow Proietti et al. (2016) in arguing that dependence on imported feed needs can reduce protein requirements, and that locally sourced materials are a good option for livestock feeding, thereby enabling sustainability [69].

4.4. Methodological Considerations

When comparing dairy production efficiency across different farm systems and genetic lines, accurately normalising for milk yield to a standard such as FPCM is essential. This comprehensive approach is critical as variation in the composition of milk—particularly the amount of fat and protein it contains—can affect the nutritional quality of the milk and how well it can be processed in factories. In this study, it was found that it is especially crucial to determine which FPCM formula to use, through a comparison of the FAO and IDF formulas. The FAO formula resulted in more conservative results compared with that of the IDF; in the case of Latvia, the IDF showed 24–26% higher FPCM results. Notably, these variations influence the environmental implications per unit of functional output [70]. This adjustment also improved the accuracy of the LCA, as obtaining an environmental product measure involves standardising the functional unit. Standardising functional units allows for appropriate comparisons regarding environmental implications, such as greenhouse gas emissions, between different production regimes [64]. This generic methodology distinguishes specific processes, such as feed production, enteric fermentation, and waste management, which significantly affect the environment collectively. This methodology is also expected to help in planning specific reductions [71]. In many situations, the available datasets do not have enough information and/or lack scope, thus limiting the accuracy of assessments. As such, relevant collections of data need to be improved [55].

4.5. Policy Implications and Future Research Directions

The differences in how LCA studies have conceptualised, allocated, and framed (i.e., regarding functional units) make it difficult to compare the results of such studies [16,55]. The issues of differences in conceptualisation make it challenging to provide harmonised data and develop effective policy. Sustainable dairy production practices must therefore be evaluated in terms of their environmental benefits, cost-effectiveness, added value generation, and impacts throughout the supply chain, especially with varying herd composition and levels of milk production [58,72]. Uncertainties in current biodiversity quantification measures within LCAs also highlight the need for less complex frameworks as well as readily applicable tools [13,73].

Future research should focus on several directions: (1) Developing multi-criteria instruments that integrate environmental, economic, and societal elements of dairy systems [74]; (2) standardising and articulating LCA techniques, especially biodiversity concepts and functional units, to facilitate comparison between studies; (3) exploring the optimisation of feed, genetics, and waste management technologies as measures for enhancing efficiency, reducing methane, and limiting nutrient losses [66,71]; (4) assessing the abatement and cost-saving potential of alternative means of producing milk under a range of regional and market conditions; and (5) conducting longitudinal LCAs to track the improvement in GHG efficiency per unit of milk under increasing absolute emissions due to the increasing global demand for dairy products.

Given the consideration that livestock farming occupies 70–80% of agricultural land and contributes significantly to methane emissions [51,75], effective and harmonised LCA practices will be key to achieving climate objectives globally. As the demand for dairy is expected to grow by 70% by 2050, policies should be developed based on studies that aim

to maintain production while reducing emissions by up to 80% to mitigate the impacts of climate change [58,76].

5. Conclusions

In Latvia, milk production is dominated by a large number of small farms (1–50 cows), while medium- (51–200 cows) and large-sized farms (201+ cows) produce the majority of milk. The most productive yields per cow (approximately 11,200 kg/year) and consistent milk quality are found on large farms, whereas small farms exhibit higher variability and higher fat content. Economically, data from 2023 reflected robust pressures across all farm sizes. Large farms generated as much as 90 times more gross income than small farms; however, they still reported a negative net income due to high production costs. In contrast, small- and medium-sized farms fared better regarding net-to-gross income ratios, despite lower yields.

Meanwhile, LCA-based environmental assessments indicate that the most significant impacts were on damage of human health, followed by damage to ecosystems, and damage to resource availability, particularly due to the consumption of fossil and mineral resources, particulate matter formation, and global warming. Environmental burdens were found to differ most significantly between small/medium and large farms, with large farms incurring larger absolute burdens. Milking was the most significant contributor (34–40% of total damage source), followed by feed production, for which hay dominates on small farms and alfalfa silage on large farms.

When comparing the production of direct greenhouse gas emissions, the most significant absolute CO₂eq contributors were the large farms; however, they were found to have the lowest emission intensity per kilogram of FPCM of all farms. Emissions identified via LCA, considering feed, were 4–5 times greater than those obtained via the 2006 IPCC Guidelines methodology, illustrating the need for careful consideration of the system boundary selection and methodological approach.

Generally, while being more productive, large farms in Latvia are characterised by higher yields and efficiencies per unit of milk; however, they are also the most vulnerable economically and carry high environmental costs. Their smaller counterparts are less productive in terms of emissions and yield per cow but possess greater economic resilience due to their size. These findings highlight key trade-offs between productivity, profitability, and environmental impacts, and indicate the milking operation and feed composition as prime areas for effective mitigation in this regard.

Further research is necessary to advance the development of coupled multi-criteria tools, harmonise LCA methods, and improve feeding approaches to enhance the sustainability of the dairy industry in response to the growing global demand for dairy. Harmonised LCA practices need to be promoted by policymakers, who should encourage innovations to improve the efficiency of this sector while minimising the associated adverse environmental impacts.

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Abbreviations

The following abbreviations are used in this manuscript:

CO ₂	carbon dioxide
CH ₄	methane
CO ₂ eq	carbon dioxide equivalent
EU	European Union
EUR	euro
FADN	The Farm Accounting Data Network
FAO	The United Nations Food and Agriculture Organization
FPCM	fat- and protein-corrected milk
GHG	greenhouse gas
IDF	International Dairy Federation
IPCC	The Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
kg	kilogram
LCA	Life cycle assessment
LCI	life cycle inventory
LLKC	Latvian Rural Advisory and Training Centre
N ₂ O	nitrous oxide
SO	Standard Output
TMR	total mixed ratio

Appendix A

Table A1. The type of fodder and ration in small, medium, and large farms, kg dry matter, daily in Latvia [31–33].

Indicators/Number of Cows per Herd	1–50	51–200	≥201	Total/Overall Average
Hay	5.70	2.47	2.19	3.46
Haylage/Grass silage	6.20	7.02	5.80	6.34
Legume and grass silage	9.00	8.61	4.12	7.24
Corn silage	0.55	2.43	3.80	2.26
Straw	0.75	0.63	0.49	0.62
Roots	1.40	0.00	0.00	0.47
Fodder	4.05	4.31	3.49	3.95
Molasses	0.35	0.33	0.45	0.38
Expeller and meal	0.65	1.59	1.28	1.17
Salt	0.10	0.09	0.08	0.09
Minerals and vitamins	0.20	0.19	0.18	0.19
Total mixed ratio (TMR)	10.00	21.72	24.77	18.83

Table A2. Composition of Total Mixed Ratio feed per cow, kg, and its weight in total TMR feed in Latvia [33].

Indicators	TMR per Day in kg per Cow	% of Total TMR
Alfalfa grass silage	31	61%
Maize silage	7	14%
Wheat	3	6%
Barley	3	6%
Maize chop	1.5	3%
Soy expellers	2.7	5%

Table A2. *Cont.*

Indicators	TMR per Day in kg per Cow	% of Total TMR
Molasses	0.5	1%
Mineral supplements	0.18	0%
Fodder chalk	0.2	0%
Sodium	0.1	0%
Salt	0.05	0%
Water	2	4%
Total	51.23	100%

Table A3. Nutrient provision in feed rations in Latvia [31].

Nutrient Provision in Feed Rations/ Number of Cows per Herd	1–50	51–200	>201	Total/ Overall Average
Dry matter, kg	18.8	23.25	25.04	22.36
Crude protein, g	2565.295	2681.45	3322.59	2856.44
Crude fats, g	565.44	698.15	730.82	664.80
Crude fiber, kg	5.7	5.67	5.63	5.67
Nitrogen-free extract, kg	10.4	10.60	13.33	11.44

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