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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) climate neutrality agenda prioritises sustainable agriculture, and within that, the dairy sector is central to food security, rural life, and trade competitiveness. Latvia's contribution to EU milk production is comparatively small; yet, dairy farming constitutes a structurally important sector that must reconcile economic sustainability with environmental concerns, including greenhouse gas (GHG) emissions and resource use. Therefore, *the 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 different sizes of farms in Latvia. This study applies an LCA methodology to evaluate environmental hotspots and investigate the relationships between productivity, farm size, and economic performance of Latvian dairy farms. GHG emissions from Latvian dairy farms were analysed. Small farms dominate by number in Latvia, but the largest ones have the highest yields and milk quality, and are more economically sensitive due to their high production costs. 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 compared to in small farms. These findings present productivity-profit-trade-offs for environmental impacts, with milking and feed emerging as the key areas for enhancing sustainability.

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

## 1. Introduction

The EU has remained a core objective of sustainability; current EU strategies emphasise achieving climate neutrality by 2050, advancing the green transition, and ensuring that this transition is just and equitable [1]. Nonetheless, providing a high quality of life, particularly regarding agriculture, food security, water resources, and ecosystem health [2]. Milk production is the foundation of agricultural economics in the EU, where rural settlements derive 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 also 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, and is stimulated by the rise in demand, dietary changes, and enterprises that supply farms with production factors [3]. But current studies identify the dual dilemma of dairy farming in being capable of being profitable and alleviating environmental pressures, as a response to climate change and resource limitations [6]. Emerging trends, such as the geographical reallocation of milk production to nations in the Global South and mechanised intensification, are influencing economic and ecological performance [7]. To address these demands, global eco-efficiency modelling systems have integrated indicators of LCA with farm data to quantify sector 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 regulation having the effect of reducing economic efficiency through overcapitalization and reliance on domestic feed [11]. Understanding the impact 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 increased GHG emissions per hectare than smaller farms, requiring additional specialized policy instruments. Cluster analyses reveal that farm size and environmental indicators respond differently across farm types [12]. It is necessary to utilize 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 analyses suggest that farms can achieve high economic, environmental, and social performance simultaneously, indicating that conventional trade-offs between profitability and sustainability can be reduced [14]. 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. By integrating LCA with life-cycle costing and the Integrated Farm System Model, it provides a solid 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 capture trade-offs better [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].

Therefore, global concerns over climate change, resource scarcity, and sustainable agriculture make it critical to evaluate both economic and environmental performance of dairy farms. Despite extensive research globally, there is a lack of comprehensive data for Latvia linking economic performance, milk yield, and environmental impacts across different farm sizes. Therefore, *the research aim* is to identify key environmental hotspots and explore the relationship between productivity, economic performance, and sustainability using the LCA approach in different sizes of farms in Latvia.

According to data from the Latvian Environmental Geology and Meteorology Centre in 2023, emissions from agricultural soil management accounted for the largest share (47.1%) of the sector's total emissions. 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].

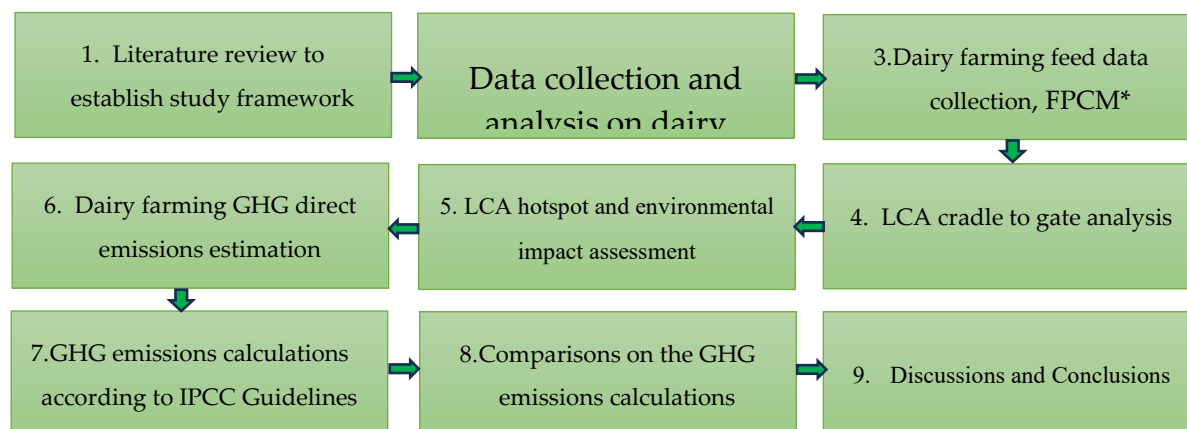
The present research is structured into five sections. Section 2 describes the research methods, as well as the data and materials used for calculations. Section 3 summarizes the calculation results in Latvia, comprehensively analysing the economic and environmental indicators of different-sized dairy farms, using various methodologies, including LCA and the Intergovernmental Panel on Climate Change Guidelines (IPCC Guidelines). Section 4 represents 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. Methodological Framework of the Study

Overall, 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 researched to identify different methodologies for GHG emission calculations. The literature review focuses on the LCA and the 2006 IPCC Guidelines [19]. The study focused on dairy farming in Latvia to determine the environmental impact and GHG emissions associated with different farm size groups. Because studies typically

reflect total emissions in a country or in agriculture, but accurate information is needed, at the very least, in different farm size groups, to reduce them, and for policymakers to develop the necessary incentive measures.



**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, the Farm Accounting Data Network (FADN) database in 2023 Latvia was used to analyse detailed information on dairy farm economic income and cattle composition, broken down by the economic size of farms. The economic size of farms is one of the main categories used in the EU typology for classifying agricultural holdings. The economic size of an agricultural holding is measured as the total Standard Output (SO) of the holding expressed in EUR. SO is the average monetary value of the farm output at 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 economic size in SO: 4–< 15, 15–< 25, 25–< 50, 50–< 100, 100–< 500, and ≥ 500 thousand EUR [20].

Third step. As FADN provides data on the selection and representation of dairy farming in Latvia, it does not include all farms, and the data required on milk quality indicators is not available. Consequently, it is necessary to find the 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 (i.e., milk fat and protein content), was utilised. The RSS database contains milk monitoring data on dairy cow herds [21]. Each herd was regarded as one farm. To ensure an in-depth analysis, all dairy farms were categorized 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). Data was compiled as of 30.09.2024 and 365 days before, thus considered as data for 2024, and aggregated per each of three groups, based on the number of total dairy cows, average milk yield per cow, and the milk quality parameters. To compare the various qualities of milk yields per year, milk yield was recalculated to what is known as FPCM in kg, assuming a conversion to FPCM with 4.0% fat and 3.3% protein.

FPCM of fat and protein corrected milk, while the approaches in scientific literature differ, the prevailing approach is to use the following two formulas:

1. FPCM, according to the International Dairy Federation, the FPCM shall be calculated by using the first formula [22]:

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

2. FPCM, according to the United Nations Food and Agriculture Organization (FAO) (2007), using the second formula [23]:

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

FPCM was used for both formulas to obtain descriptive statistics and analyse the Latvian dairy segment. For LCA and per 1kg of emissions, the  $\text{FPCM}_{\text{FAO}}$  formula was used.

The functional unit was set for FPCM milk, where the output was per 1 cow annually generated  $\text{FPCM}_{\text{FAO}}$  formula milk amount, and the input was the respective feed amount per cow annually for the LCA model. The average dairy cow's life span is 3-4.5 years of active milking life in developed countries [24]. As LCA serves for comparison purposes of three dairy farm sizes, the annual data was not multiplied.

The allocation method was used, although according to the International Organization for Standardization (ISO) standards [25], the recommendation is to avoid allocation whenever possible. However, here, allocation is 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, live weight, 12% and for milk, 88% [26]. This allocation was also used in the LCA research conducted in the SimaPro model (see subdivision 2.2), applied to all farms, and served as the basis for the result output.

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

LCA analysis was performed according to the study's overall framework, Steps 5 and 6. To further evaluate the hotspots of environmental damage impact, and to assess whether the feed and size of dairy farming operations differ, LCA analysis was used, with the use of LCA using SimaPro 10.2.0.2., using database Ecoinvent 3.0, cut-off by classification—system, and using method ReCiPe 2016 Endpoint (H) V1.11/World (2010) H/A [27].

To LCA, there are two general approaches: bottom-up or top-down. As identified in ISO 14072:2024, the bottom-up approach involves compiling various Life Cycle Inventories (LCI) of the organization'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 organization as a whole, where adding upstream models (known as “cradle-to-gate”) for all outputs [28] is crucial. LCA enables the identification of key environmental hotspots and opportunities for improvement. Buxel et al. (2014) note 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 the product's life cycle [30]. The life cycle impact assessment step should describe and assess the environmental impacts of the inventory outcomes. LCA technique was applied to study the cradle to gate, which analyses from raw materials to the manufacturing, including at the factory/farm level [30], defines the function unit and allocation method, collects data for LCI—feed data and milk output for each farm size according to the RSS farm size (see Figure 2).

The dairy farming feed structure and components for Latvia were compiled from various sources: research articles, farmer advisory and consulting articles, and a handbook [31–33]. The types of fodder and ration in small, medium, and large farms, in kg dry matter per day, are shown in Appendix Table 1A. It can be observed that for larger-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 Leguma combination with grass silage, hay, and grass silage/haylage, and the addition of roots in the feed mixture is also observed.

A total mixed ratio (TMR) was created in SimaPro based on the following inputs, derived from Latvian Rural Advisory and Training Centre (LLKC) data [33], and presented in Appendix Table 2A. In smaller farms, TMR is less used. At the same time, well-balanced feed, which is already premixed before feeding, called TMR, is administered in medium and especially in larger-sized farms, to ensure

homogeneity of feed and consistency in milk output and quality. While these mixed results depend on each farm, and the farm works, especially in collaboration with feed sellers, to optimise results for their own farm, the average recommendation has been obtained from the recommendations of LLKC.

Averages per group, especially for mid- to large-sized farms, were used as assumptions for lactation phases. In Degola et al. (2016), lactation is distinguished as lasting 150 days. According to the notes, the period from lactation to the end of lactation lasts 305 days, the lactation end phase is 155 days, and the dry period averages 40-65 days [31]. To approximate the calendar year, 60 days were used. To calculate the average feed for medium and large-sized farms, the days were used to proportionate the feed intake according to the third formula.

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

Nutrient provision in feed rations is shown in Appendix Table 3A.

ISO standards (especially 14040:2006 and 14044:2006) standardise the LCA process and are widely used globally [34], including in the life cycle inventory stage of the SimaPro software. Impact analysis in SimaPro software methods was chosen ReCiPe2016 endpoint data usage for the world, which allows the environmental impact assessment to be aggregated in a single score and compared among all three sizes of dairy farms. The single score (Pt) is calculated by applying a weighting factor to each impact category to normalise the score of damage assessment [35].

### 2.3. GHG Emissions Calculations and Analysis

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

According to FAO (2007), GHG emissions from dairy farming are quantified as carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O), including milked cows, animals for replacement in the herd, and surplus calves for meat. However, boundaries exclude land use, capital goods, the retail stage, and disposal of packaging [23]. GHG emission calculation will be performed using LCA and the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [19].

To calculate the dairy sector, especially the dairy farming contribution to GHG emissions, using the 2006 IPCC Guidelines, the results are based on the calculation according to formulas 4-8.

For CH<sub>4</sub> intestinal fermentation and manure, a formula is used annually, per country, as shown in formulas 4 and 5 [19].

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

where CH<sub>4</sub> intestinal fermentation—CH<sub>4</sub> emissions from feed intestinal fermentation in country, expressed in kg of CH<sub>4</sub> annually; EF<sub>1(Dairy cows)</sub>—CH<sub>4</sub> emission factor/multiplier for dairy cows, which varies according to 2006 IPCC Guidelines for Western Europe it is 117, and Eastern Europe it is 99 [19], while calculations of Popluga et al. (2019), specific for Latvia, obtained 141.2 kg of CH<sub>4</sub> emissions per dairy cow annually [36], thus this is used for Latvia; N—number of dairy cows in Latvia.

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

where CH<sub>4</sub> manure—CH<sub>4</sub> emissions from dairy cow manure in the country, expressed in kg of CH<sub>4</sub> annually; EF<sub>2(manure)</sub>—CH<sub>4</sub>(manure) emission factor/multiplier for dairy cows. For Latvia, Popluga et al. determined the multiplier to be 17.28 [36], but according to the 2006 IPCC Guidelines, the coefficient is dependent on the weather temperature. According to Tradingeconomics, in 2024, the average temperature in Latvia was 8.51 degrees Celsius, which is below 10 degrees in the 2006 IPCC Guidelines and a coefficient of 11 [37]. As the indicator for Latvia has been calculated, it will be used; N—number of dairy cows in Latvia.

For N<sub>2</sub>O, a formula is used annually, per country, as shown in formula 6 [19].

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

where, N<sub>2</sub>O<sub>Dmm</sub>—direct N<sub>2</sub>O emissions from manure management (mm) in the country, kg N<sub>2</sub>O annually; N—number of dairy cows in Latvia; N<sub>ex</sub>—annual average N excretion per dairy cow in the country, kg N per animal annually, as of 2021 data it is 119.90 according to Latvia's National



Figure 2 illustrates the separation and analysis components of on-farm and off-farm processes. On the farm are data and processes that take place on the dairy farm, from providing feed to cows and the milking process, as well as manure from cows, where the feed is prepared off farm, and also milk and calves/meat are sold outside the farm; the dairy farm itself does not process milk. LCA analysis, cradle-to-gate, was performed for the on-farm processes from feed to milking, inclusive, thereby estimating the environmental impact and its components. The separately analysed GHG emissions of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O were also considered. These emissions were compared to 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 GHG emissions for the dairy sector on farm were calculated using IPCC Guidelines; 2) cradle to gate for LCA was chosen for annual data, for hotspot detection; 3) off-farm processes were out of the study scope.

### 3. Results

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

#### 3.1. Characteristics of Dairy Farms in Latvia

In Latvia, according to statistical data, at the end of 2024, there were 113,000 dairy cows [41], and the average milk yield per cow was 8,239 kg, representing a 15% increase compared to 2020 [42]. The number of cattle and cows has shown a trend to decline each year for the period 2020-2024, when a reduction in total cattle was observed by 12%, a decrease in the number of cows by 11%, and dairy cows had a reduction of 17% in 2024 compared to 2020 [43]. In Latvia, at the end of 2024, there were 58.6 thousand farms, and of these, only 7194 farms or 12% of the total were engaged in dairy farming [44].

An overview of dairy farming composition in Latvia in 2023, based on FADN data, is presented in Table 1. The FADN included 270 farms, or 4% of the total, but these farms represent 74% of the total dairy farms in Latvia.

**Table 1.** Characteristics of dairy farms by size groups in Latvia in 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	270	7	42	63	61	84	13
Farms represented	5 347	350	2 085	1 387	817	601	107
<i>Dairy farms as % of the total in the dairy farm sector</i>	5%	2%	2%	5%	7%	14%	12%
<i>Dairy farms as % total farms</i>	24%	5%	39%	34%	32%	23%	18%
Average gross income per farm, EUR	33 824	-14	8 439	10 761	25 973	84 605	713 972
Average farm net income per farm, EUR	9 586	-939	6 959	7 664	16 627	23 877	-13 976
<i>Average farm net income to gross income</i>	28%	<i>n.a.</i>	83%	71%	64%	28%	-2%
Average number of dairy cows	20	3	5	9	18	54	344
Average number of cattle <1 year	10	1	3	3	7	25	225
Average number of cattle from 1 but less than 2 years	7	1	1	2	5	18	153
Average number of other cattle	3	0	1	2	3	12	26
Milk yield per cow, tons per year	7.37	5.34	5.10	5.21	5.66	6.60	10.24

In Latvia, even when looking at farms, when dairy farm size exceeds 100 cows, its annual milk yield increases significantly, the reason being that it is commercial, larger-scale operations, and they are very focused on the milk output amount, thus also adjusting and constantly looking for the right mixture of the feed to optimise the yields. The main number of dairy farms, by their economic size, is 15-50 thousand EUR SO.

Economic analysis of gross and net income per farm varies significantly, while significant farm net income in 2023 was negative, that large farms represented overall experienced losses, despite having significantly even 8 to 90 times larger gross income compared to the other dairy farms, that indicated the pressures the dairy farming is experiencing even despite of its large size and possibility of economies of the scale, but in the meantime also the cost of the milk production in 2023 did impact the bottom line of largest farms the most. The highest net income to gross income was for farms with SO 15-<100 thousand EUR, while these farms also had the lowest milk yield per cow, expressed in tons per year, from 5.10-5.66, while larger farms with higher and highest yields, SO group 100 -500 thousand EUR, and SO above 500 thousand EUR, had lower profit or loss, respectively, but the highest yields. High yields for the year 2023 came with additional pressure on the net income line, especially for the largest dairy farms in Latvia. Therefore, to assess the differences and potential hotspots for environmental impact, a detailed analysis of the LCA process was conducted. The above six groups are too fragmented for analysis; therefore, the dairy farms were grouped into three categories: small, with 1-50 dairy cows; medium, with 51-200 dairy cows; and large, with 201 or more dairy cows.

**Table 2.** Dairy production indicators and FPCM in Latvia breakdown by herd sizes on 30.09.2024 for 365 days 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	11220	7314
Total number of cows	32776	30021	38308	101105
Total milk output, tons per year	231060	273248	441392	945701
% 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	11185	7470
Deviation IDF/FAO formula	124%	125%	126%	125%

When compiling and analysing RSS data about dairy farms in Latvia, Table 2 shows that under the milk monitoring system, there are 2,794 farms, or 39% of the total in the country. However, these farms have 101,000 cows, which account for 89% of the total number of cows in Latvia. The most significant number of herds in Latvia is small-sized dairy farms, with 1-50 cows per herd. It is important to note, as shown in the FADN data in Table 1, that very small 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 on average by 21% less kg milk per cow, compared to medium-sized dairy farms, and 38% less kg of milk per cow per year (p.a.) compared to large-sized dairy farms. When breaking down the data of 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—1350 herds or 48% of herds in the RSS milk monitoring system. Very small farms with 1 to 4 cows are 302 herds or 11% of the total number of herds in milk monitoring. Together, 1-15 dairy cow farms comprise over half (59%) of the number of dairy herds in Latvia, while producing only 9% of the total milk output in 2024 [43]. Medium-sized dairy farm group comprises farms with herds from 51 to 200 dairy cows, generating 29% of total annual milk output in Latvia. In contrast, small farms generate 24% of yearly milk output despite having 9% more dairy cows in the group compared to medium-sized farms. The majority—47% or almost half of Latvia's annual milk output is generated by large-sized farms with 201 or more cows per herd. By number, these are only 79 dairy farms with the highest milk yield per cow, 11,200 kg per year. The farms, in terms of their sizes, are also different in terms of the quality of the milk they produce. When measured in terms of fat and protein components, the highest fat content is found in milk from small farms—4.17%, while medium farms have a lower average fat content, at 4.07%, and the lowest indicator is found in milk from large farms—3.9%. However, the most significant differences among herds in terms of milk fat content from the average are in the small farm group, ranging from 2.27% to 6.04%. In contrast, the more consistent results among farms are found in large farms, where the deviation is the smallest from the average indicator, with fat content ranging between 3.04% and 4.74%. Therefore, 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%. Then the farm milk yields become comparable. Global approach using FPCM has two sources: the FAO and IDF formulas, which have been widely used; however, using them here generates different results. The FAO formula with Latvia farm data generates a lower amount of kg FPCM milk when compared to unadjusted milk yields per year. In contrast, the IDF formula yields 24-26% higher FPCM kg milk per cow compared to the FAO formula. Also, it results in a higher average milk yield per cow in Latvia compared to the non-adjusted average milk yield in kg per cow, except for large-sized farms. Furthermore, for LCA analysis, comparability is ensured by using FPCM kg of milk yield per cow per year. This is achieved by applying the FAO formula, which yields more conservative FPCM milk yield numbers.

### 3.2. LCA Calculation Results for Dairy Farms in Latvia

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

**Table 3.** Life cycle impact assessment (cradle-to-gate) midpoint comparison among three different-sized dairy farms in Latvia in 2024 [21,23,27,31–33].

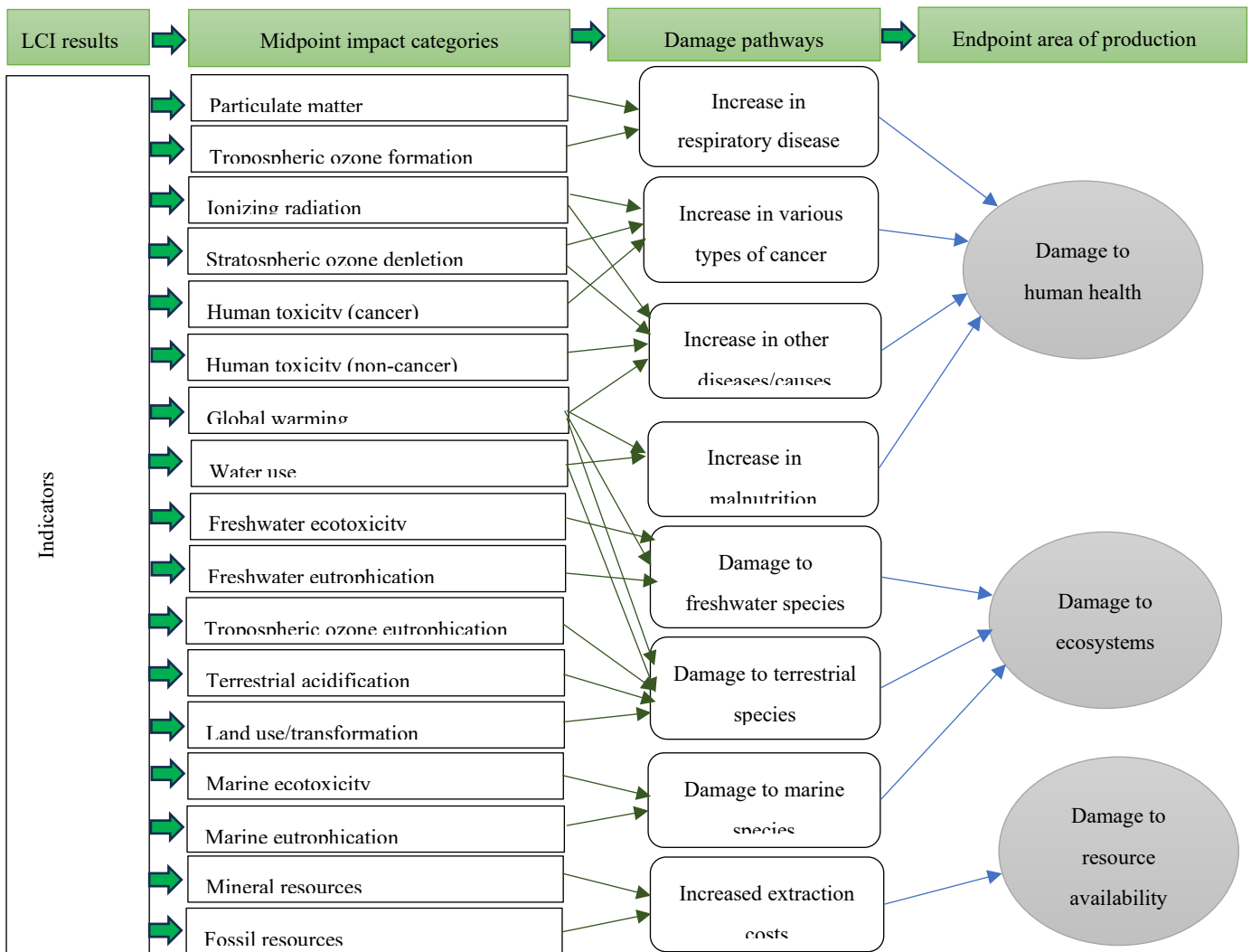
Impact Category/INDICATORS	Unit	Life Cycle Impact Assessment of			Deviation		
		Small Farms (1-50 Cows)	Medium Farms (51-200 cows)	large Farms (≥201 cows)	medium-small farms	large-medium farms	large-small farms
Water consumption, Aquatic ecosystems	species.yr*	5.44*10 <sup>-12</sup>	8.00*10 <sup>-12</sup>	9.01*10 <sup>-12</sup>	47%	13%	66%
Water consumption, Terrestrial ecosystems	species. yr	4.06*10 <sup>-8</sup>	5.81*10 <sup>-8</sup>	6.31*10 <sup>-8</sup>	43%	9%	55%
Water consumption, Human health	DALY*	5.38*10 <sup>-06</sup>	7.60*10 <sup>-6</sup>	8.35*10 <sup>-6</sup>	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 <sup>-05</sup>	1.66*10 <sup>-5</sup>	1.73*10 <sup>-5</sup>	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 <sup>-9</sup>	6.59*10 <sup>-9</sup>	7.19*10 <sup>-9</sup>	20%	9%	31%
Freshwater ecotoxicity	species.yr	2.80*10 <sup>-8</sup>	3.38*10 <sup>-8</sup>	3.69*10 <sup>-8</sup>	20%	9%	32%
Terrestrial ecotoxicity	species.yr	2.08*10 <sup>-8</sup>	2.71*10 <sup>-8</sup>	2.84*10 <sup>-8</sup>	30%	5%	36%

Marine eutrophication	species.yr	$3.71 \cdot 10^{-9}$	$6.58 \cdot 10^{-9}$	$6.99 \cdot 10^{-9}$	77%	6%	88%
Freshwater eutrophication	species.yr	$2.36 \cdot 10^{-7}$	$3.03 \cdot 10^{-7}$	$3.37 \cdot 10^{-7}$	28%	11%	43%
Terrestrial acidification	species.yr	$1.92 \cdot 10^{-6}$	$2.08 \cdot 10^{-6}$	$1.92 \cdot 10^{-6}$	8%	-8%	0%
Ozone formation, Terrestrial ecosystems	species.yr	$2.60 \cdot 10^{-7}$	$3.45 \cdot 10^{-7}$	$3.58 \cdot 10^{-7}$	33%	4%	38%
Fine particulate matter formation	DALY	0.001186	0.001397	0.001415	18%	1%	19%
Ozone formation, Human health	DALY	$1.78 \cdot 10^{-6}$	$2.35 \cdot 10^{-6}$	$2.44 \cdot 10^{-6}$	32%	4%	38%
Ionizing radiation	DALY	$3.21 \cdot 10^{-7}$	$3.69 \cdot 10^{-7}$	$4.21 \cdot 10^{-7}$	15%	14%	31%
Stratospheric ozone depletion	DALY	$3.55 \cdot 10^{-6}$	$5.24 \cdot 10^{-6}$	$5.27 \cdot 10^{-6}$	48%	1%	48%
Global warming, Freshwater ecosystems	species.yr	$5.31 \cdot 10^{-11}$	$7.51 \cdot 10^{-11}$	$8.10 \cdot 10^{-11}$	41%	8%	52%
Global warming, Terrestrial ecosystems	species.yr	$1.95 \cdot 10^{-6}$	$2.75 \cdot 10^{-6}$	$2.96 \cdot 10^{-6}$	41%	8%	52%
Global warming, Human health	DALY	0.000645	0.000911	0.000983	41%	8%	52%

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

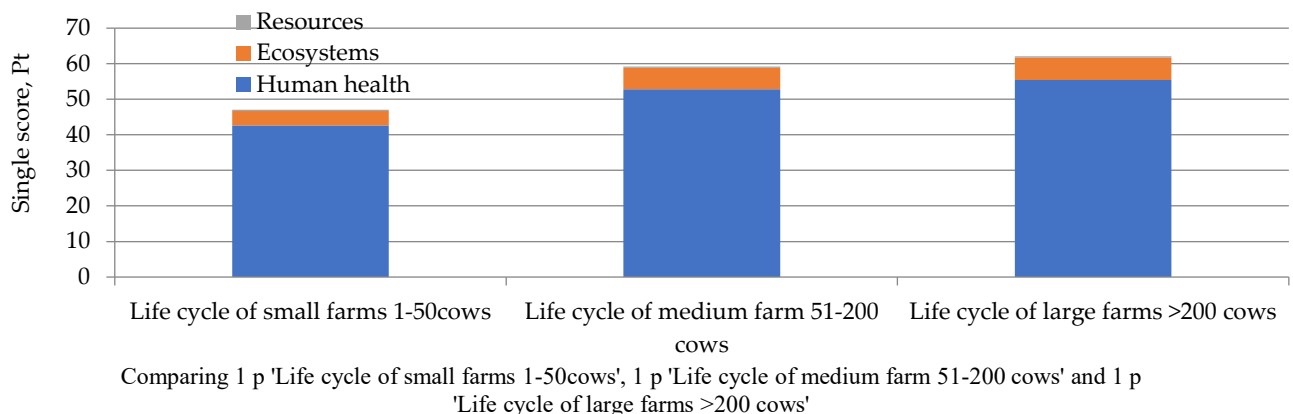
As can be analysed from the impact tables (Table 3), the most significant impacts are those related to fossil and mineral resource scarcity and fine particulate matter formation, affecting human non-carcinogenic toxicity and the impact on human health from global warming. When comparing among three dairy farm size groups, the impact does differ, especially between small size and medium size (from 2% to 58% difference in presented indicators—and larger being in medium size group compared to small size dairy farm group), as well as small size and large size farming (difference in presented indicators (or deviation was observed between 0% to 66%, with higher damage factor being in larger scale dairy farm. Less deviation is observed between medium-sized group and large-sized dairy farms (between 1-14%, with one exception for a decrease in terrestrial acidification). Therefore, significant differences have been observed when comparing the three size dairy farm groups in terms of environmental impact/damage categories. When expressed in relative terms, as in 100%, where the farm size with the most significant indicator is described as 100%, and respective other farm sizes impact categories' values is expressed as % of that main factor most important contributor, it can be assessed that with all 22 midpoint impact categories, large size farms are the main contributors, with exception of the category Terrestrial acidification, where the main contributed is midsized farms, and is assigned value of 100% [43].

How, in particular, the midpoint impact categories in Table 3 above translate into three aggregated endpoint areas of production/categories—Damage to human health, Damage to ecosystems, and Damage to resource availability—and what the damage pathway is shown in Figure 3.



**Figure 3.** Presentation of the relationships between impact categories, midpoint, and endpoint in ReCiPe 2016, SimaPro database manual – methods library [45].

In Table 3, an analysis was performed for each damage impact factor. Still, to assess which of the three significant factors is the most impactful on the environment and damage, Figure 4 represents the results in 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 in 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 less impact on ecosystems and a minimal impact on resource scarcity. The hotspot affects human health, as shown in the figure above, resulting from ozone depletion, particulate matter, etc. The impact difference is most observed between small-scale dairy farms and medium/to large-scale dairy farms in Latvia.

**Table 4.** Life cycle impact assessment (cradle-to-gate) comparison among three various-sized dairy farms in Latvia, expressed as a single score (Pt), and its structure in Latvia 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%
Alfaalfa-grass mixture, Swiss integrated	3.10	7%	2.88	5%	1.38	2%
Alfaalfa-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%

The environmental impact from cradle to gate (Table 4), that is, from feed to milking process, is a significant influencing factor, expressed as a single score, Pt, in ReCiPe. The most important factor, by single score, is the milking process, comprising 34% of all processes analysed in small and medium farms, and 40% in large farms. This can be a place to examine in more depth for the search for damage assessment reduction possibilities. At the same time, it is observable that the differences in small farming compared to medium and large-scale farming are that alfalfa silage is the second contributor, in large size farms 18%, while medium 17% in the overall damage assessment normalized score, while in small farms, the second position by damage impact weight among analysed factors is hay.

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

The results of the GHG emissions calculations, 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 the dairy sector, broken down by farm size groups, according to the 2006 IPCC Guidelines methodology, in Latvia in 2024 [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	32776	30021	38308	101105
CH <sub>4</sub> (fermentation)	kg	4627999	4238979	5409090	14276068
CH <sub>4</sub> (manure)	kg	566373	518765	661962	1747100
CH <sub>4</sub> to CO <sub>2eq</sub>	kg	145442421	133216830	169989452	448648702
N <sub>2</sub> O <sub>Dmm</sub> (direct manure)	kg	10807	9899	12631	33337

N <sub>2</sub> O to CO <sub>2eq</sub>	kg	2766626	2534069	3233563	8534258
<i>Total CO<sub>2eq</sub>, by size groups</i>	<i>tons</i>	<i>148209</i>	<i>135751</i>	<i>173223</i>	<i>457183</i>
FPCM kg per cow, per year (FAO formula)	kg	5748	7164	8875	5999
<i>CO<sub>2eq</sub> per 1kg of milk</i>	<i>kg</i>	<i>0.79</i>	<i>0.63</i>	<i>0.51</i>	<i>0.75</i>

The main difference is that the number of dairy cows changes the emissions (Table 6). The same deviation among groups in cows would lead to the same deviation in the results of total direct emissions from the dairy sector. Notably, this gives rather simplistic and overall numbers of GHG emissions from the sector; it benefits when adding analysis from LCA on the hotspots in the feed.

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

Indicators/Number of Dairy Cows	Unit	1-50	51-200	≥ 201
Total number of cows	cows	32776	30021	38308
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
<i>Total carbon dioxide, per cow</i>	<i>kg</i>	<i>3012</i>	<i>3877</i>	<i>3613</i>
<i>Total carbon dioxide per whole group</i>	<i>tons</i>	<i>987350</i>	<i>1163978</i>	<i>1384183</i>
Nitrogen oxide N <sub>2</sub> O per cow	kg	1.84	2.44	2.53
<i>Nitrogen oxide per group</i>	<i>tons</i>	<i>60</i>	<i>73</i>	<i>97</i>
<i>Nitrogen in CO<sub>2eq</sub></i>	<i>tons</i>	<i>15982</i>	<i>19412</i>	<i>25684</i>
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
<i>Methane per group</i>	<i>tons</i>	<i>43</i>	<i>52</i>	<i>72</i>
<i>Methane in CO<sub>2eq</sub></i>	<i>tons</i>	<i>1210</i>	<i>1446</i>	<i>2009</i>
<i>Total CO<sub>2</sub> in CO<sub>2eq</sub>, p.a.</i>	<i>tons</i>	<i>1004542</i>	<i>1184836</i>	<i>1411876</i>
<i>Deviation from the previous group</i>	<i>%</i>	<i>N/A</i>	<i>18%</i>	<i>19%</i>
FPCM kg per cow, per year (FAO formula)	kg	5748	7164	8875
<i>CO<sub>2eq</sub> per 1kg of FPCM milk</i>	<i>kg</i>	<i>5.33</i>	<i>5.51</i>	<i>4.15</i>

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, it has to be calculated separately to compare the three groups to obtain a more in-depth picture. Notably, the results are 4-5 times higher than using the 2006 IPCC Guidelines methodology. The reason could be that in IPCC calculations, only the number of cows is taken into account, and the agricultural feed production side is calculated separately. LCA, the main differences among groups are the feed composition and the yield of milk obtained as a result. When evaluating the overall CO<sub>2eq</sub>, 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 among the three groups per 1 kg of FPCM milk, making them more efficient. A similar result was also obtained when evaluating by the 2006 IPCC Guidelines methodology, that the large-sized dairy farms generate the most emissions in CO<sub>2eq</sub>, while when recalculating not per cow, but per 1kg of FPCM milk, the result is that also large dairy farms with cows above 201 cows are generating the least of all three groups' 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. The study looks at the effect of herd size on milk yield, yield components, fat content, and protein content. It is worthwhile addressing the reasons for the larger agricultural sectors to produce negative net income when gross revenues can be in the millions of dollars [46]. The research compares small- and medium-sized farms' economic resilience to that of the larger sector's vulnerability and adaptive economies in the dairy sector.

The performed analysis of various-sized dairy farms has provided insights into the operational differences, as noted by Brkic et al. (2024), which would provide a comprehensive understanding of sustainable dairy production [46]. Additionally, it is indicated that herd size does influence milk yield and quality, specifically the fat and protein content, which is a critical area for optimizing dairy farm productivity [47]. This has also been discovered in the research that larger-sized herds are yielding significantly more milk per cow compared to smaller-sized dairy farms. In the meantime, it is assumed that larger herds should benefit from economies of scale in terms of infrastructure and purchasing in bulk, which could lead to lower per-unit production costs [48]. However, the study and use of FADN data for Latvia in 2023 indicates that, especially the largest farms, with SO >500 thousand EUR on average, experience losses per year, compared to other-sized farms.

However, the relationship between herd size and milk quality is different; smaller farms tend to have higher fat indicators, especially. In contrast, there is a more significant deviation from the mean value. In comparison, larger farms have lower fat content with less variation around the mean value, as this research has discovered. 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 keeping optimal nutrient management. As noted by Holly et al. (2018), feed costs can make up a substantial part of total operating expenses [49]. A similar discovery is presented that 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 have efficient feed management [50].

### 4.2. Environmental Impact and Sustainability

As yields and efficiency are crucial for farm 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 –the processes that contribute to the environmental footprint of the dairy industry [51]. The author has examined how the impacts vary based on different-sized farms. The results do indicate variability, with larger farms overall having a greater impact on the environment. However, when recalculated not per cow but per kilogram of milk, the results differ, showing that large farms per kilogram of milk are the least contributors to the environment. As noted, it is necessary to establish the size-specific contributions of farms to human health implications, ecosystem damage, and resource scarcity [52], which has been done in this research through an LCA assessment and comparison of various farm sizes. The analysis highlighted the primary areas of environmental impact and illustrated opportunities for targeted efforts to mitigate these impacts, enabling sustainable dairy farming [46]. Further, calculations were made to specifically look at CO<sub>2</sub>eq emissions by LCA and by the 2006 IPCC Guidelines methodology, comparing three different dairy farm sizes. Additionally, total direct GHG emissions were assessed, as well as emissions per kilogram of FPCM milk, to investigate the variations in efficiency among small, medium, and large dairy operations in terms of their environmental performance. This type of analysis and interaction between dairy farming practices and environmental outcomes will provide a framework for informed decision-making, supporting the pursuit of more sustainable dairy agriculture [10].

The overall purpose is to identify potential places and points of intervention that could minimise environmental burden while maintaining economic viability and social acceptance of dairy production [53]. The results could allow us to explore how advanced feed practices, such as different feed formulations or differences, can significantly reduce the environmental impact per unit of milk produced, moving towards a more circular agricultural economy [54]. The dairy sector is recognised as a significant contributor to greenhouse gas emissions; therefore, it is necessary to examine its contributions to these emissions [55].

#### *4.3. Balancing Productivity, Profitability, and Environmental Performance*

The trade-offs in 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 are in large farms, which produce 47% of total milk in Latvia, and simultaneously, these farms have the lowest environmental impact and emissions per 1 kg of produced milk; however, the absolute largest farms were experiencing losses in 2023. Dairy production is essential for global nutrition, but it faces significant environmental scrutiny [46]. Growing consumer demands, climate change, and global food security concerns necessitate a re-evaluation of traditional dairy management practices to enhance profitability and sustainability [56]. This re-evaluation looks at strategies for large farms to boost financial returns while reducing their ecological footprint. It also examines the policy and management implications for achieving sustainable intensification [57]. Historically, improving productivity in ruminant systems, including dairy, has led to lower resource use and greenhouse gas emissions for each product unit. This mainly occurs by diluting maintenance effects [58]. With respect to dairy production, high feed efficiency is key to minimising costs in feed and the negative impacts of milk production on the climate and environment. However, there is a limited understanding of the relationship between feed efficiency, eating behaviour, and activity [59], and achieving this balance is difficult. It requires careful use of technology and management practices that maximize resource use without compromising animal welfare or economic stability [60]. Genomic selection and precise ration formulation can significantly improve the efficiency of high-performing herds. This contributes to a lower environmental impact per unit of milk produced [61]. Nevertheless, despite these improvements, dairy systems continue to create environmental pressures. They include direct GHG from enteric fermentation, manure management, and feed production, as well as significant water and land usage [10].

#### *4.4. Methodological Considerations*

When comparing dairy production efficiency across different farm systems and genetic lines, accurately normalising for milk yield to a standard FPCM is essential. This comprehensive approach is critical because variation in the composition of milk, particularly the amount of fat and protein it contains, can affect the quality of the milk nutritionally and how well it can be processed in factories. This research discovered that it is especially crucial to determine which formula and approach for FPCM to use, either the FAO or the IDF formula. The FAO resulted in more conservative results compared to the IDF. In the case of Latvia, the IDF showed 24-26% higher FPCM results. These issues influence the actual environmental implications of each unit of functional output [62]. This adjustment also improves the accuracy of the LCA, since an environmental product measure involves standardizing the functional unit. Standardizing functional units allows for appropriate comparisons of environmental implications, such as greenhouse gas emissions, between different production regimes [61]. This generic methodology distinguishes specific processes, such as feed production, enteric fermentation, and waste management, which significantly affect the environment in total. This methodology will also assist in planning specific reductions [63]. In many situations, the available data sets do not have enough information and/or lack scope. This limiting factor will impact the accuracy of the assessments, and the required data collection needs to be improved [53].

#### 4.5. Policy Implications and Future Research Directions

The differences in how LCA studies have conceptualised, allocated, and framed functional units make it difficult to compare results of LCA studies [16,53]. The issues of differences in conceptualisation make it challenging to provide harmonised data and effective policy. Sustainable dairy production practices will therefore have to be evaluated in terms of their environmental benefit, cost-effectiveness, and impact throughout the supply chain, especially when herd composition and levels of milk production vary [55]. Uncertainties in current biodiversity quantification within LCAs also highlight the need for lower-complexity frameworks as well as applied tools to apply [13,64].

Future research should focus on several directions: 1) Develop multi-criteria instruments that integrate environmental, economic, and societal elements of dairy systems [65]; 2) Standardise and articulate LCA techniques, especially the concept of biodiversity and functional unit, to enable comparability between studies; 3) Explore feeding optimisation, genetics, and waste management technologies as measures for enhancing efficiency, reducing methane, and limiting nutrient loss [63,66]; 4) Assess the abatement and cost-saving potential of alternative means of producing milk under a range of regional and market conditions; 5) Conduct longitudinal LCAs to track improving GHG efficiency per unit of milk under increasing absolute emissions due to rising world demand for dairy products.

Given the consideration that livestock farming occupies 70–80% of agricultural land and contributes significantly to methane emissions [51,67], effective and harmonised LCA practices will be key to achieving climate objectives globally. As demand for dairy is expected to grow by 70% by 2050, policies should be developed based on studies that maintain production while reducing emissions by up to 80% to mitigate the impacts of climate change [54,68].

## 5. Conclusions

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

Meanwhile, LCA environmental assessments indicate that the most significant contributions are to damage of human health, followed by damage to ecosystems, and damage to resource availability, particularly from the consumption of fossil and mineral resources, particulate matter formation, and global warming. Environmental burdens differ most significantly between small/middle and large farms, with large farms incurring larger absolute burdens. Milking is the most significant hotspot (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 greenhouse gas direct emission production, the most significant absolute CO<sub>2</sub>e contributors are the large farms. Yet, they have the lowest emission intensity per kilogram of FPCM milk of all types. Emissions identified by LCA, considering feed, are 4–5 times greater than those reported by the 2006 IPCC Guidelines methodology, illustrating the need for careful consideration of the system boundary selection and methodology approach.

Generally, while being more productive, large farms in Latvia generate higher yields and efficiencies per unit of milk; however, they are economically most vulnerable 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 impact, and point to the milking operation and feed composition as prime areas for effective mitigation.

Increased research is necessary to advance coupled multi-criteria tools, harmonise LCA methods, and improve feeding to enhance dairy industry sustainability in response to growing global demand. Harmonised LCA practices need to be promoted by policymakers, who should encourage innovations to improve dairy efficiency while minimising adverse environmental impacts as global demand grows.

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## Abbreviations

The following abbreviations are used in this manuscript:

CO <sub>2</sub>	carbon dioxide
CH <sub>4</sub>	methane
CO <sub>2</sub> 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 <sub>2</sub> O	nitrous oxide
SO	Standard Output
TMR	total mixed ratio

## Appendix

**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
Leguma 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 Ratio per Day in kg per Cow		% of Total TMR
Alfaalfa grass silage	31		61%
Maize silage	7		14%
Wheat	3		6%
Barley	3		6%
Maize chop	1.5		3%
Soy expellers	2.7		5%
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	2 681.45	3 322.59	2 856.44
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

## References

1. Muska, A.; Pilvere, I.; Viira, A.-H.; Muska, K.; Nipers, A. European Green Deal Objective: Potential Expansion of Organic Farming Areas. *Agriculture* **2025**, *15*, 1633. <https://doi.org/10.3390/agriculture15151633>.
2. Peng, B.; Melnikiene, R.; Baležentis, T.; Agnusdei, G.P. Structural dynamics and sustainability in the agricultural sector: The case of the European Union. *Agric. Food Econ.* **2024**, *12*, 31. <https://doi.org/10.1186/s40100-024-00321-x>.
3. Bórawski, P.; Pawlewicz, A.; Parzonko, A.; Harper, J.K.; Holden, L. Factors Shaping Cow's Milk Production in the EU. *Sustainability* **2020**, *12*, 420. <https://doi.org/10.3390/su12010420>
4. Pilvere I.; Upite I.; Muska A.; Zdanovskis K.; Nipers A.; Janmere L. Resilience of Milk Supply Chains during and after the COVID-19 Crisis in Latvia. *Rural Sustainability Research* **2021**, vol.45, no.340, pp.53-64. <https://doi.org/10.2478/plua-2021-0007>.

5. Chatellier, V.; Delattre, F.; Rat-Aspert, O. Milk price in Savoy and cheese chain. HAL (Le Centre Pour La Communication Scientifique Directe). 2006. <https://hal.archives-ouvertes.fr/hal-02822243>.
6. Brkić, I.; Puvača, N. Economic and Ecological Sustainability of Dairy Production. *Journal of Agronomy Technology and Engineering Management (JATEM)* **2024**, 7(3), 1088. <https://doi.org/10.55817/tqxu2115>.
7. Bojovic, M.; McGregor, A. A review of megatrends in the global dairy sector: what are the socioecological implications? *Agriculture and Human Values* **2022**, 40(1), 373. <https://doi.org/10.1007/s10460-022-10338-x>.
8. Summaries. *Advances in Animal Biosciences* **2016**, 7(1), 1. <https://doi.org/10.1017/s2040470016000042>.
9. Capper, J. L.; Bauman, D. E. The Role of Productivity in Improving the Environmental Sustainability of Ruminant Production Systems. *Annual Review of Animal Biosciences* **2012**, 1(1), 469. Annual Reviews. <https://doi.org/10.1146/annurev-animal-031412-103727>.
10. Peterson, C. B.; Mitloehner, F. M. Sustainability of the Dairy Industry: Emissions and Mitigation Opportunities. *Frontiers in Animal Science* **2021**, 2. <https://doi.org/10.3389/fanim.2021.760310>.
11. Slade, P.; Hailu, G. Efficiency and regulation: a comparison of dairy farms in Ontario and New York State. *Journal of Productivity Analysis* **2015**, 45(1), 103. <https://doi.org/10.1007/s11123-015-0456-9>.
12. Latruffe, L.; Desjeux, Y.; Hanitravelo, G. L. J.; Hennessy, T.; Bockstaller, C.; Dupraz, P.; Finn, J. A. Tradeoffs between Economic, Environmental and Social Sustainability: The Case of a Selection of European Farms. HAL (Le Centre Pour La Communication Scientifique Directe) **2016**. <https://hal.archives-ouvertes.fr/hal-01611416>.
13. Wilfart, A.; Baillet, V.; Balaine, L.; Otálora, X. D.; de, Dragoni, F.; Król, D.; Frątczak-Müller, J.; Rychła, A.; Rodriguez, D. G. P.; Breen, J.; Anestis, V.; Buckley, C.; Alem, H.; Winiwarter, W.; Akkal-Corfini, N.; Amon, B. DEXi-Dairy: an ex post multicriteria tool to assess the sustainability of dairy production systems in various European regions. *Agronomy for Sustainable Development* **2023**, 43(6). <https://doi.org/10.1007/s13593-023-00935-3>.
14. Koutouzidou, G.; Ragkos, A.; Theodoridis, A.; Arsenos, G. Entrepreneurship in Dairy Cattle Sector: Key Features of Successful Administration and Management. *Land* **2022**, 11(10), 1736. <https://doi.org/10.3390/land11101736>.
15. Tamburini, E.; Pedrini, P.; Marchetti, M. G.; Fano, E. A.; Castaldelli, G. Life Cycle Based Evaluation of Environmental and Economic Impacts of Agricultural Productions in the Mediterranean Area. *Sustainability* **2015**, 7(3), 2915. <https://doi.org/10.3390/su7032915>.
16. McClelland, S. C.; Arndt, C.; Gordon, D. R.; Thoma, G. Type and number of environmental impact categories used in livestock life cycle assessment: A systematic. *Livestock Science* **2018**, 209, 39. <https://doi.org/10.1016/j.livsci.2018.01.008>
17. Milani, F.; Nutter, D. W.; Thoma, G. Invited review: Environmental impacts of dairy processing and products: A review. *Journal of Dairy Science* **2011**, 94(9), 4243. <https://doi.org/10.3168/jds.2010-3955>.
18. SLLC Latvian Environment, Geology and Meteorology Centre (LVMEO). Kopsavilkums par 2025.gada siltumnīcefekta gāzu inventarizāciju/Summary of the 2025 greenhouse gas inventory (in Latvian). Available online: <https://videscentrs.lv/gmc.lv/lapas/informacija-par-latvijas-seg-emisijam> (accessed on September 08, 2025).
19. IPCC 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S.; Buendia L.; Miwa K.; Ngara T.; Tanabe K. (eds). Published: IGES, Japan. Available online: <https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol1.html> (accessed on 17 July, 2025).
20. Farm Accounting Data Network (FADN). 2023 data. Available online: <https://sudat.arei.lv/Login.aspx?ReturnUrl=%2f> (accessed on June 14, 2025).
21. Rural Support Service (RSS). 2024 data. Monitoring data of herds in 2023/2024. Available online: <https://registri ldc.gov.lv/lv/parraudziba> (accessed on August 11, 2025).
22. International Dairy Federation (IDF). A common carbon footprint approach for dairy sector: The IDF guide to standard life cycle assessment methodology. Bulletin of the International Dairy Federation 479/2015. Available online: [https://www.fil-idf.org/wp-content/uploads/2016/09/Bulletin479-2015\\_A-common-carbon-footprint-approach-for-the-dairy-sector.CAT.pdf](https://www.fil-idf.org/wp-content/uploads/2016/09/Bulletin479-2015_A-common-carbon-footprint-approach-for-the-dairy-sector.CAT.pdf) (accessed on August 04, 2025).

23. United Nations Food and Agriculture Organization (FAO). Greenhouse Gas Emissions from the Dairy Sector: A Life Cycle Assessment. 2007. Available online: <https://www.fao.org/4/k7930e/k7930e00.pdf> (accessed on August 11, 2025).
24. SaimnieksLV portal. Article Dažāda auguma izmēra govju ražotais piena daudzums vienā dienā/Amount of milk produced by cows of different sizes in one day (In Latvian). By LLKC on 02.03.2022. Available online: <http://saimnieks.lv/raksts/dazada-auguma-izmera-govju-razotais-piena-daudzums-viena-diena#:~:text=Vid%C4%93jais%20piena%20govju%20produkt%C4%ABv%C4%81s%20dz%C4%ABves,5%20%C4%ABdz%206%2C5%20gadiem> (accessed on September 05, 2025).
25. International Organization for Standardization (ISO). 2006: Environmental management—Life cycle assessment – Principles and framework. ISO 14044:2006, 4.3.4.2. section, Switzerland: ISO.
26. European Commission (EC). Annex I. Product Environmental Footprint Method. 2021. Available online: <https://environment.ec.europa.eu/system/files/2021-12/Annexes%201%20to%202.pdf> (accessed on August 21, 2025).
27. PRé Sustainability, SimaPro software 10.2.0.2., using database Ecoinvent 3.0, cut-off by classification – system, and using method ReCiPe 2016 Endpoint (H) V1.11/World (2010) H/A. Available online: [https://simapro.com/\(licence since August 05, 2025\).](https://simapro.com/(licence%20since%20August%2005,2025))
28. International Organization for Standardization (ISO). ISO 14072:2024 standard: Environmental management – Life cycle assessment – Requirements and guidance for organizational life cycle assessment. 2024, Switzerland: ISO.
29. Buxel, H.; Esenduran, G.; Griffin, S. Strategic sustainability: Creating business value with life cycle analysis. *Business Horizons* **2014**, 58(1), 109. <https://doi.org/10.1016/j.bushor.2014.09.004>.
30. International Organization for Standardization (ISO), 2006, ISO 14040:2006: Environmental management – Life cycle assessment – Principles and framework. Switzerland: ISO.
31. Degola L.; Cielava L.; Trupa A.; Aplocina E. Barības devas dažāda lieluma piena lopkopības saimniecībās/Feed rations in different size dairy farms (In Latvian). Scientific practical conference „LĪDZSVAROTA LAUKSAIMNIECĪBA”, 25.–26.02.2016., LLU, Jelgava, Latvia. Available online: [https://llufb.llu.lv/conference/lidzsvar\\_lauksaim/2016/Latvia-lidzsvarota-lauksaimnieciba2016-161-168.pdf](https://llufb.llu.lv/conference/lidzsvar_lauksaim/2016/Latvia-lidzsvarota-lauksaimnieciba2016-161-168.pdf) (accessed on August 02, 2025).
32. Holstein Foundation Inc. Milking and Lactation. 2017. Available online: [https://www.holsteinfoundation.org/pdf\\_doc/workbooks/Milking\\_Lactation\\_Workbook.pdf](https://www.holsteinfoundation.org/pdf_doc/workbooks/Milking_Lactation_Workbook.pdf) (accessed on August 16, 2025).
33. Latvian Rural Advisory and Training Centre (LLKC). Slaucamo govju ēdināšanas nozīme svaigpiena saunas saturā izmaiņā/The role of dairy cow nutrition in changing the dry matter content of raw milk (In Latvian). 21.11.2019. Available online: <https://arhivs.llkc.lv/lv/nozares/lopkopiba/slaucamo-govju-edinasanas-nozime-svaigpiena-saunas-satura-izmaina> (accessed on August 18, 2025).
34. European Commission. Green Forum, Life Cycle Assessment & the EF methods, comprehensive coverage of impacts, 2025. Available online: [https://green-forum.ec.europa.eu/green-business/environmental-footprint-methods/life-cycle-assessment-ef-methods\\_en](https://green-forum.ec.europa.eu/green-business/environmental-footprint-methods/life-cycle-assessment-ef-methods_en) (accessed on August 11, 2025).
35. Frazier R.S.; Jin E.; Ajay Kumar A. Life Cycle Assessment of Biochar versus Metal Catalysts Used in Syngas Cleaning. *Energies* **2015**, 8(1), 621-644. <https://www.mdpi.com/1996-1073/8/1/621>.
36. Popluga D. Pārskats par zinātniskās izpētes projekta izpildi “Latvijas lauksaimniecības siltumnīcefekta gāzu un amonjaka emisiju, kā arī CO<sub>2</sub> piesaistes (aramzemēs un zālājos) robežsamazinājuma izmaksu līkņu (MACC) pielāgošana izmantošanai lauksaimniecības, vides un klimata politikas veidošanā”/Review of the implementation of the scientific research project “Adjustment of marginal abatement cost curves (MACC) of Latvian agricultural greenhouse gas and ammonia emissions, as well as CO<sub>2</sub> sequestration (in arable land and grassland) for use in agricultural, environmental and climate policy-making” (in Latvian). 2019. Available online: [https://www.lbtu.lv/sites/default/files/files/projects/Popluga\\_19-00-SOINV05-000018\\_1.pdf](https://www.lbtu.lv/sites/default/files/files/projects/Popluga_19-00-SOINV05-000018_1.pdf) (accessed on August 22, 2025).
37. Trading Economics. Latvia’s average temperature. 2025. Available online: <https://tradingeconomics.com/latvia/temperature> (accessed on August 20, 2025).

38. Latvia's National Inventory Report Greenhouse Gas Emissions in Latvia from 1990 to 2021 in Common Reporting Format (CRF). Riga, 2023, 489 p. Available online: <https://unfccc.int/documents/627724> (accessed on August 15, 2025)
39. International Organization for Standardization (ISO), 2018, 14067/2018. Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification standards. 2018, Switzerland: ISO.
40. Statistics Netherlands. What is the scale of greenhouse gas emissions? 2025. Available online: <https://www.cbs.nl/en-gb/dossier/greenhouse-gas-emissions/what-is-the-scale-of-greenhouse-gas-emissions-> (accessed on September 04, 2025).
41. Statistical database. Business sectors: Agriculture. Livestock. LAL090. Number of livestock and poultry at the end of the year (thousand heads) 1915 – 2024. Available online: [https://data.stat.gov.lv/pxweb/en/OSP\\_PUB/START\\_NOZ\\_LA\\_LAL/LAL090/](https://data.stat.gov.lv/pxweb/en/OSP_PUB/START_NOZ_LA_LAL/LAL090/)(accessed on September 02, 2025).
42. Statistical database. Business sectors: Agriculture. Livestock. LAL070. Livestock productivity 1940 – 2024. Available at: [https://data.stat.gov.lv/pxweb/en/OSP\\_PUB/START\\_NOZ\\_LA\\_LAL/LAL070/](https://data.stat.gov.lv/pxweb/en/OSP_PUB/START_NOZ_LA_LAL/LAL070/) (accessed on September 02, 2025).
43. Pilvere, A. Datasets for Efficiency and Emissions Performance in Latvian Dairy Farming: An LCA-Based Comparison Across Farm Sizes. 2025. Available online: <https://dv.dataverse.lv/dataset.xhtml?persistentId=doi:10.71782/DATA/ZRTIQV>, DataverseLV (accessed on September 10, 2025).
44. Central Statistical Bureau of Latvia. Agriculture of Latvia. Collection of Statistics. 2025, 84 p. Available online: [https://admin.stat.gov.lv/system/files/publication/2025-06/Nr\\_13\\_Latvijas\\_Lauksaimnieciba\\_2025\\_%2825\\_00%29\\_LV\\_EN\\_1.pdf](https://admin.stat.gov.lv/system/files/publication/2025-06/Nr_13_Latvijas_Lauksaimnieciba_2025_%2825_00%29_LV_EN_1.pdf) (accessed on August 31, 2025).
45. PRé Sustainability. SimaPro Database Manual, Methods library, 2022. Available online: <https://simapro.com/wp-content/uploads/2022/07/DatabaseManualMethods.pdf> (accessed on August 19, 2025).
46. Brkić, I.; Puvāča, N. Economic and Ecological Sustainability of Dairy Production. *Journal of Agronomy Technology and Engineering Management (JATEM)* **2024**, 7(3), 1088. <https://doi.org/10.55817/tqxu2115>.
47. Zanon, T.; Hörtenhuber, S.; Fichter, G.; Peratoner, G.; Zollitsch, W.; Gatterer, M.; Gauly, M. Effect of management system and dietary seasonal variability on environmental efficiency and human net food supply of mountain dairy farming systems. *J. Dairy Sci.* **2025**, 108(1):597–610. <https://doi.org/10.3168/jds.2024-25438>.
48. Fariña, S.; Chilibroste, P. Opportunities and challenges for the growth of milk production from pasture: The case of farm systems in Uruguay. *Agricultural Systems* **2019**, 176, 102631. <https://doi.org/10.1016/j.agsy.2019.05.001>
49. Holly, M. A.; Kleinman, P. J. A.; Bryant, R. B.; Bjorneberg, D. L.; Rotz, C. A.; Baker, J. M.; Bogges, M.; Bräuer, D.; Chintala, R.; Feyereisen, G. W.; Gamble, J. D.; Leytem, A. B.; Reed, K. F.; Vadas, P. A.; Waldrip, H. M. Short communication: Identifying challenges and opportunities for improved nutrient management through the USDA's Dairy Agroecosystem Working Group. *Journal of Dairy Science*, **2018**, 101(7), 6632. <https://doi.org/10.3168/jds.2017-13819>.
50. Gillespie, J.; Njuki, E.; Terán, A. Structure, costs, and technology used on U.S. dairy farms. *Economic Research Service* **2024**. <https://doi.org/10.32747/2024.8534118.ers>.
51. Singh, A. B.; Bhakar, V.; Gaurav, G.; Khandelwal, C.; Sarkar, P. K.; Singh, H.; Dangayach, G. S. Environmental sustainability of milk production: a comparative environmental impact analysis and sustainability evaluation. *Frontiers in Sustainability* **2024**, 5. <https://doi.org/10.3389/frsus.2024.1352572>.
52. Kwon, H.-C.; Jung, H. S.; Kothuri, V.; Han, S. G. Current status and challenges for cell-cultured milk technology: a systematic review. *Journal of Animal Science and Biotechnology* **2024**, 15(1). <https://doi.org/10.1186/s40104-024-01039-y>.
53. Salari, F.; Marconi, C.; Sodi, I.; Altomonte, I.; Martini, M. Environmental Sustainability of Dairy Cattle in Pasture-Based Systems vs. Confined Systems. *Sustainability* **2025**, 17(9), 3976. <https://doi.org/10.3390/su17093976>.

54. Reddy, P. R. K.; Kumar, D.; Rao, E. R.; Seshiah, Ch. V.; Sateesh, K.; Rao, K. A.; Reddy, Y. P. K.; Hyder, I. Environmental sustainability assessment of tropical dairy buffalo farming vis-a-vis sustainable feed replacement strategy. *Scientific Reports* **2019**, 9(1). <https://doi.org/10.1038/s41598-019-53378-w>.
55. Ni, H.; Zeng, H.; Liu, Z.; Li, W.; Miao, S.; Yang, A.; Wang, Y. Towards decarbonizing the supply chain of dairy industry: current practice and emerging strategies. *Carbon Neutrality* **2025**, 4(1). <https://doi.org/10.1007/s43979-025-00124-z>.
56. Silvi, R.; Pereira, L. G. R.; Paiva, C. A. V.; Tomich, T. R.; Teixeira, V. A.; Sacramento, J. P.; Ferreira, R.; Coelho, S. G.; Machado, F. S.; Campos, M. M.; Dórea, J. R. R. Adoption of Precision Technologies by Brazilian Dairy Farms: The Farmer's Perception. *Animals* **2021**, 11(12), 3488. <https://doi.org/10.3390/ani11123488>.
57. Bhat, R.; Infascelli, F. The Path to Sustainable Dairy Industry: Addressing Challenges and Embracing Opportunities. *Sustainability* **2025**, 17(9), 3766. <https://doi.org/10.3390/su17093766>.
58. Capper, J. L.; Bauman, D. E. The Role of Productivity in Improving the Environmental Sustainability of Ruminant Production Systems. *Annual Review of Animal Biosciences* **2013**, 1(1), 469. <https://doi.org/10.1146/annurev-animal-031412-103727>.
59. Thorup, V.; Munksgaard, L.; Terré, M.; Henriksen, J.; Weisbjerg, M.; Løvendahl, P. The relationship between feed efficiency and behaviour differs between lactating Holstein and Jersey cows. *The Journal of Dairy Research* **2023**, 90, 1-4. <https://doi.org/10.1017/S0022029923000420>.
60. Clasen, J.; Fikse, W. F.; Ramin, M.; Lindberg, M. Effects of herd management decisions on dairy cow longevity, farm profitability, and emissions of enteric methane – a simulation study of milk and beef production. *Animal* **2023**, 18(2), 101051. <https://doi.org/10.1016/j.animal.2023.101051>.
61. Britt, J. H.; Cushman, R. A.; Dechow, C. D.; Dobson, H.; Humblot, P.; Hutjens, M. F.; Jones, G.; Mitloehner, F. M.; Ruegg, P. L.; Sheldon, I. M.; Stevenson, J. S. Review: Perspective on high-performing dairy cows and herds. *Animal* **2021**, 15, 100298. <https://doi.org/10.1016/j.animal.2021.100298>.
62. Mondière, A.; Corson, M. S.; Auberger, J.; Durant, D.; Foray, S.; Glinec, J.-F.; Green, P.; Novak, S.; Signoret, F.; Werf, H. van D. Trade-offs between higher productivity and lower environmental impacts for biodiversity-friendly and conventional cattle-oriented systems. *Agricultural Systems* **2024**, 213, 103798. <https://doi.org/10.1016/j.agsy.2023.103798>.
63. Triky, S.; Kissinger, M. An Integrated Analysis of Dairy Farming: Direct and Indirect Environmental Interactions in Challenging Bio-Physical Conditions. *Agriculture* **2022**, 12(4), 480. <https://doi.org/10.3390/agriculture12040480>.
64. Hamelin, L.; Wenzel, H. Methodological aspects of environmental assessment of livestock production by LCA (Life Cycle Assessment). IX International Livestock Environment Symposium (ILES IX), American Society of Agricultural and Biological Engineers, 2012, ILES12-0945, . <https://doi.org/10.13031/2013.41541>.
65. Díaz de Otálora, X.; del Prado, A.; Dragoni, F.; Estellés, F.; Amon, B. Evaluating Three-Pillar Sustainability Modelling Approaches for Dairy Cattle Production Systems. *Sustainability* **2021**, 13, 6332. <https://doi.org/10.3390/su13116332>.
66. Ferronato, G.; Tobanelli, N.; Bani, P.; Cattaneo, L. Carbon Footprint Assessment of Dairy Milk and Grana Padano PDO Cheese and Improvement Scenarios: A Case Study in the Po Valley (Italy). *Animals* **2025**, 15(6), 811. <https://doi.org/10.3390/ani15060811>.
67. Neethirajan, S. Innovative Strategies for Sustainable Dairy Farming in Canada amidst Climate Change. *Sustainability* **2023**, 16(1), 265. <https://doi.org/10.3390/su16010265>.
68. Berton, M.; Bittante, G.; Sturaro, E.; Gallo, L. Thirty years of global warming potential evolution for the Italian dairy cow sector measured by two different metrics. *Italian Journal of Animal Science* **2024**, 23(1), 1002. <https://doi.org/10.1080/1828051x.2024.2373211>.

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