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From Carbon Footprint Accounting to Decision Support Systems in Dairy Sheep: Harmonised LCA Evidence, Digital Infrastructure, and Benchmarking

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General Abstract

This PhD thesis targets carbon footprint (CF) assessment as a decision-support and governance lever for dairy sheep systems, under the premise that its usefulness depends on three enabling conditions: high-quality and structured farm data, methodological robustness and transparency, and the translation of Carbon Footprint (CF) results into actionable priorities and monitorable KPIs from farm to supply-chain level. **Chapter 1** delivers an integrative PRISMA based systematic review (2010–2025) to clarify why Life Cycle Assessment (LCA) results for sheep products (milk, meat, wool) are often difficult to compare. The review confirms that variability across studies is strongly influenced by methodological settings system boundaries, functional unit, allocation, Global Warming Potential (GWP) metric choices, and the inclusion/exclusion of soil carbon sequestration besides real differences among production systems. **Chapter 2,** developed within the project LIFE Green Sheep framework, translates CF from a comparative indicator into an operational tool by applying an intra-national profiling approach. Beyond comparing national calculators, the chapter focuses on identifying measurable differences between low- and high-emission farms and on prioritising drivers that explain emission intensity within the same production system. This approach operationalises four complementary research questions to answer, "what to mitigate" and "how", distinguishing generalisable levers from those that must be adapted to the specific farm profile (e.g., productivity per head, purchased feed dependence, grazing management, direct energy use, nitrogen pressure, reproduction and milk composition). **Chapter 3** addresses a key bottleneck, without a reliable data

infrastructure, CF remains episodic and not auditable. The thesis contributes through APPàre, an integrated digital platform for the Italian sheep sector, embedding a GHG calculator designed to reuse existing farm data, formalise calculation rules, and ensure traceability and repeatability of the assessment. Validation on 10 Sardinian dairy sheep farms provides CF results expressed in kg CO_2 eq/kg FPCM, with an emissions profile dominated by enteric sources and a negative relationship between emission intensity and production level, supporting productivity as a guiding KPI and purchased inputs/energy as secondary levers to be managed according to yield. **Chapter 4** closes the accounting to decision support cycle through the CAO cooperative case study (18 farms, Sardinia), applying standardised LCA. The chapter frames CF as a diagnostic-strategic device to identify hotspots and convert farm variability into a streamlined KPI dashboard supporting cooperative benchmarking, capacity building and continuous annual monitoring. Overall, the thesis systematises three levels that are often treated separately, evidence synthesis, profiling methods, and digital/cooperative governance, showing how their integration makes CF a management indicator rather than a communication-only metric, particularly in sheep milk supply chains where climate impact is strongly farm-driven.

General introduction

Introduction

In recent years, sustainability has become an integral part of decision-making in livestock supply chains, not as a communication issue, but as a management variable (Atzori et al., 2015). In a sector such as sheep farming, characterised by multiple outputs (meat, milk, wool, ecosystem services) (Ripoll-Bosch et al., 2013), heterogeneous production models and a strong dependence on local resources and territorial conditions (Geß et al., 2020; Vagnoni et al., 2024), the key question is no longer whether environmental impact should be measured. The challenge is how to make this measurement useful, comparable, auditable and operational through clear methodological rules (Cossu et al., 2024; Ledgard et al., 2011), and how to translate it into priorities that can effectively support management choices aimed at improving both environmental and economic efficiency (Escribano., 2020; Vagnoni et al., 2019). Within this framework, the carbon footprint represents a strategic interface between technical assessment and governance, because it provides an accessible indicator for communicating environmental performance to policy makers and supply-chain stakeholders (Batalla et al., 2014; Zervas et al., 2016). At the same time, it offers an objective benchmark on which mitigation targets can be defined (Eldesouky et al., 2018; Jones et al., 2014), by condensing into a single metric (CO_2 equivalent) the combined effects of complex biological processes, such as enteric fermentation and nitrogen dynamics, and specific management choices, such as feeding strategies, manure management, energy use and reliance on external inputs (Batalla et al., 2014;

Escribano et al., 2020; Ceyhan et al., 2020). However, the usefulness of carbon footprint assessment is not automatic. Its reliability and practical value depend on a set of critical conditions that remain widely discussed in the literature. First, carbon footprint assessment depends on the quality and specificity of the farm data collected through the LCI (Life Cycle Inventory), because incomplete, generic or inconsistent data increase model uncertainty and may distort results (Bech et al., 2019; Ravani et al., 2024; Vagnoni et al., 2017). Second, it depends on methodological consistency and standardisation, including the application of shared rules such as Product Environmental Footprint Category Rules, to reduce the scope for subjective choices in key steps such as allocation and to improve the comparability and robustness of assessments (Cossu et al., 2024; Wiedemann et al., 2019). Third, it depends on the possibility of linking the indicator to management levers that are governable at farm level, so that the assessment does not remain a static accounting exercise but becomes a tool for supporting mitigation and resource-use optimisation (Horrillo et al., 2021; Vagnoni et al., 2017; Vagnoni et al., 2019). These conditions are particularly relevant in sheep farming, where the scientific literature shows that the application of Life Cycle Assessment (LCA) continues to be affected by a structural criticality: the fragmentation and limited comparability of results (Battacone et al., 2021; Eldesouky et al., 2018; Ripoll-Bosch., et al., 2013). A substantial part of this heterogeneity derives from the intrinsic flexibility of international standards, which leave room for different analytical choices (Eldesouky et al., 2018; Horrillo et al., 2021). Differences in system boundaries and functional units, for example, can substantially change the interpretation of impacts and may favour intensive or extensive systems depending on the perspective adopted (Arca et al., 2021; Batalla et al., 2014). The same applies to the management of multifunctionality in sheep systems, which simultaneously generate milk, meat, wool and ecosystem services (Ripoll-Bosch et al., 2013; Cottle et al., 2016). The selection of economic, mass or biophysical allocation, as well as the use of system expansion, can substantially alter the impact attributed to each product and generate asymmetries among studies (Cottle et al., 2016; Dakpo et al., 2017; Wiedemann et al., 2015). Additional divergence arises from the use of different characterisation factors for Global Warming Potential (GWP), including different metrics and time horizons for methane conversion into CO_2 equivalent, which produces carbon footprint values that are not directly comparable (Mazzetto et al., 2023). The inclusion or exclusion of soil carbon sequestration introduces a further critical point, especially in grazing-based systems, where its integration within system boundaries can offset a majority of gr CH_4 emissions and thus generate results that are not comparable with studies that omit this component, even when the same real production context is considered (Arca et al., 2021; Batalla et al., 2015; Horrillo et al., 2020). For this reason, a central need in the field is not only to increase the number of available assessments, but to improve their interpretability and comparability by clarifying the methodological assumptions that shape the final value of the indicator. Without this step, the variability observed among farms, products and territories risks being interpreted as a difference in environmental efficiency when it may partly reflect differences in accounting settings, reporting criteria or modelling choices (Eldesouky et al., 2018; O'Brien et al., 2016; Horrillo et al., 2021). In this sense, environmental assessment in the sheep sector requires a more robust analytical basis capable of distinguishing actual system differences from effects generated by methodological and reporting configurations (Eldesouky et al., 2018; Batalla et al., 2015). This issue becomes even more relevant when the objective is not only scientific interpretation but also territorial and managerial application. In practice, one of the major unresolved challenges is how to transfer environmental assessment from the scale of the individual LCA study to the scale of the territory, and from the territory back to the individual farm in a form that is understandable, usable and decision oriented. This requires methods that remain scientifically coherent while becoming sufficiently simplified, transparent and operational to support large-scale application. In sheep systems, this passage is particularly delicate because the sector includes very heterogeneous farms, uneven data availability and different levels of technical and managerial organisation. As a result, the problem is not only how to calculate emissions, but how to make the calculation portable across contexts, how to express it through indicators that can support comparison, and how to connect those indicators to concrete intervention priorities. In this perspective, the experience of initiatives aimed at harmonising methods and making carbon footprint assessment operational highlights a broader need within the sector: moving from isolated calculations to shared frameworks that allow diagnosis, comparison and action (Ledgard et al., 2011; Eldesouky et al., 2018). The key point is not simply the coexistence of different calculators, but the possibility of understanding which inputs and management choices most affect emission intensity, which differences are structural and which are managerial, and which mitigation levers can be generalised or instead need to be adapted to specific production profiles. This also requires an analytical perspective capable of reading variability within the same production system, since farms that appear similar in structural terms may show markedly different emission intensities because of differences in feeding strategies, input use, grazing management, energy demand, nitrogen pressure or productivity per head. A further critical bottleneck concerns data infrastructure. If carbon footprint assessment is expected to support routine management, benchmarking and planning, it cannot rely only on occasional and highly customised data collection. It requires digital systems capable of transforming environmental accounting into a repeatable, traceable and scalable process. This need is particularly evident in extensive and semi-extensive sheep systems, where digitisation remains uneven and available tools are often fragmented and weakly interoperable (Verdouw et al., 2016). In this context, the challenge is twofold: on the one hand, reducing the burden of data entry by reusing information that is already available at farm level; on the other hand, integrating heterogeneous domains such as herd structure, milk production, feeding practices, purchased inputs, manure management and energy use into a coherent data architecture that supports reliable calculations and consistent interpretation. This need is fully aligned with the broader literature on smart farming, data governance and supply-chain integration (Wolfert et al., 2017), as well as with the principles of data reusability and interoperability expressed by the FAIR framework (Wilkinson et al., 2016). In addition, the value of simplified calculation tools does not lie only in reducing complexity, but in making assessment more accessible without losing methodological transparency. In the sheep sector, simplified approaches are relevant only if they preserve alignment with the logic of LCA, maintain explicit assumptions, and remain capable of linking results to the main hotspots of the system. Otherwise, simplification risks weakening comparability and reducing the credibility of the indicator. The real requirement, therefore, is not simplification per se, but operational simplification supported by clear rules, transparent emission factors and a data structure that allows verification, updating and replication over time. This need becomes strategically decisive in the sheep dairy supply chain, where the literature consistently shows that the primary farm phase accounts for the predominant share of climate impact, often exceeding 90% of the total carbon footprint of sheep dairy products and cheese systems (Cossu et al., 2024; Eldesouky et al., 2018; Nunes et al., 2020; Vagnoni et al., 2017). This means that the main mitigation potential is concentrated at farm level, especially around enteric fermentation, feed production and purchased feed use, and that improvement depends largely on technical and managerial efficiency, including feeding precision, reproductive performance and ration quality (Atzori et al., 2022; Bosco et al., 2021; Sabia et al., 2020; Vagnoni et al., 2024). Under these conditions, environmental assessment becomes relevant only if it supports prioritisation: identifying where emissions are concentrated, which farms differ most, which levers are actually manageable, and how performance evolves over time. Within this framework, cooperatives can play a decisive role not only as economic and organisational actors, but also as governance infrastructures for environmental performance. By standardising metrics, defining internal benchmarks and transforming heterogeneous farm-level information into comparable indicators, cooperatives can reduce information asymmetries, strengthen the readability of results and support technical assistance based on shared and verifiable criteria (Escribano et al., 2020; Nsabiyeze et al., 2024; Batalla et al., 2015; Salcedo et al., 2022; Cossu et al., 2024). For this reason, benchmarking is not simply an output of calculation, but one of the main conditions for turning environmental assessment into a practical support tool for coordination, capacity building and continuous improvement at supply-chain level. Against this background, the thesis addresses a set of interconnected problems that remain open in the sheep sector: the need to strengthen the comparability of carbon footprint studies; the need to transfer environmental assessment from individual studies to territorial and farm-level application through simplified but robust calculation approaches; the need to improve data entry and digital interoperability in order to make calculations repeatable and auditable; and the need to use environmental indicators not only for reporting, but also for benchmarking and cooperative-level decision support. In this sense, the thesis is positioned at the intersection of methodological rigour, operational simplification, digitalisation and governance, with the aim of contributing to a more usable, comparable and action-oriented environmental assessment framework for sheep farming.

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Objective of the Thesis

The overall aim of this thesis is to make carbon footprint assessment in the dairy sheep sector methodologically robust, operationally applicable and useful for decision-making at both farm and supply-chain level.

To address this aim, the thesis pursues four specific objectives:

Objectives one: Clarify which methodological choices most strongly influence the comparability of carbon footprint results, with particular reference to system boundaries, functional unit, allocation procedures, GWP metrics and soil carbon sequestration.

Objectives two: Identify which inputs and management choices explain emission intensity within dairy sheep production systems, in order to derive practical mitigation guidance and distinguish between broadly applicable measures and system-specific interventions.

Objectives three: Address current data limitations by developing APPàre as an integrated platform for the Italian sheep sector and by implementing a greenhouse gas calculation module designed to maximise the reuse of existing farm data, ensure traceability of assumptions and enable repeatable assessment.

Objectives four: Apply carbon footprint assessment to the primary phase of the dairy sheep supply chain in order to identify emission hotspots and translate results into a KPI-based framework capable of supporting benchmarking and technical guidance among cooperative members.

CHAPTER 1

Life Cycle Assessment Applied to Ovine Milk, Meat and Wool: An Integrative Systematic Literature Review

Abstract

Life cycle assessment (LCA) is increasingly used as a decision-making tool to quantify the carbon footprint (CF) of livestock systems and to support benchmarking, mitigation planning and sustainability communication. However, data on sheep production are fragmented across different products (milk, meat and wool) and are strongly influenced by methodological choices, which can compromise the comparability and transferability of conclusions.

This systematic review aims to consolidate and critically evaluate peer-reviewed LCA studies on sheep production on a global scale, focusing on two aspects: (i) CF results reported across different functional units and products, and (ii) methodological approaches that drive variability and limit harmonised interpretation. The review followed a PRISMA aligned workflow (identification, screening, eligibility, and inclusion). Searches were conducted on Scopus, Google Scholar and Web of Science, using search strings that combined terms related to LCA/CF, sheep, product categories (milk, meat and wool) and greenhouse gases (e.g., CH_4, N_2O and CO_2eq). The inclusion period was 2010-2025. A total of 666 records were identified; after removing duplicates (n=136) and applying the screening/eligibility criteria, 119 studies were included in the final synthesis. The CF results show a wide dispersion by product and functional unit: for milk, studies reporting kg CO_2eq/kg FPCM (n=21) (1.6 to 8.4); for wool, kg CO_2eq/kg wool (n=17) (0.45 to 97); for meat, kg CO_2eq/kg live weight (LW) (n=47) (1.29 to 62.6), while kg CO_2eq/kg carcass weight (CW) (n=11) (9.3 to 70). The hotspot models are structurally consistent: enteric fermentation is always included in the milk dataset (100%) and is the largest contributor (19-83.4%); equally high shares are reported for wool (46-99.4%) and meat production systems (29.8-100%), followed by variable contributions from feed, manure management and energy/fuel. Methodological concentration is evident in milk LCAs (cradle to farm in 91%; tier 2 in 63%; economic allocation in 53%), but persistent gaps remain in the reporting of inventory variables (e.g. feed and electricity), signalling residual constraints in terms of verifiability and benchmarking between studies. The available evidence confirms that mitigation plans in sheep systems must prioritise biological efficiency and feed-related levers, but the current heterogeneity of functional units, boundaries, allocation and inventory reporting materially limits comparability. Standardised reporting and harmonisation of key methodological choices are therefore strategic factors in translating LCA results into robust benchmarks and valuable decision support for farms and value chains.

Keywords

Life Cycle Assessment; Carbon footprint; Ovine systems; Sheep milk; Sheep meat; Wool; Functional unit; Allocation; Enteric methane; Hotspots

Introduction

The transition towards a more sustainable livestock sector represents one of the key strategic challenges of our time. Against a backdrop of climate change and population growth, it is essential to improve the sustainability and resilience of agricultural systems throughout the entire value chain (Lanzoni et al., 2023). In particular, unsustainable food supply chains are recognised as a key driver of significant environmental impacts and a factor contributing to the depletion of non-renewable resources (Cossu et al., 2024). Like all human activities, the livestock sector contributes to global greenhouse gas emissions, including CO_2, N_2O and CH_4, which are expressed in CO_2 equivalent units to facilitate comparison. The conversion of N_2O and CH_4 to CO_2 eq is based on their respective contributions to atmospheric radiative forcing, relative to CO_2. This conversion depends on various factors, including the atmospheric lifetime of the gases in question, their current concentration levels and their ability to absorb infrared radiation. Although they have relatively low atmospheric concentrations compared to CO_2, CH_4 and N_2O have a significantly higher global warming potential (GWP) over a 100-year timeframe, with values of 25 and 273 respectively, according to the Intergovernmental Panel on Climate Change (IPCC) et al. (2021). Consequently, even small variations in these parameters can have relatively substantial consequences for climate change and related mitigation strategies. With regard to global emissions, the total anthropogenic emissions over the period 2010-2019 were estimated at approximately 56 Gt CO_2eq/yr. Of this total, approximately 14% (equating to 16 Gt CO2eq/yr) was attributed to the AFOLU sector (agriculture, forestry and land use). As stated by Nabuurs et al. (2022) and Shurpali et al. (2019), the global livestock sector emitted approximately 7.1 gigatonnes (Gt) of CO_2, which accounted for approximately 14.5% of total anthropogenic greenhouse gas (GHG) emissions (Shrivastava et al., 2025). Moreover, data from the Food and Agriculture Organization of the United Nations' Global Livestock Environmental Assessment Model (FAO GLEAM) system reveal that total emissions from small ruminants, namely sheep and goats, amount to approximately 475 million tons of CO_2 eq per yr. This corresponds to approximately 6.5% of total agricultural emissions (Giamouri et al., 2023). As stated by Latiolis et al. in 2025 and FAO in 2013, the socio-economic importance of the production of milk, meat and wool in sheep farming must be acknowledged. In 2020, Europe led the world in the production of sheep's cheese, with Sardinia (Italy) being the foremost region within the European Union in terms of sheep's milk production (Atzori et al., 2022). Cossu et al. (2023) observe that the textile sector, including wool production, is increasingly orienting towards the circular economy to enhance its sustainability. This is due to the recognition of the sector's significant environmental impact in comparison to other fibres (Bianco et al., 2023). At the methodological and operational level, studies on products derived from small ruminants confirm that LCA estimates and greenhouse gas emissions assessments can support informed decisions along the supply chain by clarifying the relative impacts of products and activities (Peri et al., 2020; Sabia et al., 2020). This paper aims to examine the factors that have led to the current situation. It will firstly review the literature on the subject, to establish which factors have been identified by previous research. It will then proceed to analyse the data to identify any trends or patterns that may be indicative of the causes. Finally, it will offer a conclusion based on the findings of its analysis and a discussion of the implications of these findings. CF is employed with a high degree of frequency to convey to stakeholders the contribution of sheep production to climate change. In certain markets, consumer awareness of CF is elevated and is translated into a demand for information on the CF of products, especially in flows to large supermarket chains or intermediaries (Zervas et al., 2012). As indicated by Eldesouky et al. (2018), research interests in this area include understanding how consumer choices are influenced by different product characteristics, and whether a price premium can be recognised when a product is differentiated by its CF attribute. This issue is of pertinence in the context of extensive systems, wherein the environmental values associated with livestock production can be eclipsed by comparatively higher emissions, particularly when the consideration of carbon sequestration by the environment is not given due attention (Eldesouky et al., 2018). In this sense, the label CF serves as a useful tool for guiding purchasing decisions and, most importantly, for raising awareness of the significant influence that food production exerts on greenhouse gas emissions (Ceyhan et al., 2020). It is evident that the global population of small ruminants has continued to exhibit consistent growth in recent years, thereby solidifying their strategic position within the broader global livestock sector. According to the most recent FAOSTAT series (FAO, 2024), the global sheep population surpassed 1.3 billion, while the goat population reached approximately 1.1 billion. Consequently, the total number of sheep and goats exceeds 2.4 billion head. A recent analysis of FAOSTAT data has revealed a notable increase in the global population of sheep and goats, with an estimated growth of +12% and +16%, respectively, between 2013 and 2023. This finding corroborates the assertion posited in extant literature that describes this expansion as both structural and consequential for the agricultural sector (FAO, 2024). The increase is most evident in developing countries, where small ruminants serve as a pivotal operational strategy for enhancing food security and stabilising family income. Ethiopia provides a pertinent case study: between 2011 and 2020, the country experienced significant annual growth in its sheep and goat populations, at rates of 4.2% and 6.7% respectively. This resulted in a total population of approximately 96 million head (Jemberu et al., 2022). Concurrently, within more sophisticated, market-oriented production systems, the implementation of efficiency-enhancing solutions facilitates an increase in productivity while concomitantly enabling the adoption of emission mitigation strategies (Atzori et al., 2022). In the context under consideration, production efficiency emerges as a pivotal factor in shaping the CF. Systems that demonstrate high performance are observed to exhibit a reduced CF, attributable to their enhanced efficiency in resource utilisation per unit of product. The objective of this research is to evaluate and quantify the environmental impact of these systems. The methodology employed to achieve this objective is LCA. LCA has established itself as the preferred methodology for estimating the CF per unit of product. LCA is regarded as the gold standard for evaluating the environmental impact of agricultural systems, representing a standardised and internationally recognised methodology (Lanzoni et al., 2023). This comprehensive approach entails the quantification of greenhouse gas emissions generated in all stages associated with a product, from raw material extraction to production, use, recycling and disposal within the boundaries of the system (ISOa,b). Its primary objective is the identification of production systems and technical practices that utilise fewer natural resources per unit of product, thereby reducing the environmental impact of food production (Eldesouky et al., 2018). Notwithstanding the ubiquity of the LCA concept, the extant literature continues to emphasise discrepancies and lacunae, notably in the context of comparing disparate systems and the consistent integration of diverse sustainability dimensions. A review of the literature reveals that the number of LCA studies on sheep production and its meat, milk and wool products is still limited compared to other types of livestock (Shrivastava et al., 2025). Nonetheless, it is feasible to delineate a sufficiently perspicacious delineation of the global distribution of LCA research and environmental impact analysis in the ovine sector. The extant evidence signifies regional specialisation driven by production traditions, climatic conditions and market demands. However, it also accentuates a more pronounced paucity of data availability in comparison to other livestock sectors, such as cattle. In this sense, a preponderance of studies concurs that, notwithstanding a surge in interest, LCA as applied to the ovine sector remains comparatively underdeveloped relative to its application to dairy and beef cattle and pigs (Shrivastava et al., 2025).

The aim of the first chapter is to provide a systematic and integrative review of the literature on the application of Life Cycle Assessment (LCA) to sheep systems, considering milk, meat and wool together. In essence, the chapter serves to: (i) collect and summarise the carbon footprint results reported in the literature for different products and functional units; (ii) critically analyse the main methodological choices that influence the results, in particular system boundaries, functional units, allocation, tiers/calculation methods and inventory reporting, to understand which factors limit comparability between studies; (iii) highlight hotspots, knowledge gaps and harmonisation needs that are useful for making future LCA assessments more robust and more useful for supporting business and supply chain decision-making.

General gaps

Bhatt et al. (2022) explicitly state that research in the sheep sector is ‘relatively scarce’ and that most peer-reviewed studies are limited to Europe and Oceania. A review of the literature reveals a dearth of research on wool as a primary product, with only a limited number of detailed studies published, predominantly from Australian scholars (Cottle et al., 2016). Wiedemann et al. (2015) note that data concerning the effect of precision feeding on sheep milk production are limited, particularly when compared to the wealth of information available for cow milk. This observation is consistent with that of Bosco et al. (2021), who emphasize the need for further research in this area, particularly with regard to the development of effective precision feeding strategies for ovine species. In regions such as Canada or Greece (despite the economic importance of the latter), there is a paucity of specific or updated data (Ravani et al., 2024). Within this perimeter, the literature tends to polarise according to the main product of each area. Oceania (comprising Australia and New Zealand) boasts the most comprehensive and meticulously documented array of studies on wool and meat exports. Australia, a preeminent wool exporter, has undertaken analyses that are predominantly centered on high-quality Merino wool. These studies encompass a wide range of subjects, including land use and greenhouse gas emissions across diverse climatic zones, such as New South Wales and Western Australia (Wiedemann et al., 2015). As Henry et al. (2015) note, the subject of this study is of particular relevance to the broader field of research in this area. In parallel, the allocation of impacts between wool and meat in Merino systems has been explored in depth by Cottle and Cowie (2016). Furthermore, meat (often a co-product or main product, such as lamb for export) has also been analysed in terms of its CF in flows to foreign markets (Ledgard et al., 2011; Wiedemann et al., 2015). The distinguishing characteristic in this case is that wool possesses a high economic value; consequently, a substantial proportion of emissions is attributed to it. In the Mediterranean region of Europe, encompassing countries such as Italy, Spain, Greece, and Portugal, the dietary emphasis is predominantly on milk and Protected Designation of Origin (PDO) cheeses, including renowned varieties like Pecorino, Manchego, Feta, and Roquefort. Meat, particularly milk-fed lamb, typically assumes a subordinate role in this culinary tradition. A plethora of studies conducted in Italy (specifically in Sardinia, Tuscany, and Basilicata) have assessed the LCA of sheep's milk utilized in the production of renowned cheeses such as Pecorino Romano and Toscano. These investigations have centered on drawing parallels between intensive and extensive farming systems, while also scrutinizing the significance of feed in these contexts (Bosco et al., 2021; Vagnoni et al., 2014; Sabia et al., 2020). In Spain, research has been conducted in the Basque Country (Latxa) and Castile and León (Assaf) to examine the CF of milk in relation to grazing practices (Batalla et al., 2015). Plaza et al. (2021) observed that in Greece and Portugal, recent contributions remain focused on ovine milk and traditional cheeses (Ravani et al., 2024; Nynes et al., 2020). They noted that meat is often treated as “suckling lamb” slaughtered at a very young age, and Battacone et al. (2021) emphasize the contingent nature of its impact, which is contingent upon the emissions of the mother. In the context of environmental impact assessment, wool has historically been regarded as a low-value by-product or waste, with limited attribution of environmental impacts in studies (Palomo et al., 2024). In Northern and Central Europe (including the United Kingdom, Ireland, and Norway, as well as Sweden), the emphasis has traditionally been on meat production, with a more recent interest in the valorisation of wool, a material that has historically been underutilized or even destined for disposal. In the United Kingdom and Ireland, sheep production has primarily been associated with lamb meat. Studies such as Jones et al. As asserted by recent research findings and Brok et al. (2013), the CF in grazing systems is a focal point in contemporary environmental science. In Norway, Åby et al. (2024) undertake an exhaustive analysis of extensive grazing-based systems in marginal areas. In recent years, the Nordic countries have demonstrated a growing commitment to exploring circular economy approaches in the context of wool utilisation. A prevailing theme in the latest literature from Sweden and other Nordic countries is the comparison of virgin and recycled wool, with a view to promoting recycling and valorisation practices to minimise waste generation (Martin and Herlaar, 2021; Bianco et al., 2022). In the Americas, studies are characterised by fragmentation and association with extensive or mixed systems. In South America (Patagonia), Peri et al. (2020) undertake an analysis of systems on large natural pastures (steppes) that produce both meat and high-quality wool. These systems represent the region most comparable to Oceania in terms of its joint focus on fine wool and extensive meat production. In contrast, scientific production in North America (comprising the USA and Canada) is more constrained. Dougherty et al. (2019) undertake an analysis of sheep meat in California, encompassing both the CF and the water footprint. In Canada, Bhatt et al. (2022) draw attention to the absence of specific national data. Finally, in Asia (China, Turkey), the availability of evidence is increasing, albeit not yet reaching uniformity. In Turkey, studies such as Yetişgin et al. (2022) and Ceyhan et al. (2020) examine mixed systems (milk and meat) and transhumance in contexts that are frequently semi-arid. China is frequently cited as a major global producer; however, an examination of the sources reveals that it functions more often as a processing hub (e.g., for washing and spinning Australian wool) than as a subject of primary studies on livestock farming, despite contributions such as that of Wang et al. (2024) on emissions in grassland steppes. In conclusion, the evidence presented in the report substantiates a paucity of standardised global data, in contrast to pronounced regional abundances. The literature on wool is dominated by Oceania, while Mediterranean Europe preeminates in the domain of sheep's milk. However, the treatment of meat is transversal, albeit with considerable heterogeneity in methodological approaches and economic weights that are contingent upon geographical location. This discrepancy is frequently ascribed to variations in greenhouse gas calculations, choices regarding LCA models, or the farms that are selected. A fundamental issue is the management of the multifunctionality of sheep farming systems, which are capable of producing milk, meat and wool simultaneously: the allocation of environmental impacts between these co-products is thus a pivotal methodological decision, with the potential to exert a considerable influence on the CF and classification of systems. A variety of allocation methods exists, including those based on mass, economic value, protein, biological energy, or system expansion. The selection of a particular method can significantly impact the relative differences among CF and their subsequent classification (Vagnoni et al., 2017; Lunesu et al., 2025).

Uusitalo et al. (2019) note a further challenge, namely the lack of a common consensus on the inclusion of soil carbon sequestration in CF calculations, despite its mitigation potential. The assessment of emissions due to land use change also remains an area of methodological disagreement. As Escribano et al. (2020) assert, the findings of Salvador et al. (2017) and Batalla et al. (2015) substantiate the existence of a nexus between the variables under scrutiny. Pardo et al. (2024) have noted that LCA tends to reward situations of greater intensification, whilst failing to consider other crucial aspects adequately. In particular, Lanzoni et al. (2023) have highlighted a lack of harmonisation and standardisation in the integration of animal welfare assessment with LCA. The present review seeks to offer a comprehensive and lucid synopsis of the literature published over the past 15 years concerning the application of LCA to the ovine sector. Its objective is twofold: firstly, to delineate the methodological approaches that have been adopted, and secondly, to summarise the predominant findings. By meticulously examining the strengths and limitations inherent in this approach, the review aspires to pave the way for the development of enhanced LCA analyses in the future. This research aims to investigate and study the aspects of the subject in order to facilitate the implementation of the most advanced approach to LCA on farms involved in future projects, thereby stimulating the development of new mitigation strategies at the territorial level.

Life cycle assessment for estimating greenhouse gas emissions

The universal adoption of LCA as the standardised and most suitable method for quantifying the environmental impacts of livestock products is well documented (Arca et al., 2021). The objective of the methodology is to quantify the environmental impacts, particularly greenhouse gas emissions, associated with a product, good, service or process throughout its entire life cycle, from “cradle to grave” or in specific stages such as “cradle to farm gate” (ISO). The primary reasons for its utilisation can be enumerated as follows:

A Holistic Approach: It circumvents the allocation of responsibility for environmental impact from one stage of the production cycle to another, thereby enabling the comprehensive evaluation of the impact from the extraction of raw materials to the final product's disposition (Fois et al., 2022).

Identification of Hotspots: This is imperative for the identification of critical junctures (hotspots) within the production process, where intervention is requisite for the mitigation of emissions (Biswas et al., 2010).

Comparison and Benchmarking: This methodology facilitates comparisons between disparate production systems (e.g. intensive vs extensive, organic vs conventional) or between products that serve an analogous function (Peri et al., 2020).

Decision Support: The provision of scientific data to inform agricultural policies, business decisions and consumer choices is facilitated through environmental labelling (e.g. Made Green in Italy, PEF) (Cossu et al., 2024).

Methodological Basis and Structure

LCA is an internationally standardised methodology, the principles and framework of which are described by ISO 14040, and the requirements and guidelines of which are described by ISO 14044 (ISO).

Moreover, within the domain of the small ruminant sector, the particular FAO-LEAP (Livestock Environmental Assessment and Performance Partnership) guidelines are frequently referenced (Sodi et al., 2024).

The standard LCA (Life Cycle Assessment) structure comprises four mandatory stages:

1. Definition of the objective and scope: The boundaries of the system, the functional unit, and the allocation rules are established during this phase.
2. The second stage of the process is that of the life cycle inventory (LCI). This stage is the most time-consuming, and consists of the collection and quantification of all input flows (energy, feed, water) and output flows (products, emissions to air/water/soil). Primary data is typically obtained through direct interviews with farmers, whereas secondary data (e.g. electricity or fertiliser production) is sourced from databases such as Ecoinvent, Agri-footprint, or national databases (Bevilacqua et al., 2011)
3. Life cycle impact assessment (LCIA): Inventory data is categorised according to its environmental impact (e.g. global warming) with the aid of specific characterisation factor.
4. Interpretation: The results are analysed and any limitations and uncertainties identified in order to draw conclusions.

The LCA's estimations

The primary objective of the LCA is to estimate the contribution to climate change by quantifying greenhouse gas (GHG) emissions. These emissions are expressed in CO_2

equivalent (-eq) over a time horizon of 100 years (GWP100). The primary gases that are considered are as follows:

Carbon dioxide (CO_2): Derived from the utilisation of fossil fuels, fertiliser and feed production, and changes in land use.

Methane (CH_4): Derived primarily from enteric fermentation in ruminants and manure management. It possesses a global warming potential (GWP) that is significantly higher than CO_2. The values employed in the study range from 25 to 34, contingent upon the specific IPCC reference report utilised.

Nitrous oxide (N_2O) is derived from the management of manure and agricultural soils, encompassing fertilisers and grazing manure. It exhibits a remarkably high Global Warming Potential (GWP), with a factor of 265 or 298 times that of CO_2.

System Boundaries

The selection of system boundaries is instrumental in delineating the processes that are encompassed within the study. A plethora of studies have been conducted that elucidate diverse methodologies.

These are succinctly delineated in Figure 1.

Cradle-to-Farm-Gate: This approach is the most prevalent boundary employed in livestock studies. As Atzori et al. (2015) and Kilcline et al. (2024) observe, the approach encompasses all upstream activities, that is, feed production and fertilisers, as well as on-farm activities until the animal or milk departs the farm. In other words, it is a ‘cradle-to-grave’ approach. This concept encompasses various domains, including transportation, industrial processing (for instance, cheese production and wool spinning), the utilisation phase (e.g. washing sweaters and cooking meat), and ultimate disposal. It finds application in studies pertaining to finished products such as cheese or woolen attire (Dimakis et al., 2022). Cradle-to-Retail: As Verduna et al. (2020) observe, the subject of retail distribution is sometimes excluded from consideration.

The rationale for this exclusion is that infrastructure and capital goods (e.g. barn construction, machinery) are considered to have a negligible impact in the long term. However, as Sodi et al. (2024) and Pardo et al. (2024) note, there are some studies that suggest including them.

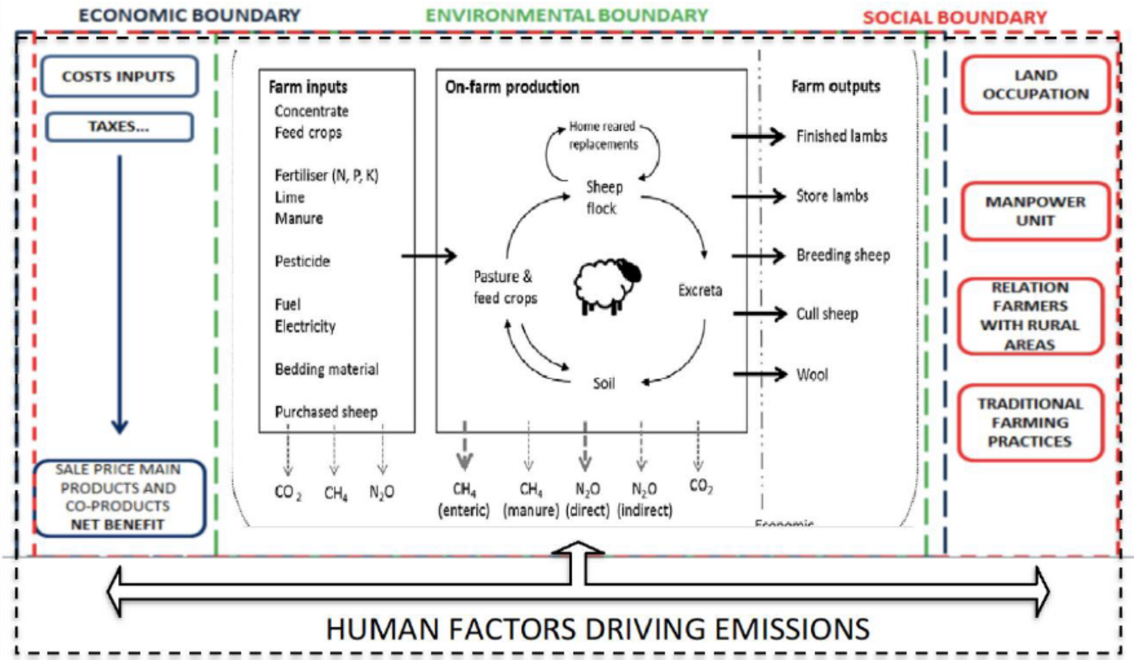

Figure 1. The boundaries of the environmental system encompass economic and social aspects (adapted from Jones et al., 2014; Batalla et al., 2014).

Functional Units (FU)

The Functional Unit is the reference unit for standardising results. It is evident from the available literature that there are different options depending on the objective.

The basis of this study is the mass of the product.

◦ Milk: 1 kg of FPCM (Fat and Protein Corrected Milk) (Pulina et al., 2005) is employed to standardise milk according to its fat and protein content, or ECM (Energy Corrected Milk) to standardise milk according to its energy content (Arca et al., 2021). As stated by Batalla et al. (2014) and Bosco et al. (2021), the methodology entails the utilization of a specific quantity of meat, equivalent to either 1 kg of live weight (LW) or 1 kg of carcass weight. This approach has been previously validated by the works of Ahlgren et al. (2024) and Battacone et al. (2021).

◦ Meat: 1 kg of live weight (LW) or 1 kg of carcass weight (Ahlgren et al., 2024; Battacone et al., 2021).

◦ Wool: One kg of greasy or clean wool (Bianco et al., 2022; Cottle et al., 2016).

In the context of area-based metrics (i.e. metrics that focus on the surface area), a measurement of 1 hectare (ha) of utilised agricultural area (UAA) is employed. This unit of measurement is often favoured in the assessment of land use efficiency and the evaluation of localised impacts (e.g. eutrophication) within extensive or pastoral systems (see references: Batalla et al., 2014; Escribano et al., 2020). Nutrient-based: Protein content, employed for the purpose of comparing nutritional efficiency (Shrivastava et al., 2025).

Allocation Method

Another fundamental methodological choice is the allocation method the distribution of environmental impacts among the different co-products of a system. Since sheep produce multiple outputs simultaneously (milk, meat, wool), it is necessary to allocate the environmental impacts among these co-products. The different methodologies have been extensively discussed in studies in this field.

Economic Allocation: The distribution of impacts is determined by the market value of products. This approach is extensively utilised, particularly in the context of milk and cheese production, where milk's value predominates. However, it has been the subject of criticism due to its susceptibility to price volatility (Arca et al., 2021; Ahlgren et al., 2024; Biswas et al., 2010).

Biophysical Allocation: Based on the energy or protein requirements of the animal to produce different outputs. This method is recommended by the IDF and FAO-LEAP guidelines as the most stable and scientific approach (Sodi et al., 2024; Mazzetto et al., 2023).

Mass Allocation: Determined by the weight of the products. Frequently deemed unsuitable for wool (produced in limited quantities but with a significant impact) or for comparing milk and meat (Escribano et al., 2020; Åby et al., 2024).

Protein Mass Allocation (PMA): This approach is specific to wool and meat, and it bases the allocation on the protein content. Wool is penalised more heavily because it is pure protein (Cottle et al., 2016).

System Expansion: This strategy circumventsthe issue of allocation by incorporating alternative functions within the system. An illustrative example would be the substitution of beef with sheep meat production. This approach is frequently utilized in the context of consequential strategies (Wiedemann et al., 2016).

Impact Categories

Impact categories are the environmental dimensions selected for analysis. In addition to climate change, which remains the most extensively researched category, the methodology of LCA enables the evaluation of other environmental impacts relevant to agriculture.

The most common of these include eutrophication, defined as the enrichment of nutrients (N, P) in fresh water, marine water and soil (Sharma et al., 2018).

Acidification refers to the increase in acidity of the air and soil due to the release of acid emissions (Cerrato et al., 2023; Bosco et al., 2021).

Land Use: This concept pertains to the occupation and transformation of land, which is crucial for biodiversity (Batalla et al., 2014; Geß et al., 2022).

Resource consumption: The utilisation of water (i.e. the water footprint) and the depletion of fossil fuels and energy have been extensively documented (Dimakin et al., 2022).

Toxicity: The ecotoxicity of both terrestrial and marine ecosystems, as well as its impact on humans, has been thoroughly investigated. These issues are frequently associated with the employment of pesticides or heavy metals (Sodi et al., 2024). Cerrato et al. (2023) assert that certain studies employ methodologies such as ReCiPe, which consolidate these impacts into final damage categories, including Human Health, Ecosystems, and Resources, with the objective of enhancing communication (Sabia et al., 2020; Vagnoni et al., 2014).

Hotspots

Identification of the critical points, i.e. the processes or stages contributing most to the overall environmental impact, is a useful exercise when analysing a system. In the context of ovine systems, the most prevalent critical points are Enteric Fermentation: This phenomenon is consistently identified as the predominant source of greenhouse gases, with CH_4 emissions frequently contributing 40-70% to the total CF, particularly within extensive systems (Dakpo et al., 2017; Silva et al., 2024). Feed Production: Feed procurement represents a critical hotspot, in particular within the context of intensive systems, due to emissions associated with cultivation (fertilisers), transport and energy use (Lunesu et al., 2025; Vagnoni et al., 2014). The management of manure is a crucial aspect of agricultural practices, as it involves the emission of greenhouse gases such as CH_4 and N_2O during the storage and distribution of the material (Escribano et al., 2020). The consumption of energy is another pivotal factor, with the utilisation of electricity and fuel for machinery, although less substantial in terms of volume than biological emissions, playing a significant role in dairy operations and highly mechanised systems (Cossu et al., 2024). A review of the scientific literature reveals substantial variability in the outcomes of LCA studies. This variability can be attributed to two primary factors. Firstly, differences among production systems and local conditions, such as climate, breed, and pastures, contribute to divergent results. Secondly, the utilization of varied methodological approaches also leads to inconsistencies in the findings (Palomo et al., 2024; Ripoll et al., 2013). In particular, the decision regarding the inclusion or exclusion of soil carbon sequestration, the choice of IPCC level, or the use of regional algorithms has the potential to introduce significant variations in estimates (Lesschen et al., 2011).

As Zervas et al. (2012) observe, the absence of methodological harmonisation continues to represent a significant challenge. In this context, there has been an increasing recourse to tools such as sensitivity analysis and Monte Carlo simulation in order to assess the robustness of results, as Vagnoni et al. (2015) demonstrate.

Table 1. Emission categories considered in the FAO estimates

Category	Description
Feed N_2O	Direct and indirect N_2O emissions from manure deposited on pasture Direc and indirect N_2O emissions from organic and synthetic N applied to crops an pasture
Feed CO_2	
blending and transport	CO_2 arising from the production and transportation of compound feed
fertiliser production	CO_2 from energy use during the manufacture of urea and ammonium nitrat (and small amounts of N_2O)
processing and transport	CO_2 from energy use during crop processing (e.g. oil extraction) an transportation by land and (in some cases) sea
field operations	CO_2 arising from the use of energy for field operations (tillage, fertilize application). Includes emissions arising during both fuel production and use.
Feed LUC CO_2	CO_2 from LUC associated with soybean cultivation and pasture expansion
Indirect (embedded) energy CO_2	CO_2 arising from energy use during the production of the materials used t construct farm buildings and equipment
Manure N_2O	Direct and indirect N_2O emissions arising during manure storage prior t application to land
Manure CH_4	CH_4 emissions arising during manure storage prior to application to land
Enteric CH_4	CH_4 arising from enteric fermentation
Direct energy CO_2	CO_2 arising from energy use on-farm for heating, ventilation, etc.
Post-farmgate	Energy use in processing and transport

Consistent with the findings on hotspots in sheep farming systems, the Food and Agriculture Organization (FAO) assessments furnish an operational reference for identifying the primary emission sources that are concentrated along the supply chain, as demonstrated in Table 1. In the realm of FAO estimates of greenhouse gas emissions from the livestock sector, with a particular emphasis on small ruminants, a pivotal moment was the publication of the report Tackling Climate Change through Livestock (Gerber et al., 2013). Building on this foundation, the FAO has persisted in refining and developing methodologies and models to enhance the robustness and intricacy of its estimates. As posited by the Global Livestock Environmental Assessment Model (GLEAM) v3.0 and the reports published in 2016, 2017, 2019 and 2023, more recent resources propose a more granular breakdown of emission categories. It is asserted that this allows for more accurate tracking of the contribution of different stages along the entire production chain of small ruminants (Figure 2).

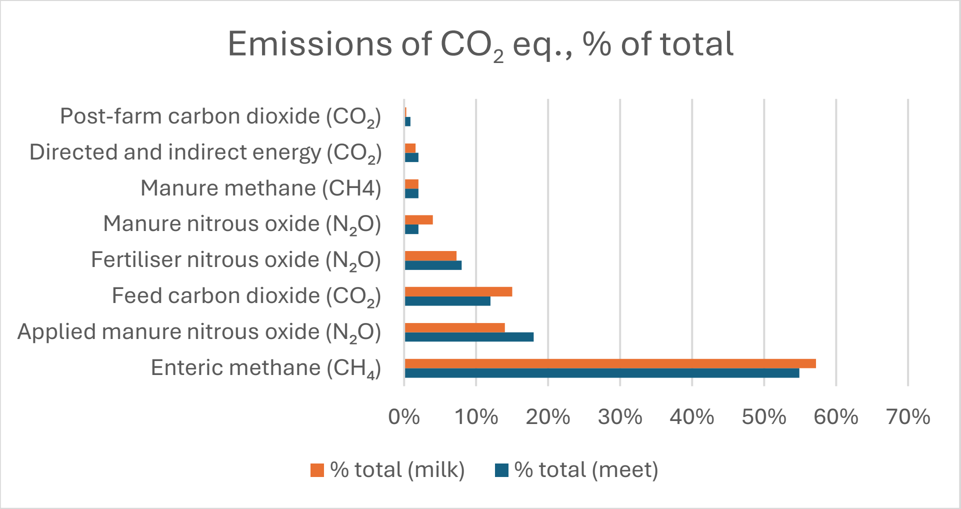

Figure 2. Emission source contribution to small ruminant CO2-eq for meat and milk production (adapted from Fig. 14 of Gerber et al., 2013).

Materials and methods

Over the past 15 years, there has been a marked proliferation of LCA studies within the domain of livestock production, particularly in Europe, Oceania, and the United States. Concurrently, scientific literature focusing on emissions, with particular attention to enteric CH_4, has demonstrated clear and continuous growth: bibliometric analyses that explicitly include cattle, sheep and goats reveal a marked increase in publications since the early 2000s, with an acceleration up to the most recent peaks and expansion driven by large scientific and production centres. However, when the scope is narrowed to sheep systems and small ruminant products alone, the number of peer-reviewed LCA studies is limited and concentrated geographically and by

product, with a prevalence of ork on meat and more limited coverage of milk and wool (Sikiru et al., 2024; Evangelista et al., 2024). In view of the aforementioned increase and the persistent gaps in knowledge, a comprehensive literature review focusing on ovine production on a global scale was undertaken. The proposed list offers a wide-ranging and contemporary overview of the extant research, though it does not preclude the possibility of other pertinent studies being in existence.

Protocol and research strategy (PRISMA)

The review was conducted in accordance with the PRISMA guidelines, adopting a structured workflow comprising identification, screening, eligibility assessment and inclusion of studies. This approach is in line with recent methods that formalise the decision-making process through PRISMA flow charts and explicit selection criteria. The bibliographic search was conducted utilising renowned databases such as Scopus, Google Scholar, and Web of Science. The search strings employed were meticulously crafted based on combinations of terms pertaining to LCA/CF, ovine species, and products (milk, meat, wool), along with predominant emission drivers (GHG, CH_4, N2O, CO2, CO2e).

Keywords for Google Scholar:

("life cycle assessment" OR LCA OR "carbon footprint" OR CF) AND (sheep OR ovine OR lamb OR ewe OR ram OR rams) AND (milk OR meat OR wool OR fleece) AND (emissions OR "greenhouse gas" OR "greenhouse gases" OR GHG OR methane OR CH4 OR N2O OR CO2 OR "CO2-eq" OR CO2e) AND ("environmental impact" OR footprint OR footprints OR sustainable OR sustainability)-(goat OR goats OR caprine OR cattle OR bovine OR cow OR cows)

Keywords for Scopus:

("life cycle assessment" OR LCA OR "carbon footprint" OR CF) AND (sheep OR ovine OR lamb OR ewe OR ram OR rams) AND (milk OR meat OR wool OR fleece) AND (emission OR emissions OR "greenhouse gas" OR "greenhouse gases" OR GHG OR methane OR CH4 OR N2O OR CO2 OR "CO2 eq" OR "CO2-eq" OR CO2e) AND ("environmental impact" OR footprint OR footprints OR sustainable OR sustainability) AND NOT TITLE-ABS-KEY(goat) AND NOT TITLE-ABS-KEY(goats) AND NOT TITLE-ABS-KEY(caprine) AND NOT TITLE-ABS-KEY(cattle) AND NOT TITLE-ABS-KEY(bovine) AND NOT TITLE-ABS-KEY(cow) AND NOT TITLE-ABS-KEY(cows)

Keywords for Web of Science:

(("life cycle assessment" OR LCA OR "carbon footprint" OR CF) AND (sheep OR ovine OR lamb OR ewe OR ram OR rams) AND (milk OR meat OR wool OR fleece)

AND (emission OR emissions OR "greenhouse gas" OR "greenhouse gases" OR GHG OR methane OR CH4 OR N2O OR CO2 OR "CO2 eq" OR "CO2-eq" OR CO2e) AND ("environmental impact" OR footprint OR footprints OR sustainable OR sustainability)) NOT (goat OR goats OR caprine OR cattle OR bovine OR cow OR cows)

The time frame that has been adopted for the purpose of inclusion extends from 2010 to 2025, a period that is consistent with the objective of comparing results and methodological choices in a recent and more comparable context.

The context in question encompasses datasets, characterisation factors, guidelines and reporting.

The selection of studies and the PRISMA flow

A total of 666 records were identified. Following the removal of duplicate records (n = 136), a total of 530 unique records remained for the screening process. Subsequently, based on criteria including type and thematic relevance, as well as species, the following records were excluded: reviews (n = 58, residual 472), studies on other animal species (n = 104, residual 368). Following the exclusion of irrelevant articles (n = 157, residual 211) and theses/abstracts/books (n = 41, residual 170), the remaining articles were analysed. Following a thorough evaluation of the full text of the remaining 170 articles against the predetermined eligibility criteria, 119 were found to meet the stipulated inclusion criteria and were consequently incorporated into the final synthesis. Conversely, 51 articles were excluded due to their failure to meet the prescribed methodological and reporting requirements, Figure 3.

The inclusion and exclusion criteria

- The present review included studies that met the following criteria: (i) they assessed the environmental impact of the sheep sector, with a particular focus on milk (FPCM/ECM), meat (LW/CW/carcass) and wool (greasy/clean wool); (ii) they explicitly stated an LCA approach that was compliant with recognised standards (ISO 14040/14044); It is evident that the study adequately addresses the key criteria for consideration, including the following: (i) the definition of PEF/EF; (ii) the establishment of clear system boundaries (e.g. cradle-to-farm gate); (iii) the presentation of an explicit functional unit and results, particularly in the context of climate change, expressed in kg of CO_2 eq per functional unit; (iv) the documentation of key inventory hotspots, such as CH_4, waste management, NO, energy-related CO_2, and upstream feed; (vi) denoted multifunctionality/allocation management (or system expansion) and, preferably, tested sensitivity; (vii) specified whether and how they included soil carbon sequestration and with what horizon/approach; (viii) declared GWP100 and characterisation factors (IPCC/EF) to enable comparability; (ix) Quality, scope and representativeness: studies that clearly report the origin of primary data compared to secondary data; reference year; methodological consistency with ISO/PEF.
- The following were excluded: The present study identifies several areas of concern with respect to the methodology employed in the extant literature. These include non-sheep studies or studies without sheep disaggregation, non-LCA studies or studies without clear FU/boundaries, studies lacking transparency on

co-production management where relevant, studies applying SCS without describing methods/assumptions or in a manner inconsistent with boundaries, and studies only on “downstream textiles” without explicit links to upstream agriculture and allocation rules along the supply chain. Please review the narratives that lack comparable methods, as well as the abstracts that do not include inventory or methods.

Data Extraction and Synthesis

The employment of a structured file (Excel) with fields dedicated to bibliographic metadata, LCA methodological choices, and key results for FU proved essential to ensure traceability and consistency in the data extraction process. This approach replicated that of recent reviews that used extraction and coding spreadsheets for synthesis. The studies considered in this literature review were meticulously classified using two main criteria. Firstly, the studies were divided according to their primary product, which could be meat, milk or wool. Secondly, the division was made according to key methodological variables, such as follow-up, boundaries, allocation, SCS inclusion and GWP factors. The objective of this classification system was to facilitate a structured comparison of results in order to ascertain both similarities and differences between studies As illustrated in Table 2, included in the supplementary materials, the review covered 119 studies focusing on milk, meat and wool, the objectives of which are described in detail in the table itself.

Statistical analysis

The analysis was primarily descriptive and aimed to characterise the methodological patterns of the literature and the range of carbon footprint results reported for sheep products. Absolute frequencies and percentages were calculated for the main methodological variables within each product category. Carbon footprint values were summarised according to product and functional unit and are reported as observed ranges across the studies included in the review. Due to the heterogeneity among studies in terms of functional units, system boundaries, allocation criteria, modelling assumptions, and reporting formats, no formal meta-analysis was performed. The results of this descriptive synthesis are presented in the corresponding tables in the Results section.

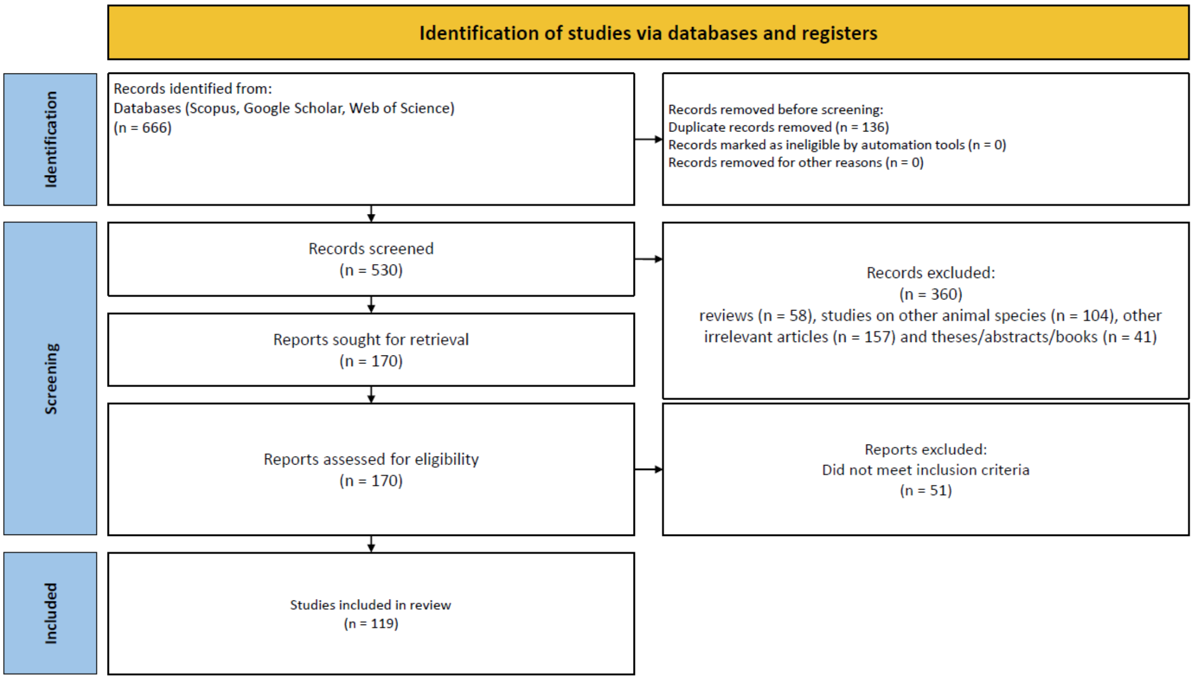

Figure 3. PRISMA flow chart of the study selection process.

Results

Milk

A critical review of the extant literature on milk production reveals an evolutionary trend over time. A meticulous examination of the available evidence, encompassing 32 studies published between 2010 and 2025, elucidates two distinct phases. An initial phase, spanning from 2014 to 2019, is characterised by more sporadic production, succeeded by a subsequent phase, commencing in 2020, wherein increasingly regular and numerous production is observed. Concerning the temporal aspect of the research, it is evident that a significant proportion, amounting to 62.5% of the conducted research (20 out of 32), is concentrated within the period spanning from 2020 to 2025. This is followed by a 37.5% concentration (12 out of 32) within the earlier period of 2014 to 2019. A period of modest activity, characterised by the conduction of one to three studies per annum until 2019, was followed by a stabilisation at high levels in the subsequent years. As illustrated in the accompanying dataset, the years 2020 and 2021 exhibited an average of four studies per year, followed by substantial increases in 2022 and 2024, with five studies per year in each of these years. A closer examination of the dataset reveals a paucity of studies conducted in 2023, with a marked reduction in the number to two studies in 2025. From a geographical perspective, a clear pattern emerges: countries located in the Mediterranean region of Europe are primarily responsible for scientific production focused on sheep's milk. Italy stands out, accounting for an exact 50.0% of the total number of studies conducted, with a contribution of 16 out of 32 studies. The results of the analysis indicate that Sardinia has the highest specific weight, with 28.1% (9 out of 32; 28.1%), followed by 6 studies, equal to 18.8%, which focus on both Sardinia and Tuscany. Basilicata is represented by a single study, equal to 3.1%. At the subsequent level are Spain (6/32; 18.8%) and Greece (3/32; 9.4%). The remaining regions are represented by individual contributions (a single study; 3.1% each: Turkey, Portugal, Romania, Latin America, China, and other European countries), as well as one "global/review" study. As illustrated in Table 3. However, it displays a notable degree of concentration, with Italy, Spain, and Greece collectively accounting for 78.1% of the total. This peculiarity, however, presents an advantageous opportunity for the development of robust and reliable benchmarks within the Mediterranean context. Nevertheless, a cautious methodology is imperative when interpreting discrepancies between studies or extrapolating outside the geographical area, due to the limited representativeness of non-European data.

Table 3. The distribution of articles examined on sheep milk production is presented by year during the study period and geographical area.

Year	Geographical Area	N. of Studies	References
2014	Spain	1	Batalla et al., 2014
	Italy (Sardinia)	1	Vagnoni et al., 2014
2015	Italy (Sardinia)	2	Atzori et al., 2015 Vagnoni et al., 2015
	Spain	1	Batalla et al., 2015
2016	Global / Review	1	Yáñez-Ruiz et al., 201
2017	Italy (Sardinia)	1	Vagnoni et al., 2016
2018	Spain	1	Eldesouky et al., 2018
	Italy (Sardinia)	1	Vagnoni and Franca 2018
2019	Greece	1	Sintori et al., 2019
	Italy (Sardinia)	2	Franca and Vagnoni 2019 Vagnoni et al. 2019
2020	Turkey	1	Ali et al.,. 2020
	Spain	1	Escribano et al., 2020
	Portugal	1	Nunes et al., 2020

Year	Geographical Area	N. of Studies	References
2021	Italy (Basilicata)	1	Sabia et al., 2020
	Italy (Sardinia Tuscany)	3	Arca et al., 2021 Battacone et al, 2021 Bosco et al., 2021
	Spain	1	Plaza et al., 2022
2022	Italy (Sardinia)	1	Atzori et al., 2022
	Romania	1	Ghinea et al., 2022
	Latin America	1	Meza-Herrera et al. 2022
	Spain	1	Salcedo et al., 2022
	China	1	Zhang et al., 2022
2024	Italy (Sardinia Tuscany)	3	Cossu et al., 2024; Sod et al., 2024; Vagnoni e al., 2024
	Europe (Multi country)	1	Torres-Miralles et al. 2024
	Greece	1	Ravani et al., 2024
2025	Greece	1	Laliotis and Bizelis 2025
	Italy (Sardinia)	1	Lunesu et al., 2025

Goal and Scope Definition Phase Milk

In the sample studied, the use of models shows an approach predominantly guided by standards rather than by a single software program. The most frequently cited reference is IPCC, present in 15 studies (46.9%), used both as a basis for inventory/equations (IPCC 2006 or 2019) and as a characterization framework. At the same time, ISO appears in 9 studies (28.1%), generally associated with more structured LCA workflows geared towards methodological transparency. Another significant group follows a CF approach based on PAS 2050 + IPCC 2007 (4 studies; 12.5%).

At the operational level, more than half of the studies use dedicated LCA software (18/32; 56.3%), with a clear prevalence of SimaPro (12/32; 37.5%), while GaBi and OpenLCA are less frequent (3 studies each; 9.4%). In studies that adopt explicit LCIA methods, ReCiPe and CML coexist (ReCiPe in 9 studies; 28.1%, CML in 5 studies; 15.6%), suggesting caution in the direct comparability of results when methods and factor sets change. More specific or innovative approaches (e.g., custom models, system dynamics, DEA, carbon calculators) appear sporadically, as individual cases, and represent more a sign of experimentation than an established trend. As illustrated in Table 4.

Table 4. Standards followed in the reviewed studies

Model	Tipe	N. of Studies	Model	Tipe	N. of Studies
	ISO, ReCiPe, SimaPro	4		ISO, SimaPro, System dynamic modeling tools	1
	PAS 2050, IPCC 2007	4		ISO, ReCiPe Midpoint, CML, SimaPro	1
	IPCC 2006 inventory equations	3		ISO, SimaPro, IPCC 2013, CML	1
	GaBi, CML, ReCiPe Midpoint	2		OpenLCA, FAO LEAP, ISO	1
	Deterministic LCA accounting	1		OpenLCA, IPCC	1
	Excel-based, FAO LEAP	1		PEFCR, SimaPro	1
	FAO, Simulation Mode	1		SAS 9.4; custom LCA model	1
	GaBi, CML	1		SimaPro, IPCC	1
	Integrated DEA, IPCC	1		SimaPro, IPCC GWP100, Petersen Cseq	1
	IPCC 2013, ReCiPe SimaPro	1		SimaPro, ISO	1
	IPCC 2019 inventory equations	1		Solagro Carbon Calculator, OpenLCA ReCiPe Midpoint	1

Functional Unit

As revealed by the analysis of the milk dataset (n = 32), seven functional units were identified. The most commonly used metric was kg CO_2eq/kg FPCM (n = 21; 66%), exhibiting values that ranged from 1.6 to 8.4. In the subsequent analysis, ECM (three studies; 9%; 1.84–6.8) was observed, followed by units per area (ha) (also three studies; 9%; 964.11–12,634). In contrast, units per head (kg CO_2/ewe) were less prevalent, with only two studies reporting this measure (6%; 501.5–891). The remaining choices are sporadic in nature, with each option being supported by only a single study (3%): MMWP (reported value 75.96), LU (6,397-7,810), and annual farm emissions (reported value 85,535.2). As illustrated in Table 5.

Allocation method

A comprehensive review of the extant literature reveals that, the allocation method was documented in 28 studies (87%) within the milk dataset. A review of the literature reveals that the most prevalent methodology employed in the extant research was economic allocation, a strategy utilized in 17 studies (53%). This approach was followed by biophysical allocation, which was employed in 10 studies (31%).

A combined economic and biophysical methodological approach was employed in only one study (1; 3%). Furthermore, the allocation method was not documented (NR) in four studies (13%). As illustrated in Table 6.

System boundaries

As indicated by the findings of the analysis, the system boundaries exhibit a pronounced concentration along the cradle-to-farm-gate perimeter, a methodology that finds adoption in 29 studies (91%). A select few contributions expand the analysis beyond the agricultural setting. Specifically, two studies (6%) employ cradle-to-grave boundaries, while one study (3%) considers the cradle-to-retail perimeter. As illustrated in Table 6.

Tier

As indicated by the results obtained from the analysis, the declared methodological level is predominantly Tier 2, having been adopted in 20 studies (63%). Meanwhile, Tier 1 is reported in 7 studies (22%), while Tier 3 is less frequent (4 studies; 13%). It is noteworthy that in 1 study (3%), the level is not reported (NR) As illustrated in Table 6.

Data source

In the milk dataset, the data source is mainly based on primary data: 22 studies (69%) use only primary data. In 5 studies (16%), primary data is supplemented with Ecoinvent, an LCI database that provides standardized process inventories (e.g., energy, fertilizers, feed, transport) to complete items not directly measured. National Farm Survey sources appear in 3 studies (9%), of which 2 (6%) use primary data + National Farm Survey and 1 (3%) is based on literature + National Farm Survey. The National Farm Survey is a national sample survey of farms that collects standardized data on structure, production, and inputs, used as a basis for comparison and benchmarking. Finally, two studies (6%) use FAO as a reference. As illustrated in Table 6.

Hotspot

In the studies examined, the environmental hotspots correspond to the stages of the system that contribute most significantly to the total impact (in terms of percentage share) and are therefore quantified and reported by the studies. Enteric fermentation is always included (32/32; 100%) and represents the main contributing item, with a share of between 19% and 83.4%. The production and purchase of feed is quantified in 18 studies (56%), with contributions ranging from 6% to 49%. Manure management (storage and treatment of waste) is reported in 10 studies (31%), with a range of 2.1–26%. Finally, energy and fuel (direct consumption on the farm and mechanized operations) appear in 8 studies (25%), with lower incidences (1.5–9%). As illustrated in Table 7.

Inventory Analysis Phase

The quality of inventory data is of critical importance to the accuracy and repeatability of LCA studies. As documented in 27 studies (84%), the number of farms included is explicitly stated; however, in 5 studies (16%), this information is not provided. The sample size among studies reporting this data varies from 1 to 144 farms, yielding an average sample size of 14.45 farms per study. The type of farming under consideration is primarily located in intermediate systems. More specifically, semi-extensive systems represent the largest share (12 studies; 38%), followed by semi-intensive systems (7 studies; 22%). It is evident that the extreme categories are underrepresented in the dataset, exhibiting comparable frequencies: extensive (n = 5 studies; 16%) and intensive (n = 5 studies; 16%). Mixed systems are observed in 3 studies (9%). the Sarda breed has been the most frequently considered, with 14 studies (44%) reporting on this particular breed. A significant proportion of studies (9 studies; 28%) refer to mixed breeds, while the Merino breed is mentioned in 3 studies (9%). In four studies (13%), the breed remains unspecified (NR). The Awassi and Lacaune breeds are marginal, with only one study documented for each (3%). The weight of the animals is documented in 19 studies (59%). Conversely, in 13 studies (41%), the pertinent data remains NR (not reported). An examination of the studies that do specify the weight of the animals reveals a range from 10 to 75 kg, with an average of 43.61 kg. the duration of lactation is reported in 21 studies, constituting 66% of the total sample. The range of the reported data varies from 120 to 240 days, with a standard deviation of 199 days. Notably, in 11 studies, accounting for 34% of the sample, the duration of lactation is not specified (NR). As documented in 27 studies (84%), the number of animals is specified; however, in 5 studies (16%), it remains unspecified (NR). The range of animals reported in the studies that specify the data varies from 3 to 1,000,000 animals, with a total range of 321,574. A review of the literature revealed that quantity of feed administered to animals is reported in 18 studies (56%) as kg per yr, whereas this information is not reported in 14 studies (44%). For the subset of studies that do include this data, the values range from 29 to 204,000 kg per yr. As documented in 21 studies (66%), the grazing area is a prominent feature; however, in 11 studies (34%), this information is not specified (NR). Examining the studies that do report it, the variable is predominantly expressed in hectares (18 studies; 56%), exhibiting values that span from 3 to 1,013 hectares (average 169.17 hectares). The results of three studies (9%) indicate that the area is normalized per head (ha/ewe), with a range of 0.01–3.8 ha/ewe (average 1.58 ha/ewe). As indicated in the findings of 14 studies (44%), the area cultivated per crop is expressed in hectares, with values ranging from 9.2 to 500 hectares (average 73.22 hectares). Conversely, in 18 studies (56%), this information remains unspecified (NR). The utilization of fertilizers (N, P, K) is documented in 13 studies (41%) at a rate of kg/yr, with values spanning from 2 to 6,171 kg/yr (range 581 kg/yr). In contrast, 19 studies (59%) do not specify the relevant information (NR). The analysis revealed that diesel consumption was not reported in 59 % of the studies (19). Among the remaining 41 % (13), the data was expressed in various units. Specifically, 10 studies (31 %) reported l per yr, with values ranging from 10 to 18,478 l per yr. As indicated by the findings of a single study, the range of MJ/yr was between 295,150 and 331,666, while the kg per 1 kg of cheese was determined to be 3%. The first study examined the ratio of 3.21 kg, and the second study examined the ratio of kg per 100 kg of milk. The range of values for the latter study was between 4.56 and 13.64 kg per 100 kg of milk. Electricity consumption is not reported in 63% of the studies (20 out of 32). In the remaining 37% of the studies (12 out of 32), the data is expressed in different units. Specifically, in 8 studies (25%), the units of measurement were kWh/yr, with values ranging from 9.75 to 49,910 kWh/yr. In 1 study (3%), the units of measurement were kWh per 1 kg of cheese. The energy density of milk was determined to be 0.83 kWh/kg in a single study, representing a 3% variation. Another study reported a value of 0.165 kWh/L for the energy density of milk, also with a 3% variation. Additionally, the energy expenditure of breeding ewes was measured at 14.94 kWh/head in one study, and 883 MJ in another study, both with a 3% variation. The results are shown in Table 8.

Table 8. Inventory Analysis Phase

N. of farms	**N**	**N. of Studies**	**min**	**max**	**range**
	NR	5			
	N	27	1	144	14.45
Farming system	**Tipe**				
	Extensive	5			
	Intensive	5			
	Mixed systems	3			
	Semi extencive	12			
	Semi intensive	7			
Breed	**Tipe**				
	NR	4			
	Sarda	14			
	Merino	3			
	Awassi	1			
	Laucone	1			
	Mixed	9			
Weigh	**kg**				
	NR	13			
	kg	19	10	75	43.61
Lactation period	**Time**				
	Days	21	120	240	199
	NR	11			
Number of animals	**Number**				
	NR	5			
	N	27	3	1E+06	321574

Feed nutrients	**kg**				
	NR	14			
	kg/yr	18	29	204000	16249
Pasture area	**UM**				
	NR	11			
	ha	18	3	1013	169.17
	ha/ewe	3	0.01	3.8	1.58
Cultivated area per crop, ha	**UM**				
	ha	14	9.2	500	73.22
	NR	18			
Fertiliser use (N,P,K	**UM**				
	kg/yr	13	2	6171	581
	NR	19			
Diesel use	**UM**				
	NR	19			
	litre/yr	10	10	18478	3419
	MJ/yr	1	295150	331666	313408
	kg per 1 kg of cheese	1			3.21
	kg per 100 kg milk	1	4.56	13.64	9.1
Electricity use	**UM**				
	NR	20			
	kWh per 1 kg of cheese	1			0.83
	kWh/L milk	1			0.165
	kWh per reproductive ew	1			14.94
	kWh/yr	8	9.75	49910	15021
	MJ	1			883

Wool

A time trend analysis reveals that research on wool spans the period from 2010 to 2025, encompassing a total of 15 years with at least one publication per year. The annual number of publications fluctuates, with a range from one to four studies per year. The maximum is observed in 2022, with four studies conducted that year, accounting for 13.3% of the total. 2018, 2024, and 2025 each have three studies per year, which constitutes 10.0% of the total in each year. A review of the dataset reveals an absence of studies for the year 2017. Regarding the specified periods, the years 2010 to 2016 encompass 11 studies, constituting 36.7% of the total, while the subsequent period, 2018 to 2025, comprises 19 studies, representing 63.3% of the dataset.

The geographical distribution of studies within the literature is predominantly focused on Oceania, with Australia being the primary region of production, contributing 10 studies, equivalent to 33.3% of the total. Italy accounts for 13.3% of the studies, with 4 studies, while New Zealand and the United Kingdom each contribute 2 studies, accounting for 6.7% of the total. Latin America also contributes 2 studies, equivalent to 6.7% of the overall studies examined. The remaining geographical areas are represented by individual studies, with each area constituting 3.3% of the total. These include the United States of America, Argentina, Norway, Spain and India. There are five analyses that encompass multiple areas or have a global scope, representing 16.7% of the total. The results are shown in Table 9.

Table 9. The distribution of articles examined on sheep wool production is presented by year during the study period and geographical area

Year	Geographical Area	N. of Studies	References
2010	Australia (Victoria)	1	Biswas et al., 2010
2011	Global / Soutl Africa	1	Bevilacqua et al., 2011
2012	Australia	1	Eady et al., 2012
2012	United Kingdom	1	Worrall et al., 2012
2013	Australia (NSW)	1	Brock et al., 2013
2013	New Zealand	1	Wheeler, 2013
2014	Australia	1	Harrison et al., 2014
2015	Australia	1	Henry et al., 2015
2015	Australia, NZ UK	1	Wiedemann et al., 2015
2016	Australia	1	Cottle and Cowie, 2016
2016	Australia	1	Wiedemann et al., 2016
2018	Australia	1	Moazzem et al., 2018
2018	Global / USA	1	Nolimal et al., 2018
2018	USA	1	Sim and Prabhu, 2018

Year	Geographical Area	N. of Studies	References
2019	UK / Global	1	Bech et al., 2019
2019	Australia	1	Wiedemann et al., 2019
2020	Argentina (Patagonia)	1	Peri et al., 2020
2021	Sweden / Europe	1	Martin and Herlaar, 2021
2022	Italy	1	Bianco et al., 2022
2022	United Kingdom	1	Dimakin et al., 2022
2022	Latin America	1	Meza-Herrera et al., 2022
2022	Latin America	1	Villarreal-Ornelas et al. 2022
2023	Italy	2	Bianco et al., 2023 (x2)
2024	Norway	1	Åby et al., 2024
2024	Spain	1	Palomo et al., 2024
2024	India	1	Vade et al., 2024
2025	Australia	1	Blignaut et al., 2025
2025	Italy (Sardinia)	1	Lunesu et al., 2025
2025	New Zealand	1	Nautiyal et al., 2025

Goal and Scope Definition Phase Wool

As indicated by the findings of the present study, the wool dataset (n = 71) comprises 44 distinct configurations of model/calculation tools. The most prevalent approach was IPCC 2006 (inventory/equations), which was employed in five studies, accounting for 7.0% of the total. Subsequent to this, the Agrecalc GHG calculator was employed with a comparable frequency (4; 5.6%), followed by the Edwards-Jones carbon model (4; 5.6%), and SimaPro + ReCiPe Midpoint (4; 5.6%). An additional group of approaches is documented in three studies, accounting for 4.2% of the total (e.g., Attributional LCA, Integrated DEA + IPCC, ISO 14040/44 Excel model, SimaPro + IPCC). A review of the literature reveals that SimaPro appears in 15 studies (21.1%) with different combinations of methods and databases. The distribution is characterized by a "long tail": 30 configurations are present in only one study each (30/71; 42.3%). As illustrated in Table 10.

Table 10. Standards followed in the reviewed studies

Model	N. articles	Model	n article
IPCC 2006 inventory / equations	5	Field flux measurements, Monte Carl uncertainty	1
Agrecalc GHG calculator	4	GaBi, CML, ReCiPe Midpoint	1
carbon model Edwards-Jones	4	GLEAM, FAO 2016	1
SimaPro, ReCiPe Midpoint	4	GrassGro	1
Attributional LCA	3	GrassGro, SimaPro	1
Integrated DEA, IPCC	3	HolosNorSheep	1
ISO 14040/44 Excel model	3	IPCC 2019 inventory / equations	1
SimaPro, IPCC	3	ISO, SimaPro	1
MDSM (Moorepark Dairy System Model)	2	LCA with optimization via Genetic Algorith (GA)	1
GaBi, CML	2	MATLAB, ecoinvent, IPCC, ReCiPe	1
ISO 14040/44, Ecoinvent	2	National attributional accounting b state/species	1
PAS 2050, IPCC 2007	2	NFS	1
SAS 9.4; custom LCA model	2	OVERSEER® Nutrient Budgets v6	1
SimaPro 9, CML, Ecoinvent	2	SEM	1
CGE (Computable General Equilibrium)	1	SimaPro, CML	1
Durham Carbon Model integrating	1	SimaPro, CML, IPCC	1
Dynamic stochastic simulation model	1	SimaPro, ecoinvent	1
Environmentally Extended Input–Output (EIO LCA) model	1	SimaPro, IPCC, US EPA TRACI Ecotoxicit	1
Excel-based, IPCC 2013	1	Solagro Carbon Calculator, OpenLCA ReCiPe Midpoint	1
Excel-based, FAO LEAP	1	stochastic simulation	1
FAO	1	TLPM (Excel), LCA model excel	1
FAOSTAT, DGHGE (Direct Greenhouse Ga Emissions)	1	ULICEES, IPCC 2006	1

Functional Unit

In the context of wool, the functional unit was extracted in a total of 31 studies. The predominant choice among these studies was kg of wool, with 17 studies (55%) reporting values ranging from 0.45 to 97. Subsequently, ha (2; 6%, 1,710–4,200) and kg of fiber (2; 6%, 5.07–75.8) were observed. Additionally, a multi-product indicator (kg Milk–Meat–Wool Protein, MMWP) manifested in a single study (3%) (69.56–75.96). The functional units that remain are episodic in nature, with each study contributing a single percentage point to the overall sum, which amounts to 3%. The metrics associated with these units pertain to the domain of textile products and their utilization, focusing on the event of garment use. The following categories should be considered when analyzing the environmental impact of apparel production: use of materials (e.g., kg of clothing per yr, kg of CO_2 emissions per sweater), production/processing (e.g., meters of fabric per batch), specific products (e.g., square meters of carpet tile, sweaters with defined net weight), and usage scenarios (e.g., supply of T-shirts for six months, one yr of mask use). As illustrated in Table 5.

Allocation method

As reported in 19 studies (59%), the allocation method is specified; however, in 13 studies (41%) the method remains unclear (NR). Of the studies that report allocation, the predominant approach is biophysical allocation (n = 7; 22%), followed by economic allocation (n = 6; 19%). Hybrid solutions, which combine elements of different disciplines, are less prevalent in this field. The existing hybrid solutions include the following: a combination of biophysical and economic factors, as well as PMA (2; 6%), a combination of economic and biophysical factors (2; 6%), and a combination of PMA (2; 6%). As illustrated in Table 6.

System boundaries

The boundaries of the system are principally defined as cradle-to-farm-gate, a methodology adopted in 21 studies (66%). A smaller number of studies extend the analysis to encompass the entire life cycle (cradle-to-grave), with 9 studies (28%) following this approach. It is evident that the remaining approaches are negligible; cradle-to-consumption was only observed in one study (3%) and gate-to-industrial-gate in another study (3%). As illustrated in Table 6.

Tier

As indicated in 17 studies (53%), the Tier level constitutes a significant proportion of the data. Tier 2 emerges as the most prevalent, appearing in 15 studies (47%), while Tier 1 is identified in 2 studies (6%). Notably, in 15 studies (47%), the Tier level remains unspecified (NR). As illustrated in Table 6.

Data source

A review of the literature reveals that primary data is the most prevalent data source, accounting for 31% of the studies examined (10 studies). This is followed by a combination of primary data and Ecoinvent, which constitutes 22% of the studies (7 studies). Notably, in 13% of the studies (4 studies), Ecoinvent is employed as the exclusive secondary data source. According to the findings of this study, a total of six studies (19%) derived their data from the National Farm Survey, with some of these studies combining the survey data with information from other literature sources. One study (3%) also included references to the US carpet supply chain. In contrast, the use of Food and Agriculture Organization (FAO) sources was reported in only two studies (6%), while three studies (9%) drew their information from a simulation model. As illustrated in Table 6.

Hotspot

As indicated by the findings of the wool dataset, hotspots have been documented in both the agricultural phase and the downstream phases. Among the on-farm phase hotspots, enteric fermentation (CH_4) has been the most frequently quantified (14 studies), with a contribution ranging from 0.46% to 99.4% of the total impact. A total of six studies have been conducted on emissions related to manure and soil management (N_2O), with contribution levels ranging from 5.2% to 27%. Furthermore, four studies have been carried out to quantify feed production/procurement, with a range of 0.03–20%.

As indicated by the findings of six studies, the consumption of energy in industrial processing during post-farm stages (e.g., washing/scouring, spinning, dyeing) ranges from 0.02% to 66.7% of the overall impact. As demonstrated in two empirical studies, the impact of the use phase (domestic washing/maintenance) is indicated as significant, albeit without a comparable percentage quantification. As illustrated in Table 7.

Inventory Analysis Phase

The quality of inventory data is a key prerequisite for ensuring consistency across LCA studies. In the wool dataset (n = 32), the number of farms included is explicitly reported in 8 studies (25%), while in 24 studies (75%) this information is not reported (NR). Among the studies that provide it, sample size ranges from 1 to 123 farms, with an average of 37.75 farms per study. The farming system is predominantly classified as extensive (23 studies; 72%), followed by mixed systems (6 studies; 19%) and semi-extensive systems (3 studies; 9%). Regarding breed, Merino is the most frequently specified (14 studies; 44%); however, breed information is NR in 12 studies (38%). Mixed breeds are reported in 3 studies (9%), while Corriedale, Lojeña, and Sarda each appear in 1 study (3%). Animal weight is reported in 13 studies (41%), whereas it remains NR in 19 studies (59%). An examination of the studies that do specify the weight of the animals reveals a range from 10 to 80 kg, with an average of 52.36 kg. The lactation period is reported in 5 studies (16%), with values ranging from 70 to 180 days (average 126.36 days), while it is NR in 27 studies (84%). The number of animals is specified in 13 studies (41%) and NR in 19 studies (59%); where reported, herd/flock size ranges from 15 to 22,000 animals (average 3,729). The quantity of feed administered is reported in 7 studies (22%) as kg/yr, ranging from 7.5 to 530 kg/yr (average 270 kg/yr), and is NR in 25 studies (78%). Pasture area is documented in 18 studies (56%) as ha, with values from 1 to 50,000 ha (average 7,603 ha), while 14 studies (44%) do not report it. The cultivated area per crop is reported in 10 studies (31%) (min 3.5 ha, max 1,294 ha, average 234.74 ha) and is NR in 22 studies (69%). Fertiliser use (N, P, K) is reported in 8 studies (25%) as kg/ha, ranging from 1.8 to 3,600 kg/ha (average 1,173 kg/ha), while 24 studies (75%) provide no information (NR). Diesel use is NR in 23 studies (72%); where reported, L/yr is used in 7 studies (22%) (min 15, max 15,000 L/yr, average 7,450 L/yr), and two additional single-study metrics are observed (L/ha = 2 in 1 study; 3%, and kg for scouring = 0.00021 in 1 study; 3%). Electricity consumption is NR in 22 studies (69%); among the remaining studies, it is reported as kWh/yr in 4 studies (13%) (0.2–6,000 kWh/yr, average 2,628 kWh/yr), as kWh/ton in 3 studies (9%) (320 kWh/ton), and as single-study metrics (kWh per reproductive ewe = 37.92, kWh/ha = 0.62, and MWh/yr = 6,500; 3% each). As illustrated in Table 11.

Table 11. Inventory Analysis Phase

Number of farms	**N**	**Number of Studie**	**min**	**max**	**range**
	NR	24			
	N	8	1	123	37.75
Farming system	**Tipe**				
	Extensive	23			
	Mixed systems	6			
	Semi extencive	3			
Breed	**Tipe**				
	Mixed	3			
	NR	12			
	Corriedale	1			
	Lojeña	1			
	Merino	14			
	Sarda	1			
Weigh	**kg**				
	NR	19			
	kg	13			
Lactation period	**Time**				
	Days	5	70	180	126.36
	NR	27			
Number of animals	**Number**				
	NR	19			
	N	13	15	22000	3729
Feed nutrients	**kg**				
	NR	25			
	kg/yr	7	7.5	530	270
Pasture area	**UM**				
	NR	14			
	ha	18	1	50000	7603
Cultivated area per crop, ha	**UM**				
	NR	22			
	ha	10	3.5	1294	234.74
Fertiliser use (N,P,K)	**UM**				
	kg/ha	8	1.8	3600	1173
	NR	24			
Diesel use	**UM**				
	NR	23			
	l/ha	1			
	kg for scouring	1			
	L/yr	7	15	15000	7450
Electricity use	**UM**				
	NR	22			
	kWh per reproductive ew	1			37.92
	kWh/ha	1			0.62
	kWh/ton	3			320
	kWh/yr	4	0.2	6000	2628
	MWh/yr	1			6500

Meat

A review of the literature on meat (n = 71) reveals a temporal concentration spanning from 2009 to 2025. A conspicuous asymmetry within the database is evident, with a pronounced inclination towards more recent years: the period 2020-2025 comprises 42 studies (59.2%), exhibiting a notable surge in 2024 (n = 16; 22.5%). The sample under scrutiny demonstrates a notable aggregation of data pertaining to the years 2022 and 2020, with seven and six cases documented, respectively. These figures represent 9.9% and 8.5% of the total, demonstrating a substantial proportion of the dataset. In the years previously, between 2009 and 2016, a total of 22 studies were contributed, constituting 31.0% of the sample. In contrast, the subsequent period, 2017-2025, includes 49 studies, representing 69.0% of the sample.

From a geographical perspective, the studies are notable for their diversification, which is concentrated in a limited number of contexts. Spain and the United Kingdom are the most represented countries, with each nation contributing seven studies, which constitutes 9.9% of the total. Subsequently, Italy has contributed six studies, amounting to 8.5%, while China and Ireland have contributed five studies each, constituting 7%. Australia and New Zealand have contributed four studies each, accounting for 5.6%. Three studies each were contributed by Turkey (4.2%), the United States (4.2%) and India (4.2%), while Canada (2.8%) and Chile (2.8%) contributed two studies each. Additional country-specific evidence is available for Argentina, Brazil, France, Iceland, Norway, Sweden, and Tunisia, with one study for each country, representing 1.4% of the total. Finally, multiregional and global assessments are represented by a total of 13 studies, accounting for 18.3% of the total. This includes 4 global reviews, accounting for 5.6% of the overall sum. As illustrated in Table 12.

Table 12. The distribution of articles examined on sheep meat production is presented by year during the study period and geographical area

Year	Geographical Area	N. of Studies	References
2025	China	1	Wang et al., 2025
	Iceland	1	Shrivastava et al., 2025
	Italy	1	Lunesu et al., 2025
	New Zealand	1	Zhang et al., 2025
	Global / Multi regional	1	Thomas et al., 2025
2024	China	3	Nsabiyeze et al., 2024; Wan et al., 2024; Zhang et al., 202
	Ireland	1	Kilcline et al., 2024
	Norway	1	Åby et al., 2024
	Spain	2	Palomo et al., 2024; Pardo e al., 2024
	Sweden	1	Ahlgren et al., 2024
	Turkey	1	Argun and Çakmakcı., 2024
	United Kingdom (Wales)	2	McNicol et al., 2024 (a) McNicol et al., 2024 (b)
	USA	1	Recktenwald and Ehrhard 2024
	India	1	Sarkar et al., 2024
	Brazil	1	Silva et al., 2024
	Europe (Multi country)	1	Miralles et al., 2024
	Romania Global	1	Trasca et al., 2024
2023	Italy	1	Cerrato et al., 2023
	Europe / Turke	1	Geß et al., 2023
	New Zealand	1	Mazzetto et al., 2023
	Chile	1	Mujica et al., 2023
2022	Canada	1	Bhatt et al., 2022
	India	1	Lal et al., 2022
	Ireland	1	Farrell et al., 2022
	Turkey / EU	1	Geß et al., 2022
	Turkey	1	Yetişgin et al., 2022
	USA	1	Handler and Pearce, et al 202

Year	Geographical Area	N. of Studies	References
	Latin Americ (Review)	1	Meza-Herrera et al., 2022
2021	Europe (UK, IE NO, FR)	1	Davies et al., 2021
	Italy	1	Battacone et al., 2021
	Australia	1	Ridoutt et al., 2021
	Spain	1	Horrillo et al., 2021
2020	Italy	2	Geß et al.; Verduna et al., 202
	Argentina (Patagonia)	1	Peri et al., 2020
	Ireland	1	Tsakiridis et al., 2020
	Spain	1	Horrillo et al., 2020
	Turkey	1	Ceyhan and Sezgin., 2020
2019	USA (California)	1	Dougherty et al., 2019
2018	Ireland	1	Sharma et al., 2018
	Spain	1	Eldesouky et al., 2018
2017	Chile	1	Toro-Mujica et al., 2017
	France	1	Dakpo et al., 2017
	India	1	Patra et al., 2017
	Tunisia	1	Ibidhi et al., 2017
2016	Australia	1	Cottle and Cowie, 2016
	Ireland	1	O'Brien et al., 2016
	United Kingdom	1	Hyland et al., 2016
	Global (Review)	1	Zervas and Tsiplakou., 2016
2015	Australia Global	2	Wiedemann et al. 2015a Wiedemann et al., 2015b
	Italy	1	Atzori et al., 2015
	United Kingdom	1	Jones et al., 2015
	Global (Review)	1	Lin et al., 2015
2014	Australia	1	Harrison et al., 2014
	Canada	1	Dyer et al., 2014
	United Kingdom	2	Audsley and Wilkinson, 2014 Jones et al., 2014
2013	New Zealand	1	Wheeler et al., 2013
	Spain	1	Ripoll-Bosch et al., 2013
	Global (Review)	1	Mundus et al., 2013

Year	Geographical Area	N. of Studies	References
2012	China	1	Schönbach et al., 2012
	United Kingdom	1	Worrall et al., 2012
2011	New Zealand	1	Ledgard et al., 2011
	Spain	1	Ripoll-Bosch et al., 2011
2010	Australia	1	Biswas et al., 2010
2009	Global (Review)	1	Gill et al., 2009

Goal and Scope Definition Phase Meat

The methodological approach is characterised by heterogeneity, with a total of 22 distinct configurations of model/calculation tool. The most prevalent combination is SimaPro 9 in conjunction with CML and Ecoinvent, occurring in 4 studies and accounting for 12.5% of the total. This is followed by OpenLCA combined with the Ecoinvent dataset and SimaPro (EF 3.0), each appearing in 3 studies and accounting for 9.4% of the total. A second group of methodologies is evident in two studies (6.3%) each, including the Edwards-Jones carbon model, the GrassGro, FarmGAS, and IPCC 2006 methodologies, and the SimaPro and ReCiPe Midpoint methodologies. The remaining configurations are episodic, with 16 configurations present in only one study (50% of the sample overall). An examination of the entire toolchain reveals that SimaPro is employed in 12 studies, accounting for 37.5% of the total, while OpenLCA is utilized in 3 studies, representing 9.4% of the studies considered. In addition to LCA software, sectoral models and dedicated inventories/algorithms are utilized (e.g., GrassGro, FullCAM, OVERSEER). A variety of tools have been employed to achieve this objective, including FAOSTAT/DGHGE, AFRC/CSIRO equations, and Excel models aligned with ISO 14040/44 and ISO 14067 standards. This approach confirms a more "multi-tool" than standardised calculation portfolio. As illustrated in Table 13.

Table 13. Standards followed in the reviewed studies

Model	Number of Studies
SimaPro 9, CML, Ecoinvent	4
OpenLCA, Ecoinvent datasets	3
SimaPro EF 3.0	3
carbon model Edwards-Jones	2
GrassGro, FarmGAS, IPCC 2006	2
SimaPro, ReCiPe Midpoint	2
AFRC model	1
Attributional LCA	1
CSIRO (2007), AFRC (1990) equations	1
Deterministic LCA accounting	1
Durham Carbon Model integrating	1
Excel -based, ISO 14067	1
FAOSTAT, DGHGE (Direct Greenhouse Gas Emissions)	1
FullCAM	1
GrassGro	1
GrassGro, SimaPro	1
HolosNorSheep	1
ISO 14040/44 Excel model	1
OVERSEER® Nutrient Budgets v6	1
SAS 9.4; custom LCA model	1
SimaPro, Ecoinvent; uncertainty via Monte Carlo	1
SimaPro, IPCC	1

Functional Unit

As indicated in the relevant literature, the functional unit is predominantly reported with a strong prevalence of mass-based metrics, particularly live weight (LW). A survey of 47 studies (52%) reveals that the impact is expressed in kg CO_2 eq/kg LW, with values ranging from 1.29 to 62.6 kg CO_2 eq/kg LW (average 17.85). The second most prevalent unit is kg of CO_2q per kg of carcass weight (CW), employed in 11 studies (12%). The range of 9.3 to 70 kg of CO_2eq per kg of CW is notable, with an average of 32.15. Area-based units are less prevalent, with only five studies (6%) reporting data in kg of CO_2 eq per hectare. The range of values across these studies is from 718 to 6704 kg of CO_2eq per hectare, with an average of 3812.28. A review of the literature reveals that units related to nutritional function are present but in the minority. Specifically, seven studies (8%) employed the metric of kg of CO_2 eq per kg of protein, with a range of 21.2 to 92.9 kg, averaging at 55.81 kg. In contrast, four studies (4%) expressed the impact per MJ of edible energy, ranging from 1.4 to 3.87 MJ, with an average of 2.48 MJ. An additional series of studies documents the impact on lamb meat directly (n = 6; 7%), with values ranging from 8.12 to 56.7 kg of CO_2eq emissions, yielding an average of 31.13.Other functional units are residual and appear in very limited proportions of the sample, as demonstrated in the following instances: GWP as an absolute value (3 studies; 3%), kg CO_2e/kg product (3; 3%), and economic indicators (kt CO_2e/€m output: The results demonstrated 2% occurrences for the dependent variable and single occurrences for both the GWP contribution/ABU (1; 1%) and kg CO_2 e·yr-1 (1; 1%). As illustrated in Table 5.

Allocation method

The allocation method is reported in a heterogeneous manner: a significant proportion of studies fail to specify the approach adopted (NR: 27 studies; 38%). Among the studies that do specify it, economic allocation prevails (22 studies; 31%), followed by biophysical allocation (9 studies; 13%).

A review of the literature reveals that more specific or combined approaches are in the minority. Protein Biophysical Allocation (PMA) is mentioned in only three studies, accounting for 4% of the total. Similarly, the combination of biophysical, economic, and

PMA appears in just four studies, representing 6% of the overall corpus. A further 6% of the studies (n = 4) employ a combination of economic and biophysical methods. The methods applied in individual cases include an area-based approach (n = 1; 1%) and a DEA-based approach (n = 1; 1%). As illustrated in Table 6.

System boundaries

It is evident that the predominant focus of the studies under consideration is on cradle-to-farm-gate approaches, with a significant majority (61; 86%) adopting this perspective. Extensions beyond the farm gate are observed marginally, with cradle-to-grave being employed in 4 studies (6%) and cradle-to-retail appearing in 3 studies (4%). According to the findings of two studies, an intermediate farm-to-industrial-gate approach is employed in 3% of cases. Finally, the most extensive approach, known as cradle-to-consumption, is present in 1 study, accounting for 1% of the total. As illustrated in Table 6.

Tier

The tier level is predominantly indicated as Tier 2, having been adopted in 54 studies, corresponding to 76 per cent of the total. Tier 1 is used in 13 studies, constituting 18 per cent of the total, while in 4 studies, corresponding to 6 per cent of the total, the level is not reported (NR). As illustrated in Table 6.

Data source

Analysis of the meat dataset (n = 71) reveals a clear predominance of primary data, with 29 studies (41%) utilising exclusively primary data. In addition to these methodologies, there exist ‘hybrid’ approaches that amalgamate corporate data with external databases or secondary sources. Three studies (4%) incorporate primary data in conjunction with

Ecoinvent, while two studies (3%) integrate primary data with FAO and Ecoinvent. A single study (1%) employs a combination of primary data and FAO (Food and Agriculture Organization) sources. Three studies (4%) utilize a combination of primary data and extant literature. Two studies (3%) integrate primary data, literature, and the National Farm Survey. National Farm Survey sources are prevalent in the literature, with 12 studies (17%) being directly based on the National Farm Survey and an additional 9 studies (13%) employing a combination of the National Farm Survey and existing literature. One study (1%) integrates the National Farm Survey with the Ecoinvent database. As revealed by an exhaustive review of the literature, a mere three studies (4%) draw exclusively from literature, while three studies (4%) adopt a more contemporary approach by directly leveraging references from the Food and Agriculture Organization (FAO). Notably, three studies (4%) employ simulation models, suggesting a shift towards a model-based paradigm rather than conventional data collection methodologies such as farm surveys. As illustrated in Table 6.

Hotspot

Enteric fermentation, specifically the emission of CH_4 from ruminal digestion, has been identified as the predominant hotspot, with its contribution to the total emissions ranging from 29.8 to 93.0%, as documented in all conducted studies. As indicated in the findings of 15 separate studies, the production of feed (comprising cultivation, processing and transport of feed, whether purchased or produced on the farm) is reported with contributions ranging from 1.0% to 43.8%. A review of the extant literature reveals that inputs to managed soils and fertilisers (with emphasis on N_2O emissions linked to fertilisation, crop residues and grazing deposits) are present in approximately 12 studies, with a range of 3.7%–29.0%. The quantification of manure management (CH4 and N2O emissions from storage and management in stables) is addressed in approximately 10 studies, exhibiting a range of 1.0% to 25.0%. Lastly, the assessment of energy and fuels (machinery, transport, and electricity) is documented in around eight studies, with contributions varying from 0.6% to 22.7%. As illustrated in Table 7.

Inventory Analysis Phase

The quality and governance of inventory data have been identified as key factors in ensuring the robustness, comparability and replicability of life cycle assessments (LCAs) for sheep meat. In the sample analysed (n = 71), the number of farms is explicitly reported in 34 studies (48%). In contrast, this information is not indicated in 37 studies (52%) (NR). When the number of farms is indicated, the sample ranges from 1 to 3,235 farms (range = 3,234). A review of the literature shows a clear prevalence of extensive farming systems (46 studies; 55%), followed by semi-extensive systems (14; 17%), intensive (9; 11%), semi-intensive (8; 10%), mixed (5; 6%) and transhumant (2; 2%). Information on the breed of the animals studied is often analysed in aggregate: 45 studies (63%) classify the subjects as mixed breeds, while 26 studies (37%) do not provide this information. The weight of the animals is documented in 46 studies (65%) and is not reported in 25 studies (35%). There is significant variability in the values reported, with a range between 10 and 80 kg (average 42.97 kg) in the studies reporting these data. Furthermore, the duration of lactation is documented in only 15 studies (21%), with a range between 60 and 300 days and an average of 180 days. In particular, in 56 studies (79%), this information is not reported. The number of animals is reported in 45 studies (63%) and is not reported in 26 (37%). In the subgroup of studies where the number of animals is available, this varies from 6 to 1,023,000 animals (range = 1,022,994). The amount of feed is quantified in 20 studies (28%) in units of kg per yr, with a range between 10 and 318,108 kg per yr. Conversely, this information is not reported in 51 studies (72%). As shown in 45 studies (63%), thegrazing area is indicated in hectares (with a range between 4 and 8,544,000 ha, with an average of 151,557 ha). Conversely, in 26 studies (37%), the grazing area is not reported. Twenty-two studies (31%) report the cultivated area per crop in hectares, while 49 studies (69%) do not provide this information. The use of fertilisers (N, P, K) is documented in 21 studies (30%) in terms of kg per yr (range: 4.5 to 16,095 kg/yr; average 1,042 kg/yr). However, this information is not reported in 50 studies (70%). Finally, there is marked heterogeneity in the units of measurement of energy consumption: diesel is expressed in NR in 63% of studies (45 studies); in the remaining cases, it is mainly expressed in L/yr (10 studies, from 10 to 15,000 L/yr, average 4,327 L/yr), or in 8 studies L/ha/yr was calculated between 2 and 4,240 l per hectare (L/ha). These results are supported by additional specific metrics, including l per kg of mutton, l per 100 kilometres, l per breeding ewe and cubic metres. The results of each individual study also include MJ. The results of 55 studies (77%) reveal that electricity was not a reported factor. Conversely, among the 16 studies (23%) that did include it, the metric of kWh/yr was used in six studies. Therefore, a wide range of data relating to energy consumption was found. These include 171-24,528 kWh/yr, with an average of 7,985 kWh/yr, as well as kWh/head/yr, with a range of 1.6-42.72 kWh/head/yr and an average of 22.3 kWh/head/yr. In addition, several individual units are reported, such as kWh/t CW, kWh/ha, GWh, MW and MWh/yr, as well as Wh per kg of mutton. As illustrated in Table 14.

Table 14. Inventory Analysis Phase

Number of farms	**N**	**Number of Studie**	**min**	**max**	**range**
	NR	37			
		34	1	3235	99.8
Farming system	**Tipe**				
	Extensive	46			
	Intensive	9			
	Mixed systems	5			
	Semi extensive	14			
	Semi intensive	8			
	transhumance	2			
Breed	**Tipe**				
	Mixed	45			
	NR	26			
Weigh	**kg**				
	NR	25			
	kg	46	10	80	42.97
Lactation period	**Time**				
	Days	15	60	300	180
	NR	56			
Number of animals	**Number**				
	NR	26			
	N	45	6	1023000	
Feed nutrients	**kg**				
	NR	51			
	kg/yr	20	10	318108	39004
Pasture area	**UM**				
		26			
	ha	45	4	8544000	151557
Cultivated area per crop, ha	**UM**				
	ha	22			
	NR	49			
Fertiliser use (N,P,K)	**UM**				
	kg/yr	21	4.5	16095	1042
	NR	50			
Diesel use	**UM**				
	NR	45			
	litre/yr	10	15	15000	4327
	L/ha/yr	8	2	4240	425
	kg/ewe	3	1.53	4.72	2.65
	L per kg mutton	1			0.133
	L/100km	1			30
	L per reproductive ew	1			37.92
	m3	1			39702
	MJ	1			4000
Electricity use	**UM**				

NR	55			
GWh	1			39702
kWh/ha	1			0.62
kWh/head/yr	4	1.6	42.72	22.3
kWh/t CW	1			329
kWh/yr	6	171	24528	7985
MW	1			6.7
MWh/yr	1			10000
Wh per kg mutton	1			11250

Table 5. Distribution of Functional Unit and results.

Milk					**Wool**					**Meat**				
Functional unit	**N of Studies**	**min**	**max**	**range**	**Functional unit**	**N of Studies**	**min**	**max**	**range**	**Functional unit**	**N of Studies**	**min**	**max**	**range**
kg COEeq/kg FPCM	21	1.6	8.4	3.4	kg of wool	17	0.45	97	22.74	kg CO$_2$e kg LW	47	1.29	62.6	17.85
ha	3	964	12634	5137	ha	2	1710	4200	2622	kg CO$_2$e kg CW	11	9.3	70	32.15
ECM	3	1.84	6.8	4.32	kg fiber	2	5.07	75.8	40.43	kg CO$_2$e kg protein	7	21.2	92.9	55.81
kg CO2/ewe	2	501	891	680	garment wear (one wear event of a 300 g wool sweater)	1			0.17	kg CO$_2$e lamb meat	6	8.12	56.7	31.13
kg Milk–Meat–Wool Protein (MMWP)	1			75.96	kg Milk–Meat–Wool Protein (MMWP)	1	69.56	76	72.76	kg CO$_2$e Per hectare	5	718	6704	3812
LU	1	6397	7810	7103	m² of carpet tile	1			6.35	kg CO$_2$e MJ edible energy	4	1.4	3.87	2.48
Whole-farm annual emissions	1			85535	kg CO$_2$e per sweater	1			22.1	GWP	3	4871	85535	31875

Milk					Wool					Meat				
Functional unit	**N of Studies**	**min**	**max**	**range**	**Functional unit**	**N of Studies**	**min**	**max**	**range**	**Functional unit**	**N of Studie**	**min**	**max**	**range**
					Provision of T-shirts for one soldier during six months in the fiel	1			8.6	kg CO_2e kg produc	3	13	19	15.53
					unit (product) of woo processed (equivalen to 1 batch of finished fabric)	1			2.76	kt CO_2e/€m output	2	24.1	56.5	42.27
					Use of 1 kg of selected apparel over the lifetime	1			65	GWP contribution/Adult Bovine Unit (ABU	1			43.85
					wear of a sweater in the EU market	1			0.17	kg CO_2e·yr^{-1}	1			272

Milk					Wool					Meat				
Functional unit	**N of Studies**	**min**	**max**	**range**	**Functional unit**	**N of Studies**	**min**	**max**	**range**	**Functional unit**	**N of Studies**	**min**	**max**	**range**
					wool sweater (net weight 264.85 g)	1			1.97					
					yr of face-mask use per person	1	4.84	11.58	8.21					

Table 6. Distribution of Allocation Method, system boundaries, level of methodological detail, Data source

	Milk		**Wool**		**Meat**	
Allocation metho	**Tipe**	**N. of Studies**	**Tipe**	**N. of Studies**	**Tipe**	**N. of Studies**
	Economic allocation	17	NR	13	NR	27
	Biophysical allocation	10	Biophysical allocation	7	Economic allocation	22
	NR	4	Economic allocation	6	Biophysical allocation	9
	Economic, Biophysical-based allocation	1	Biophysical, economic, Protein Biophysical Allocation (PMA)	2	Biophysical, economic, Protein Biophysical Allocation (PMA)	4
			Economic, Biophysical allocation	2	Economic, Biophysical allocation	4
			Protein Biophysical Allocation (PMA)	2	Protein Biophysical Allocation (PMA)	3
					Area-based	1
					DEA	1
System boundaries	**Tipe**	**N. of Studies**	**Tipe**	**N.of Studies**	**Tipe**	**N. of Studies**
	Cradle-to-farm-gate	29	Cradle-to-farm-gate	21	Cradle-to-farm-gate	61
	Cradle-to-grave	2	Cradle-to-grave	9	Cradle-to-grave	4

	Cradle-to-retail	1	Cradle-to-consumption	1	Cradle-to-retail	3
			Gate-to-industrial-gat	1	Farm to industrial gate	2
					Cradle-to-consumption	1
Tier	**Level**	**N. of Studies**	**Level**	**N. of Studies**	**Level**	**N. of Studies**
	Tier 2	20	Tier 2	15	Tier 2	54
	Tier 1	7	NR	15	Tier 1	13
	Tier 3	4	Tier 1	2	NR	4
	NR	1	Tier 3		Tier 3	
Data source	**Tipe**	**N. of Studies**	**Tipe**	**N. of Studies**	**Tipe**	**N. of Studies**
	Primary data	22	Primary data	10	Primary data	29
	Primary data, Ecoinvent	5	Primary data, Ecoinvent	7	National Farm Survey	12
	Primary data, National Farn Survey	2	Ecoinvent	4	National Farm Survey, literature	9
	FAO	2	Literature, National Farn Survey	3	FAO	3
	Literature, National Farn Survey	1	Simulation model	3	Literature	3
			FAO	2	Primary data, Ecoinvent	3
			Primary data, literature, National Farn Survey	2	Primary data, literature	3
			National Farn Survey, US	1	Simulation model	3

carpet production chain		
	Primary data, FAO, Ecoinvent	2
	Primary data, literature, National Farm Survey	2
	National Farm Survey, Ecoinvent	1
	Primary data, FAO	1

Table 7. Environmental hotspot distribution

	Milk			Wool			Meat		
Environmental hotspots	**N. of Studies**	**Min %**	**Max %**	**N. of Studies**	**Min %**	**Max %**	**N. of Studies**	**Min %**	**Max**
Enteric Fermentation	32	19	83	14	46	99.4	71	29.8	100
Manure Management	10	2	26	6	5.2	27	10	1.0	25.0
Feed Production	18	6	49	4	3	20	15	1	43.8
Energy & Fuel	8	2	9	6	2	66.7	8	1	22.7
Managed Soils & Fertilizers	-	-	-	-	-	-	12	3.7	29.0
Domestic Laundry & Maintenance	-	-	-	2	NR	NR	-	-	-

Discussion

Milk

A recurring theme in all studies is the confirmation of enteric fermentation as the predominant source of emissions, with the residual contribution attributable to manure management and feed production and supply (Batalla et al., 2015; As Vagnoni et al. (2015) and Nunes et al. (2020), both Italian studies (e.g. Bosco et al., 2021; Atzori et al., 2022; Cossu et al., 2024; Sabia et al., 2020) support this claim. As stated by Vagnoni et al. (2017), Sodi et al. (2024) and Lunesu et al. (2025), and in agreement with the Mediterranean and European studies by Batalla et al. (2015), Sintori et al. (2019), Ravani et al. (2024), Laliotis et al. (2025) and others, such as Escribano et al. (2020), Salcedo et al (2022) and Miralles et al. (2024) have previously stated that interventions in feed management (e.g., precision feeding, replacing soy with legumes and improving forage quality) and production efficiency (particularly with regard to milk production) are of particular importance in this context. Vagnoni et al. (2017) studied the mitigation of emissions (CF) per unit of product through the use of agro-industrial by-products, such as tomato or olive residues, as discussed by Ruiz et al. (2016). However, significant methodological discrepancies come to the fore. Studies such as that by Battacone et al. (2021) exemplify highly particular and circumscribed methodologies (confined to enteric CH_4 from mothers during the 28-day lactation period), proffering values that are not directly comparable with comprehensive LCAs, as exemplified by those by Bosco et al. (2021) and Atzori et al. (2022) As asserted in the 2022 study or further elaborated upon in the 2025 research by Laliotis et al. (2025) a comparative analysis of Tier 1 and Tier 2 is conducted, thereby demonstrating that the latter Tier consistently provides higher values (+22-28%), thus exhibiting a greater degree of realism. Similarly, Ceyhan et al. (2020) confine their analysis to a Tier 1 calculation of the total emissions of a solitary company, articulated as an absolute annual value, without relating them to a standard functional unit (e.g. kg FPCM). This renders comparison with advanced studies more complex. Sabia et al. (2020) and Vagnoni et al. (2017) employ the ReCiPe method, which incorporates endpoint indicators that facilitate the attribution of emissions to multiple domains, including climate change, human health, biodiversity, and resource consumption. This approach signifies a departure from conventional climate-centric methodologies. Consistent with this advancement, Sodi et al. (2024), Ravani et al. (2024) As asserted in 2024 and reiterated in Nunes et al. (2020), the EF 3.0 and ReCiPe

Midpoint methodologies are adopted, elucidating manifold impacts, including acidification, eutrophication, and water use. These studies unveil substantial disparities between breeds, as evidenced in Sodi, and within production systems, as compared semi-intensive and intensive systems in Ravani. According to Fois et al. (2022), there is a direct correlation between LCA and the United Nations Sustainable Development Goals (SDGs). The study demonstrates the significant potential for reducing CF by replacing conventional raw materials with alternative options, such as milk versus whey, and utilising renewable energy sources, including cogeneration systems. Through these substitutions, the study proposes a substantial reduction in CF, from an initial level of 5.52 kg CO_2eq /kg to a substantially lower level of 0.9 kg CO_2eq /kg. Despite the prospective nature of this design study, as opposed to a business assessment, it illustrates the potential for integrating LCA with Sustainable Development Goal (SDG) frameworks to serve as a compass for steering the sustainable development of the dairy sector. This assertion is corroborated by Atzori et al. (2022) undertake the inaugural transnational comparison of simplified LCA tools for dairy sheep farming in Europe, thereby unveiling substantial discrepancies between CAP'2ER, ArdiCarbon and CarbonSheep (up to 1.7 kg CO2eq /kg FPCM) attributable to divergences in CH_4 and manure algorithms and allocation choices. This emphasises the immediate requirement for the standardisation of LCA methodologies throughout Europe. The functional units that have been adopted demonstrate a progressive convergence towards fat- and protein-corrected milk kg (FPCM), a metric that has been utilised in the most recent studies (e.g. Sodi et al., 2024; Ravani et al., 2024; Laliotis et al., 2025; Sabia et al., 2020; As demonstrated by Atzori et al. (2022), Bosco et al. (2021), Vagnoni et al. (2017), Arca et al. (2021), and Plaza et al. (2021), this approach enables direct comparisons between different studies. The choice made by Lunesu et al. (2025) is more complex, extending the analysis to encompass meat, wool, and sheep for slaughter, thus offering a multifunctional perspective on Sardinian sheep farming systems. Sintori et al. (2019) employ per capita indicators (kg CO_2e per ewe per yr) in conjunction with efficiency analysis techniques (Data Envelopment Analysis) to establish a correlation between technical efficiency and environmental efficiency. In accordance with the PEF guidelines, Salcedo et al. (2022) and Miralles et al. (2024) adopt bifisical approaches that are contingent upon protein and fat content. In their study, Fois et al. (2022) undertake a comparative analysis of different scenarios involving milk powder and whey powder. In contrast, Atzori et al. (2022) standardise to a FPCM of 1 kg. However, they also highlight that specific allocation differences in the calculation tool can have a substantial impact on the outcomes. A number of authors combine the production unit with the unit of 1 hectare (ha) of utilised agricultural area (UAA). This serves to illustrate how extensive systems, whilst less efficient per kg of milk produced, have a lower impact per unit of area (Batalla et al., 2014; Vagnoni et al., 2015). As stated by Franca et al. (2019) and Vagnoni et al. (2024), studies encompassing the industrial phase utilize 1 kg of cheese prepared for distribution (Vagnoni et al., 2017; Nunes et al., 2020; Ghinea et al., 2022). In their 2014 study, Batalla et al. 2014 propose novel functional units to evaluate social and economic sustainability, including the impact per Manpower Unit and per Net Margin. This signifies a progressive alignment with European methodological standards, though Mediterranean research retains a degree of heterogeneity. Another crucial distinguishing factor pertains to the methods of allocation employed. Research conducted by Batalla et al. (2015) and Escribano et al. (2020), among others, as asserted by Sodi et al. (2024), Salcedo et al. (2022), Ravani et al. (2024) and Miralles et al. (2024), biophysical approaches based on energy or protein content are utilised. Conversely, Bosco et al. (2021), Atzori et al. 2022. As asserted by Sabia et al. (2020), Vagnoni et al. (2017), Cossu et al. (2024), Sintori et al. (2019), and Arca et al. (2021), economic allocation is favoured, with its rationale being the significance of milk in terms of farm revenues. Plaza et al. (2021) is distinguished by its mass allocation approach. Some authors (Lunesu et al., 2025) have demonstrated that the selection of the allocation method can lead to variations in results, underscoring the significance of methodological rigor. Nevertheless, certain studies eschew the implementation of any allocation method. Illustrative of this approach are the studies conducted by Ceyhan et al. (2020), Laliotis et al. (2025), Fois et al. (2022), and Herrera et al. (2022). The consideration of carbon sequestration serves as another distinguishing factor. Currently, there is no single method of carbon sequestration that has gained widespread acceptance. Various studies, however, have cited different approaches to carbon sequestration, including those outlined by the Intergovernmental Panel on Climate Change (IPCC) in 2006, by Vleeshouwers and Verhagen et al. (2002) by Soussana et al. (2010), and by Petersen et al. (2013). The method proposed by Petersen et al. (2013) is frequently regarded as the preferred approach due to its utilization of empirical data concerning carbon inputs, such as crop residues and manure, in conjunction with a 100-year time horizon. This time frame is widely considered to offer enhanced precision in the context of LCA (Batalla et al., 2015; Vagnoni et al., 2024). Noteworthy studies in this regard include those conducted by Batalla et al. (2015). As postulated by Escribano et al. (2015), Arca et al. (2021), and Lunesu et al. (2025), the integration of pastures and soils engenders a reduction in CF, with a maximum diminution of 30% and, in certain instances, a negative balance. It should be noted, however, that these researchers employed disparate methodologies. In contrast, a number of studies, including those referenced by Bosco et al. (2021), Sabia et al. (2020), Ravani et al. (2024), and Vagnoni et al. (2017), do not take into account the process of sequestration, instead focusing exclusively on emissions. This approach carries the risk of imposing penalties on extensive systems in comparison to intensive systems. In contrast, Plaza et al. (2021) conducts a study on 17 dairy sheep farms in Spain, with a particular focus on the relationship between CF and milk quality. The study uniquely links these two concepts, demonstrating that grazing-based systems produce milk that is higher in protein and healthy fatty acids, while emitting less per kg of FPCM. However, it should be noted that the study excludes sequestration. As asserted by Atzori et al. (2022) and Salcedo et al. (2022), an integrated approach is fundamental. Concurrently, dynamic and participatory methodologies (e.g., causal diagrams and simulation models) are employed to underscore the significance of ecosystem services. In a manner similar to that of Herrera et al. (2022), they highlight the socio-economic contribution of small ruminants to livelihoods and food security in marginal areas, despite their higher CF.

From a geographical perspective, a discernible distinction exists between extensive and intensive Mediterranean systems. Escribano et al. (2020) and Batalla et al. (2015) draw attention to the dilemma between intensification, which results in a reduction of CF per kg of milk, and extensive grazing, which, while increasing emissions per FU, contributes to ecosystem services and carbon sequestration. Building upon previous research, Miralles et al. (2024) expand this analysis to the European level, illuminating the fact that high nature value (HNV) farms boast the highest biodiversity. However, these farms also exhibit high emission values due to low productivity. In a related study, Herrera et al. (2022) broaden the scope to the regional level in Latin America and the Caribbean, leveraging FAOSTAT data spanning two decades to enhance the study's comprehensiveness. In Italy (Sardinia), discernible variations in soil fertility have been documented. Agricultural operations situated in regions exhibiting lower soil fertility (i.e., the central portion of Sardinia) have been observed to demonstrate reduced efficiency per unit weight of milk produced. However, these farms concomitantly exert a diminished impact per unit area and possess a considerable potential for carbon sequestration when contrasted with agricultural enterprises located in the plains (extending north-south across Sardinia). These observations are consistent with the findings reported by Vagnoni et al. (2024). A temporal analysis reveals a discernible progression in the methodologies employed. Previous studies, as exemplified by those conducted by Vagnoni et al. (2017) and Batalla et al. (2015), predominantly concentrated on CF and specific environmental indicators. In contrast, more recent research, such as that undertaken by Atzori et al. (2022), signifies an advancement in the field. As stated by Sodi et al. (2024), Ravani et al. (2024), Lunesu et al. (2025), Cossu et al. (2024), and Atzori et al. (2022), As Arca et al. (2021) note, there are multiple indicators relevant to this subject, including acidification, eutrophication, water use, and biodiversity. In their analysis, the authors adopt EF and PEF methodologies, as well as participatory or advanced modelling approaches, as discussed by Salcedo et al. (2022) in the context of ManleCO$_2$. A further innovative element that has been introduced by a number of studies is the link with sustainability policies and strategies. Atzori et al. (2022) utilises participatory approaches, including causal diagrams and scenario analysis, in order to propose concrete mitigation measures, while Cossu et al. (2024) applies the Made Green in Italy (MGI) scheme, thereby signalling a shift towards

European certification tools. The studies conducted by Sodi et al. (2024), Ravani et al. (2024) and Lunesu et al. (2025) are similarly oriented towards policy.

A review of the literature reveals that the CF values reported in the studies reviewed show a moderate but significant degree of variability, typically ranging between 2.0 and 6.5 kg CO_2eq/kg FPCM for sheep milk production systems (Batalla et al., 2015; As stated by Vagnoni et al. (2015) and Yáñez-Ruiz & Martín-García et al. (2016), the range was between 4.5 and 20.0 kg CO_2eq/kg in systems that also considered emissions from meat production as a by-product, expressed in kg of live weight (LW). A review of the literature reveals a wide range of values for the CF of cheese, with studies reporting figures from 15 kg of $CO_{2\ eq}$per kg of cheese (Nunes et al., 2020) to 17 kg of CO_{2eq} per kg of cheese, a figure that encompasses both industrial and artisanal production of Pecorino Romano. According to Vagnoni et al. (2017), the range of CO_2eq emissions from cheese production can reach up to 20.5 kg CO_2eq/kg, as determined through the application of the CML method (Ghinea et al., 2022). Within the context of sheep milk production systems, the majority of values are found to be within the range of 3-4 kg CO_2eq/kg FPCM. This is further exemplified by the findings of Sabia et al. (2020): 3.78, Bosco et al. (2021): 3.21, Atzori et al. (2022): 3.05-6.02, Sodi et al. (2024): 1.78-3.76, Ravani et al. (2024): 2.06-5.56, Escribano et al. (2020): 1.77-4.09, Vagnoni et al. (2017): 2.99-3.25. Intensive systems characteristically exhibit lower values per kg of product, but higher values per hectare. These lower values are attributable to factors such as high yield or management, as evidenced in the case of Lacaune in Sodi et al. (2024), which recorded 1.78 kg of CO_2 equivalent per kg. This phenomenon also occurs in farms that integrate mitigation strategies. As posited by Vagnoni et al. (2017), Sabia et al. (2020), and Sintori et al. 2019 extensive systems exhibit higher values per kg of product. This lower efficiency is accompanied by the provision of greater ecosystem services, such as carbon sequestration, and reduced impacts per hectare. Recent studies frequently document slightly elevated values, unless soil sequestration is taken into account, a factor that has the potential to substantially impact the outcomes. This phenomenon has been demonstrated by Arca et al. (2021) and Lunesu et al. (2025). Research endeavors that incorporate soil carbon sequestration, as exemplified by the studies conducted by Arca et al. (2021) As demonstrated by Batalla et al. (2021), Escribano et al. (2020), and Lunesu et al. (2025), there has been a 20-30% decrease in emissions, notably within permanent pasture systems. For example, the semi-extensive system proposed by Arca et al. (2021) demonstrates a range from approximately 3.54 to approximately 2.90 kg of CO_{2eq} per kg of FPCM when considering the inclusion of sequestration mechanisms. A similar trend is observed in the values presented by Lunesu et al. (2025), which exhibit a reduction to approximately 1.76 to 1.99 kg of CO_2eq per kg of FPCM. This finding elucidates the significance of terrestrial carbon sinks within Mediterranean ecosystems. Notably, studies encompassing the consideration of meat as a by-product tend to yield higher CF results. In this regard, Battacone et al. (2021) document a range of 4.56 to 7.30 kg of CO_2 equivalent per kg of live weight gain in lambs, consistent with the observations of Miralles et al. (2024). In the year 2024, the average values of 36.0 kg of CO_2 eq per kg of live weight (LW) were presented, with Greece reporting figures up to 40.5 kg. These values reflect the low productivity and high emissions intensity characteristic of semi-arid systems. Salcedo et al. (2022) present more moderate values (e.g., 3.78 kg CO_2 eq/L FPCM for Manchega sheep), whereas Escribano et al., (2020) document approximately 8.3 kg CO_2 eq/kg LW, inclusive of allocation to wool and soil carbon sequestration. Special mention must be made of Ceyhan et al., (2020), which reports total annual farm emissions (85,535 kg CO_2 eq/yr), yet lacks standardisation of emissions per kg of product, thus hindering comparison with other studies. As far as the present author is aware, the study by Fois et al., (2022) is the only one to focus on milk powder, with a CF of 5.52 kg CO_2 eq/kg. The study by Cossu et al. (2024). In their 2024 report, the researchers documented the impacts per unit of cheese, which were found to be 0.164 kg CO_2 eq/10 g DM (equivalent to ~16.4 kg CO_2 eq/kg DM). These findings are consistent with the anticipated outcomes for a concentrated product derived from high-emission milk. Ultimately, the investigation conducted by Meza-Herrera et al. (2022) unveils an outlier exhibiting a CF of 75.96 kg CO_2 eq/kg of milk-meat-wool protein (MMWP) across Latin America, attributable to Level 1 methodologies and the oversight in considering sequestration. The regional scale of the study in question, in conjunction with its broader FU, renders it not directly comparable to EU studies. However, it does serve to reinforce the correlation between low productivity, extensive systems, and higher emissions per product. Developments in recent years have demonstrated a clear shift towards more comprehensive and standardised approaches, which is consistent with European sustainability policies.

Wool

A review of the literature reveals that the CF of wool has been the focus of recent studies, which have employed a variety of methodologies.

This has resulted in the identification of significant similarities, as well as notable differences, pertaining to system boundaries, functional units, allocation methods and data sources (Table 5). A first similarity pertains to the centrality of the rearing phase, which is a common feature across all studies (Åby et al., 2024; Cottle et al., 2016; Peri et al., 2020; Bianco et al., 2023; Sim et al., 2018; Bianco et al., 2023a). According to the research conducted by Brock et al. (2013) and Wiedemann et al. (2016), enteric fermentation and manure are the primary sources of emissions, collectively accounting for 50 to 90% of the total CF. In the particular context of virgin wool, this dominance may be even more pronounced. As stated in their 2013 report, enteric CH_4 accounts for 86% of total farm emissions for wool produced in the Yass region (NSW). This finding is consistent with that of Wiedemann et al. (2016) As established in 2016, enteric CH_4 genesis has been determined to be a predominant factor, contributing between 79% and 89% of total greenhouse gas emissions (with the exception of land use) in various Australian regions. In accordance with the prevailing literature, CH_4 is consistently identified as the primary contributor to the climate impact of wool fibre, accounting for approximately 75% of the overall environmental burden (Nautiyal et al., 2025). This attribute of wool fibre, characterised by its substantial CH_4 emissions, results in a comparatively disadvantageous position when evaluated against polyester in standard LCA (Nautiyal et al., 2025). According to Moazzem et al. (2018), fibre production is the most impactful stage, accounting for 37.09% of the total environmental burden, when compared to polyester and cotton manufacturing. This assertion is further corroborated by studies that have a more pronounced focus on the finished product (Sim et al., 2018; Bianco et al., 2023). As asserted by Bianco et al. (2023), the grazing or primary production phase persists as the predominant factor, irrespective of subsequent industrial phases. However, when the analysis transitions to downstream processing, systems founded on waste/recycled wool or energy-intensive industrial contexts give rise to supplementary hotspots associated with industrial processes and energy. Vade et al. (2024) emphasize the significance of coal utilized for steam generation as the predominant source of emissions (0.066 tCO_2e/product) in a wool mill in India, with electricity contributing to a lesser extent. As demonstrated by Martin et al. (2021), for sweaters manufactured from waste wool, process emissions (e.g., washing, spinning, assembly) constitute the most significant portion of the environmental impact, predominantly attributable to electricity and heating requirements. This assertion is corroborated by Bevilacqua et al. (2011). As stated in 2011, the identification of key contributions in their case study encompassed transport (0.470 kg CO_2) and the manufacture of the jumper (0.384 kg CO_2), in addition to the farming component. Ultimately, within the scope of certain studies, the phase in which the fibres are used can impact the comparability between them. For instance, in the research conducted by Moazzem et al. (2018), this factor proved to be of significant importance for cotton and polyester fibres, though to a lesser extent for wool fibres, under the assumption that they are washed less frequently. This concept is further explored in the work of Nolimal et al. (2018). Researchers attributed the reduced impact of the wool jumper in all TRACI categories primarily to the assumption that it is not subjected to tumble drying, in contrast to other materials. However, clear methodological divergences have emerged. For instance, while Åby et al. (2024) and Cottle et al. (2016), Peri et al. (2020), and Wiedemann et al. (2018) prioritize a cradle-to-farm approach, employing particular models to estimate emissions (e.g., HolosNorSheep and GrassGro), studies such as those by Bianco et al. (2023) and Bianco et al. (2023a) adopt a cradle-to-gate perspective, also including the industrial processing stages of wool, with a significantly higher level of detail in the characterisation of co-products (e.g. ReviWool® noils). In a similar vein, Sim et al. (2018) expands the cradle-to-grave analysis to encompass the utilisation and ultimate disposal of textile products (carpets), emphasising the considerable impact of the use phase, particularly with regard to wool as opposed to synthetic fibres. In this context, certain studies extend beyond the mere quantification of data, proposing targeted mitigation strategies which reflect both the methodological approach and the scope of the system analysed. This finding is consistently supported by Henry et al. (2015). According to the estimate, the process of carbon sequestration through reforestation and pasture management has the potential to offset a range of greenhouse gas emissions associated with wool, with a percentage between 2% and 11% of total emissions being offset. This estimate was provided by Vade et al. (2024) in the context of discussions regarding the energy transition and waste recovery. As reported in 2024, there has been a considerable decrease in emissions due to the replacement of coal with biomass and natural gas (PNG) in an Indian wool mill. Martin et al. (2021) emphasize that the utilization of waste wool (presumed to have negligible impact) results in a nearly 50% reduction in emissions when compared to conventional chains. Furthermore, they assert that modifying the electricity mix (e.g., substituting the Swedish mix for that of Eastern Europe) leads to an additional 50% reduction in GHG emissions. As indicated in Bianco et al. (2022), recycled wool (MWool®) possesses an impact that is approximately 60% lower than that of virgin wool, primarily due to the bypassing of the breeding phase. In the domain of circular models and reuse, Bech et al. (2019), a PSS (Product Service System) model predicated upon the reuse and maintenance of wool T-shirts mitigates the overall impact in comparison with a linear model, notwithstanding the elevated initial impact of wool. A review of the literature reveals a wide variety of functional unit choices. Some studies employ standard physical units, such as kg of wool, including those by Åby et al. (2024) and Cottle et al. (2016). As asserted by Peri et al. (2020) and Wiedemann et al., (2018), the employment of use-phase- or product-specific units (e.g., m^2 of carpet, metres of yarn, number of garments) is evident in the studies conducted by Sim et al. (2018), Bianco et al. (2023), and Bianco et al. (2023a). This diversity is reflective of the objectives and limitations of the system of each individual study: ranging from assessments at the level of the farm to applications at the point of use. It is worth noting that the FU plays a pivotal role in establishing the basis for comparison, consequently shaping the manner in which the results are interpreted. In the context of the agricultural phase, a number of studies opt for the utilization of 1 kg of greasy wool at the farm gate as a benchmark, a preferred approach for evaluating the efficiency of primary production, irrespective of subsequent processing Brock et al. (2013); As asserted by Wiedemann et al. (2016), Henry et al. (2015) and Blignaut et al. (2025), when the objective entails the comparison of raw textile materials or alternative supply chains, the unit of 1 kg of fibre is employed instead. This approach was adopted in the comparison between recycled and virgin wool proposed by Bianco et al. (2022). This topic was also discussed by Nautiyal et al. (2025). In the case of consumption-oriented studies, the FU often becomes a specific product, such as a garment. For example, Bevilacqua et al. (2011) assume an average jumper (264.85 g), and Nolimal et al. (2018) As asserted by recent research, the utilisation of a jumper with variable weight depending on the material is imperative. In contrast, Martin et al. (2021) consider an average weight jumper (600 g), while Bech et al. (2019) adopt a service-based FU, i.e. the supply of T-shirts for 6 months, to integrate durability and use function. In other contributions, FU is explicitly linked to the period of use. Moazzem et al. (2018) develop a model of the use of 1 kg of clothing over the course of its useful life, which they then scale to match Australian annual consumption. In contrast, Dimakin et al. (2022) evaluate one year of face mask use per person.

A fundamental factor contributing to this variability is the allocation methods employed, since ovine animals simultaneously produce wool and meat, and the attribution of impacts to co-products becomes a pivotal methodological choice. The theory of economic allocation is advanced by Brock et al. (2013), who emphasize a variability of up to 29% in results as prices undergo fluctuation. This theory is also employed by Bevilacqua et al. (2011). In this context, Eady et al. (2011) place emphasis on the fact that economic allocation tends to result in the environmental burden being shifted to higher-value products (e.g. fine wool), thereby increasing their apparent impact. Alternatively, Wiedemann et al. (2016) prefer biophysical allocation (e.g. based on protein mass). As stated by Henry et al. (2015), and as also referred to in the LEAP/IWTO guidelines, greater stability over time is achieved through biophysical allocation. The findings of Eady et al. (2011) consistently show that the impact attributed to wool is reduced when biophysical allocation is used in comparison to economic allocation. In the context of recycled wool, Bianco et al. (2022) In 2022, the Circular Footprint Formula (CFF) was adopted, which allows for the accounting of the benefits of secondary material and quality decay over cycles. Finally, the expansion of the system was tested by Eady et al. (2011) and Wiedemann et al. (2016) in particular, Wiedemann et al. (2016) As asserted in 2016, the augmentation of the system has the potential to curtail GHG emissions by up to 70% in comparison with allocation methodologies. It is evident that the outcome is profoundly contingent upon the assumptions pertaining to the avoidance of products, with a particular emphasis on meat. For example, Åby et al. (2024) reports wool-related emissions ranging from approximately 19.9 to 26.8 kg of CO_2 eq per kg, with an average value of 25.1 kg. These figures are broadly consistent with those found in other LCA studies, such as Cottle et al. (2016), which present a wider range, between 8.5 and 35.8 kg CO_2-eq/kg, depending on the allocation method used. The sensitivity of wool's CF to the allocation strategy is a recurring theme in the literature. Wiedemann et al. (2018) provides compelling evidence for this position by undertaking a comparative analysis of the attributive and consequential approaches. The author observes that the quantity of wool under consideration (500 g) can yield a CF ranging from 6.82 to 15.75 kg CO_2-eq. This variability is attributed to the manner in which co-products are managed and the extent of system boundaries that are taken into account.

The GWP values reported for virgin wool at the farm gate demonstrate a consistent and notable variability. Blignaut et al. (2025) have determined, through a review of 14 studies, that the range of CO_2eq emissions from dirty wool is between 1.1 and 61.4 kg per kg of wool, with an average of approximately 21.9 to 23.7 kg of CO_2e per kg. On a more concentrated scale, Wiedemann et al. (2016) In the 2016 report, the range of 20.1–21.3 kg CO_2e/kg was documented, whereas Brock et al. (2013) employed economic allocation, arriving at an estimate of 24.9 kg CO_2e/kg. It is evident that the choices made when selecting a database have a considerable impact on the outcomes. In their study, Nautiyal et al. (2025) utilised Ecoinvent v3.7 and reported an emission of 5.07 kg of CO_{2eq} for every 393 grams of fibre, which is approximately equivalent to 12.9 kg per kg. The interpretation of the values becomes even more complex when LCA incorporates the use and lifespan of the product. For example, Sim et al. (2018) focuses on end applications such as carpets and estimates 6.35 kg CO_2 eq per 0.09 m^2 of wool carpet. This highlights the importance of the complete life cycle in interpreting the results. A more precise comparison on a product-by-product basis is furnished by Bianco et al. (2023), who documents 25–30 kg CO_2 eq/kg for short wool fibres and up to 97 kg for long fibres, ascribing these variances to both processing imperatives and yield characteristics. In an associated study, Bianco et al. (2023) evaluates the emissions associated with a finished wool undershirt, determining a CO_2 eq value of 11.7 kg per garment. The farming phase is identified as contributing 88% of the total emissions. Employing the same "per garment" rationale, Bevilacqua et al. (2011) estimate 1.947 kg of CO_2eq for a woollen jumper, while Martin et al. (2021) indicate approximately 6 kg of CO_2e for a jumper manufactured from waste wool in cradle-to-gate. Moazzem et al. (2018) observe that, despite a high total impact per item, the use phase imposes comparatively less of a burden on wool than on cotton. The scenario undergoes significant transformation in the case of recycled wool: Bianco et al. (2021) document 0.1–0.9 kg CO_2eq/kg for MWool® fibre, thereby underscoring a pronounced advantage over virgin wool. A further differentiating factor pertains to the inclusion of carbon sequestration, a component often underrepresented or neglected in prevailing studies (e.g., Åby et al., 2024; Peri et al., 2020). These studies largely disregard or only marginally consider the role of soil and vegetation, confining their scope to the calculation of net emissions. This oversight results in substantial discrepancies in the conclusions drawn, particularly in the context of extensive systems on natural pastures. From a geographical perspective, the range of studies is diverse, encompassing distinct contexts such as Norway (Åby et al., 2024) and Australia (Cottle et al., 2016). As reviewed by Wiedemann et al. (2018), studies have been conducted in Argentina (Peri et al., 2020), Italy (Bianco et al., 2023; Bianco et al., 2023), and the United States (Sim et al., 2018). It is evident that these territorial discrepancies are reflected in the absolute CF values, which are under the pronounced influence of animal productivity and forage quality: for example, the values reported in Patagonia by Peri et al. (2020) are significantly elevated (up to 18 kg CO_2-e/kg of wool) due to the low digestibility of pastures. In Australia, Wiedemann et al. (2016) compare three production areas and observe that greenhouse gas emissions are surprisingly similar between regions (ranging from 20.1 to 21.3 kg of CO_{2eq} per kg of wool), while fossil energy demand and land use vary more significantly, underscoring how certain territorial trade-offs become more evident in categories other than climate change alone. As asserted by Wiedemann et al. (2016), a broader level of comparability between contexts is essential for a comprehensive analysis. In a similar vein, Martin et al. (2021) observed that a European supply chain, specifically the Sweden-Baltic region, exhibits reduced social risks in comparison to those inherent in Australian or Uruguayan chains (Martin et al., 2021). Finally, Nautiyal et al. (2025) emphasise a notable methodological limitation, namely the potential inaccuracy of global datasets (Ecoinvent) in accurately representing specific systems such as the low-input New Zealand system. This may result in distortions when comparing with European or Australian systems (Nautiyal et al., 2025). Finally, there is evidence to suggest a gradual evolution in the methodologies employed over time. Previous studies (Cottle et al., 2016; Wiedemann et al., 2015) primarily focused on calculating CF with a limited number of indicators and methodological comparisons. In contrast, more recent works (Bianco et al., 2023) have expanded the scope of indicators and methodological analyses, thereby contributing to a more comprehensive understanding of the subject. As asserted by Isabella Bianco et al. (2023), there exists a greater degree of alignment with PEF guidelines in the current study, which encompasses additional impact categories, including climate change, acidification, eutrophication, water consumption, and land use. There is also an increased emphasis on data transparency and replicability in response to existing demands. A further temporal dimension also pertains to the updating of the datasets employed in LCAs. Nautiyal et al. (2025) demonstrate that Ecoinvent v3.7 utilises outdated data (from the 1990s) for the production of ethylene associated with polyester, consequently leading to an underestimation of the environmental impact of polyester, while it may overestimate the impact of wool due to a failure to update regional data. Recent versions (e.g. v3.10) have been shown to reduce the discrepancy between wool and polyester (Nautiyal et al., 2025). A review of the literature reveals that estimates of the CF of wool and wool products are highly sensitive to methodological choices, particularly in relation to allocation, system boundaries and assumptions about product longevity or processing intensity. In this context, virgin wool generally has a high "source" impact, associated with the biology of the animal and consequently with the CH_4 component; however, this profile can be mitigated when soil management and carbon sequestration practices are taken into account. Concurrently, the utilisation of recycled wool and reuse models (PSS) has been demonstrated to significantly mitigate the preliminary burden associated with the agricultural phase, thereby rendering wool competitive, and in certain instances preferable, to synthetic fibres throughout its entire life cycle. It was therefore observed that wool may appear to have a disproportionate impact when assessed in isolation from co-products and usage and reuse dynamics. This finding thus reinforces the need for transparent reporting and harmonised approaches, particularly for multifunctional systems such as sheep farming, where economic, nutritional and cultural dimensions are closely interlinked.

Meat

Recent research on the CF of sheep meat production systems demonstrates significant methodological advancements and considerable heterogeneity in system design, geographical focus and analytical choices.

A synthesis of research reveals a consistent finding: enteric fermentation (CH_4 production) is the predominant source of GHG, with a contribution ranging from 50% to 80% of total emissions (Ibidhi et al., 2017). This conclusion is supported by a robust body of research, with numerous studies identifying enteric fermentation as the primary source of greenhouse gas emissions. As asserted by Mujica et al. (2017), Lal et al. (2022), Mazzetto et al. (2023), and Shrivastava et al. (2025), the substantiating evidence is also consistent with more recent findings and varied production contexts Lunesu et al. (2025) determined that enteric CH_4 was responsible for an average of 54% of total emissions in sheep dairy farms in Sardinia, whilst Wang et al. (2025), analysing ranches in the Eurasian steppe, attributed 68.15% of emissions to enteric CH_4. Similarly, Argun et al. (2024) Recent studies, by Bhatt et al. (2022), substantiate the pivotal role of ruminant digestion as the predominant contributor to CH_4-induced global warming, considering CH_4's elevated GWP. In comparative analysis, Cerrato et al. (2023) also specify that, when comparing cattle and sheep, cattle farming has a greater impact due to higher levels of enteric CH_4. The residual variance is then explained mainly by manure management, fertilisers and grazing practices, depending on the intensity and organisation of the system (see table: Argun et al., 2024) emphasise the significance of manure management systems in relation to CH_4 and N_2O emissions. In contrast, Patra et al. (2017) estimate that in India, enteric fermentation is responsible for 92% of total CH_4 emissions from livestock, while the remaining 8% is attributable to manure. In their study, Yetişgin et al. (2022) observe that emissions from manure in transhumant systems are consistently lower compared to semi-intensive stationary systems. This finding substantiates the assertion that the management structure and methods of housing and grazing profoundly impact the composition of emissions.

Subsequent to the identification of hotspots, the extant literature also concentrates on mitigation options, proposing a plethora of strategies ranging from direct intervention on enteric CH_4 production to the reorganisation of the farm system and supply chain. From a nutritional perspective, numerous studies focus on dietary supplements: Thomas et al. (2025) explores the utilization of *Asparagopsis* seaweed as a feed additive, emphasizing its considerable potential for mitigating enteric CH_4 emissions. However, it also underscores the necessity to deliberate the potential environmental trade-offs associated with seaweed cultivation. In a more context-specific manner with regard to forage systems, Mujica et al. (2023) demonstrates that the incorporation of triticale grain as a supplement can yield superior outcomes with respect to CF reduction in Chilean dry systems, when compared to the use of oat hay or alfalfa. In addition to nutritional considerations, interventions in pasture management and the integration of novel technologies are increasingly pertinent. Schonbach et al. (2012) emphasize that the exclusion or light grazing of steppes can effect a transition from being a carbon source to becoming a carbon sink, which has direct implications for the overall emissions balance. A further strand of the discourse pertains to the enhancement of production efficiency and genetics as structural levers. Hyland et al. (2016) and Harrison et al. (2014) place considerable emphasis on the assertion that increased performance (growth rate, fertility) leads to a reduction in emissions intensity per unit of product. Farrell et al. (2022) emphasise that the implementation of genetic selection indices (e.g. maternal or terminal indices) has the potential to mitigate emissions intensity by enhancing animal performance; while Nsabiyeze et al. (2024), the application of data envelopment analysis (DEA) was employed to optimise energy input in Chinese farms, thereby reducing inefficiencies and waste. In the domain of supply chain management, logistics optimisation strategies have been demonstrated to be instrumental in reducing emissions associated with handling. Zhang et al. (2024) provide an illustrative example of this phenomenon, elucidating how the optimisation of transport routes within the sheep meat supply chain can engender a substantial reduction in the aforementioned emissions. Finally, a number of studies extend the analysis beyond the production perimeter, discussing scenarios of change in the human diet. For instance, Trasca et al. (2024) and Lin et al. (2015) consider reducing meat consumption as an option for reducing resource use and global emissions, placing mitigation within a broader framework of food system transition.

In addition to the findings regarding hotspots and mitigation options, the extant literature emphasizes methodological variability, which renders direct comparisons between studies complex. A primary point of divergence pertains to the methodology employed for estimating emissions. Argun et al. (2024) demonstrate that the IPCC Tier 1 approach, which relies on fixed emission factors, systematically underestimates emissions when compared to Tier 2, which incorporates specific information on diet and weight. As asserted by Jones et al. (2014), the transition to Tier 2 enhances the representation of the system, although a richer data set is required. Concerning the modelling approach, the preponderance of studies employs a process-based LCA (Bhatt et al., 2022). As Lunesu et al., (2025) note, alternative or integrated methods also appear. For example, Tsakiridis et al. (2020) apply EIO-LCA, which is useful for capturing indirect emissions throughout the supply chain (Tsakiridis et al., 2020). Meanwhile, Nsabiyeze et al. (2024) and Dakpo et al. (2017) a study was conducted that combined DEA and LCA in order to assess not only the impact but also the inefficiency compared to a “frontier” of best practices. In addition, Dakpo et al. (2017) introduced a “by-production” approach that treats pollution as unwanted output and estimates marginal abatement costs. Ultimately, despite employing the same LCA, the capacity for comparison may be constrained by the choices made with respect to CH_4 calculation and LCIA methodologies. This is explicitly articulated by Ahlgren et al. (2024), who assert that CH_4 is modelled as an endogenous variable contingent on feed quality, intake, and live weight. Wheeler et al. (2013) engage in a discussion concerning the utilisation of regional models (OVERSEER) that have been calibrated to systems in New Zealand. Furthermore, Harrison et al. (2014) draw attention to the fact that certain biological models (e.g. GrassGro) necessitate manual additions for unmodelled emission components. In the field of LCIA research, several studies have employed ReCiPe, as highlighted by Bhatt et al. (2022) and Verduna et al. (2020). In contrast, Cerrato et al. (2023) utilised CML, while Thomas et al. (2025) adopted EF 3.1, a method that is more aligned and standardised within the European context.

It is evident that the boundaries of the system exhibit considerable variability between studies, constituting a primary source of heterogeneity in the results. A substantial proportion of the literature employs a cradle-to-farm-gate perimeter, with a particular emphasis on aspects of livestock management, feed production, and manure (Eldesouky et al., 2018; O'Brien et al., 2016). As Mazzetto et al. (2023) note, a number of studies have been conducted on this subject, including those by Lal et al. (2022), Dougherty et al. (2018), Sarkar et al. (2023), Geß et al. (2020, 2022), Horrillo et al. (2021), and

Shrivastava et al. (2025). As stated by Lunesu et al. (2025) and Bhatt et al. (2022), certain contributions broaden the scope of analysis to encompass the entire life cycle or supply chain, thereby including downstream stages and indirect components (Mazzetto et al., 2023; Ridoutt et al., 2021; McNicol et al., 2024). Zhang et al. (2024) posit that the trajectory of expansion includes works which extend the scope of the analysis beyond climate change in isolation or livestock production in isolation. For instance, Ibidhi et al. (2017) integrate water and land footprints in Tunisia, highlighting trade-offs typical of semi-arid systems. da Silva et al. (2024) Showed the adoption of a functional basket unit that integrates sheep meat and olive oil within an agro-silvo-pastoral system is of particular significance. This approach underscores the mitigation potential of integrated models, signifying an advancement from more “linear” methods, as exemplified by the approach of Toro-Mujica et al. (2017). Applications that exploit broader boundaries to include technologies or transition scenarios are classified similarly. McNicol et al. (2024) incorporate reforestation scenarios in Welsh farms to assess the viability of achieving Net Zero. Concurrently, certain studies employ the variability of systems as a means for methodological comparison. Dougherty et al. (2019) and Recktenwald et al. (2024) analyse disparate systems in the United States, encompassing transhumance and intensive farming, and propose comparisons between divergent IPCC levels. In addition to disparities in “physical” scope, a distinction emerges concerning the capacity of methodologies to encompass indirect emissions within intricate supply chains (Tsakiridis et al., 2024). In their 2020 study, the researchers employed an EIO-LCA (environmentally extended input-output) methodology, encompassing emissions embedded in international trade and value chains. In contrast, Zhang et al. (2024) expanded the study's boundaries to include retail distribution. In this area of research, the most recent literature also emphasises the necessity to make the robustness of estimates explicit. For example, Ahlgren et al. (2024) and Tsakiridis et al. (2020) highlight the importance of uncertainty analysis, emphasising that CH_4 is often the component with the greatest variability and therefore one of the main sources of uncertainty in the results.

The selection of the functional unit (FU) is a highly heterogeneous process, directly reflecting the established objectives, whether they be productive, environmental, nutritional or economic in nature, and the system types, which can be categorised as either intensive or extensive. In the majority of studies, mass-based FUs predominate, particularly 1 kg of live weight (LW) at the farm gate, which persists as the preeminent standard for meat systems (Mujica et al., 2017; Wang et al., 2024; Jones et al., 2014; Hyland et al., 2016). As asserted by Ripoll-Bosch et al. (2013), Bhatt et al. (2022), and Lunesu et al. (2025), in certain instances, specific UFs are employed for co-products such as wool, as articulated by Wiedemann et al. (2015). As the focus of research shifts to the “edible” product or slaughter yield, several studies adopt 1 kg of carcass/dead weight (CW/DW/dwt) or even more “refined” units, such as 1 kg of boneless meat, in order to more accurately describe the final consumable product and facilitate improved comparability along the supply chain (Ibidhi et al. (2017). As discussed by McNicol et al. (2024), Toro-Mujica et al. (2017), Sarkar et al. (2024), Ahlgren et al. (2024), Nsabiyeze et al. (2024), Thomas et al. (2025), and Argun et al. (2024), the current state of research on this topic is as follows: As asserted by Wiedemann et al. (2015), a mounting corpus of literature, in conjunction with mass UFs, proffers UF per area when the objective is to evaluate land use, carbon sequestration or territorial sustainability, particularly in pastoral systems and marginal areas (cf. Horrillo et al., 2021; Sharma et al., 2018; Schonbach et al., 2012). As postulated by Worrall et al. in 2012, a concurrent development of nutritional UF has been observed. This development challenges the exclusive utilisation of mass as a metric for comparison, instead proposing the integration of nutritional value, such as protein, energy, or fatty acid quality, as a criterion for evaluation. This approach facilitates comparative analyses between disparate food systems and categories. As asserted by McNicol et al. (2024), Tsakiridis et al. (2020), Villarreal-Ornelas et al. (2022), Lin et al. (2015), Gill et al. (2009), and Verduna et al. (2020), the subject of this discourse is of considerable importance. In certain instances, economic or monetary output-based UFs manifest, particularly when analysing value chains with input-output approaches (Tsakiridis et al., 2020) or when economic analysis is integrated with environmental interpretation (Cerrato et al., 2023; Horrillo et al., 2021). Ultimately, in the context of integrated or multifunctional systems, certain authors opt for composite/basket FUs to encapsulate simultaneous, non-separable outputs. This approach is exemplified by da Silva et al. (2024), who integrate sheep meat and olive oil within an agro-silvo-pastoral system, and by Zhang et al. (2025) model, multiple FUs (milk, beef, sheep meat, wool) are employed and linked to mitigation scenarios. In contrast, Ridoutt et al. (2021) integrate the interpretation of the FU with radiative forcing indicators, going beyond CF alone over 100 years. Finally, it should be acknowledged that, within the scope of certain farm-scale investigations, the process of normalisation is not uniformly implemented at the product level. This methodological aspect directly influences the comparability of the results obtained (Cerrato et al., 2023).

The methods of allocation employed in LCA studies on the sheep sector differ substantially and remain among the most “sensitive” choices, as they determine the extent to which emissions are attributed to meat, milk and wool. A comparative analysis reveals that mass allocation has the potential to generate CFs of even >30 kg CO_2-eq/kg LW, whereas economic or biophysical/protein approaches frequently result in lower values (Dougherty et al., 2018). As asserted by Horrillo et al., (2020), the explicit inclusion of wool in the allocation process has the potential to reduce the CF attributed to meat by up to 20% (Recktenwald et al., 2024). The prevailing economic allocation is further substantiated by the works of Sarkar et al. (2024) and Shrivastava et al. (2025). As asserted by Zhang et al. (2025), Ibidhi et al. (2017), and Wang et al. (2024), the aforementioned methodologies can also be applied to allocate emissions between milk, lamb, cull ewes, and wool, based on farm gate prices or revenues (Lunesu et al., 2025). As asserted by Jones et al. (2014), Atzori et al. (2015), and Ledgard et al. (2011), the critical issue of volatility remains a concern; the proportion designated for wool can fluctuate considerably in accordance with prevailing market prices (Wiedemann et al., 2015). In contrast, a number of studies employ biophysical allocations that remain constant over time. These are frequently founded on protein or physiological/metabolic requirements (Bhatt et al., 2022; Wiedemann et al., 2015). Zhang et al. (2025) posited that this methodology could substantially modify the footprint ascribed to wool, in comparison with the economic method. Frontier approaches, though less common, do emerge in certain contexts. On one hand, there is the concept of allocation to cultural ecosystem services, as proposed by Ripoll-Bosch et al. (2013). On the other hand, there is the notion of expanding the system as a conceptual alternative to avoid allocation. This approach encompasses the functions of co-products and accounts for any avoided emissions. In the existing literature, certain studies circumvent the issue of allocation by confining their analysis to meat exclusively (Ridoutt et al., 2021; Geß et al., 2020, 2022, 2023).

Another cross-cutting but methodologically complex driver is carbon sequestration, which has the potential to substantially alter the climate balance, especially in extensive systems: According to Lunesu et al. (2025), the inclusion of sequestration in the soil is estimated to reduce emissions by approximately 30% in sheep products in Sardinia. A study of Chilean sheep meat revealed a comparable reduction, from 9.8 to 7.0 kg CO_2eq/kg. As asserted by Mujica et al. (2023), the marked effects were found to be proportionally higher in hill farms than in lowland farms (Kilcline et al., 2024). A consistent finding across studies is that some explicitly quantify sequestration and report reductions of the order of 20–30% (Eldesouky et al., 2018; As asserted by McNicol et al. (2024) and Mujica et al. (2017), the subject of net CF is treated inconsistently across studies. It has been noted that some researchers include it in their primary analyses, while others exclude it, leading to a probable overestimation of net CF. This phenomenon has been previously documented in the works of Geß et al. (2020, 2022), Horrillo et al. (2020), and Shrivastava et al., (2025), Sarkar et al. (2024) and Zhang et al. (2024). In certain instances, when specific time horizons are taken into consideration, the balance can even become negative, as demonstrated in Dehesa systems (Horrillo et al., 2021) or in simulations that incorporate improved pastures (Wiedemann et al., 2015). Nevertheless, despite the estimation of a substantial average compensation, the Net Zero target at the company level is frequently regarded as challenging to attain without structural interventions in land use (McNicol et al., 2024). Toro-Mujica et al. (2017) and Zhang et al. (2025) estimate an average compensation of 22%. However, both studies conclude that reforestation of approximately 30–80% of the area would be needed to reach a state of environmental and economic equilibrium. Furthermore, the effect of carbon sequestration is found to depend critically on pasture management and stocking rates. In steppes, the absence of grazing or light grazing maintains a sink behaviour; conversely, moderate or heavy grazing can transform the system into a net source of emissions (Schonbach et al., 2012). In addition, on sensitive soils such as peatlands, stocking rates must be respected to avoid carbon losses (Worrall et al., 2012). In the context of operational practices, a number of studies have been conducted on the subject of regenerative practices and the integration of woody elements. In this regard, soil interventions and management techniques have been found to enhance the process of carbon sequestration (Lunesu et al., 2025). On the other hand, the restoration of arboreal areas within grazing farms has been identified as a significant measure for increasing carbon sinks (Ledgard et al., 2011). With respect to estimates, given the difficulty of verification and uncertainty (i.e., small annual increases on high stocks), it is recommended that results be reported both with and without sequestration (O'Brien et al., 2016). As asserted by Hyland et al. (2016), there has been a concurrent increase in the utilisation of modelling approaches founded on carbon inputs (Petersen et al., 2013; Lunesu et al., 2025) and Net Zero scenarios predicated on average absorptions and land use changes (cf. Zhang et al., 2025). Furthermore, a number of authors acknowledge its significance yet omit it due to an absence of baselines or reference data (O'Brien et al., 2016; Palomo et al., 2024). In contrast, others redirect their attention to alternative mitigation levers (e.g., solar/agrivoltaic integration, genetic enhancement, food additives) (Mazzetto et al., 2023). In a similar vein, da Silva et al. (2024) indirectly acknowledge the potential advantages for soil health derived from the integration of olive cultivation and livestock farming, albeit without explicitly quantifying the role of carbon in the soil. Ultimately, soil type remains a distinguishing factor. The inclusion of emissions from drained organic soils significantly increases the climate impact, while their exclusion can reduce the calculated results for lamb by 22–27% (Ahlgren et al., 2024), thus confirming the centrality of peatland management (Worrall et al., 2012).

A review of the literature reveals that the CF values for sheep meat typically fall within the range of 5 to 30 kg CO_2 eq/kg live weight (LW). Deviations from this range occur when the result is expressed in terms of carcass weight/dead weight (CW/DW) or when the boundaries encompass the entire supply chain. It has been established that low levels are indicative of more efficient systems or high-performance contexts. For instance, Argun et al. (2024) reports a CO_2 eq emissions rate of 4.52–6.56 kg per kg of meat in Turkey, and also highlights the tendency of Tier 2 to estimate higher values than Tier 1. As indicated by Ledgard et al., (2011), low values are also reported for New Zealand lamb (8.6 kg CO_2e/kg LW) and for optimised systems (6.4 kg CO_2-eq/kg LW). (Zhang et al., 2025) In the context of Chile, the incorporation of sequestration leads to a reduction in the estimated value from 9.8 to 7.0 kg CO2eq/kg LW (Mujica et al., 2023). In Sardinia, for suckler lambs, Lunesu et al. (2025) documents 7.94 kg CO_2e kg LW and 13.24 kg CO_2e kg carcass, thereby explicitly demonstrating the impact of the reference base.

At intermediate levels, variability is principally driven by geography and productivity. In the United Kingdom, Jones et al. (2014) observes a gradient of plain–hill–mountain (10,85; 12,85; 17,86 kg CO_2e kg LW). Another study by Hyland et al., (2016) reported a range of 9.89 to 21.14 kg of CO_{2eq} per kg of live weight for Welsh lamb, with a mean of 15.13 kg per kg of live weight. In Ireland, Farrell et al. (2022) demonstrates more modest yet consistent variations among flocks of varying genetic merit (14.6 vs 15.5 kg

CO_2eq kg carcass). In addition to the cases previously cited, Lal et al. (2022) present intermediate values for India (approximately 5.7–9.5 kg CO_2 eq/kg LW), contingent upon efficiency and management. In a 2017 study, the Tunisian systems were placed at higher levels on a carcass basis (20.4–26.6 kg CO_2-eq/kg) Ibidhi et al. (2017). This finding is consistent with less efficient supply chains and environmental constraints. In their study on "extensive/itinerant systems", Pardo et al. (2023) observed a range of 16.5–26.9 kg CO_2 eq/kg LW, with transhumance resulting in a slight reduction in intensity in comparison with sedentary models. Conversely, in more extensive or low-productivity systems, values tend to be elevated; Ripoll-Bosch et al. (2011) documents 19.5–28.4 kg CO_2eq/kg LW (and 39–57 kg on a meat basis). Yetişgin et al. (2022) indicates 20.8 kg of CO_{2eq} per kg of liveweight (LW) in transhumance systems, compared to 25.4 kg in semi-intensive systems. Furthermore, McNicol et al. (2024) finds 21.8 to 36.4 kg of CO_{2eq} per kg on a dry weight (DW) or carcass basis. It is important to note that these results undergo further changes when the comparison shifts from mass to nutrients, such as omega-3. In accordance with the findings illustrated in the aforementioned image, the alpine systems that were the subject of analysis by Geß et al. (2020, 2023) attain remarkably elevated values (reaching up to 56.8 kg CO_2 eq/kg). Conversely, within Mediterranean and marginal contexts, the results obtained by Palomo et al. (2024) report documents elevated values for weaned and fattening lambs (27.5 ± 6.8 and 21.8 ± 8.5 kg CO_2-eq/kg LW). In addition to the cases previously cited, Lal et al. (2022) present intermediate values for India (approximately 5.7–9.5 kg CO_2 eq/kg LW), contingent upon efficiency and management practices. In a 2017 study, the Tunisian systems were placed at higher levels on a carcass basis (20.4–26.6 kg CO_2-eq/kg). This finding is consistent with less efficient supply chains and environmental constraints. In their study on “extensive/itinerant systems”, Pardo et al. (2023) observed a range of 16.5–26.9 kg CO_2 eq/kg LW. They found that transhumance slightly reduced intensity in comparison with sedentary models. Methodological choices continue to be a significant factor. Dougherty et al. (2018) provide a quantitative analysis of a range that varies according to allocation, with values between 13.9 and 30.6 when considering weight allocation, 10.4 and 18.1 when considering economic factors, and 6.6 and 10.1 when considering protein mass. Additionally, Recktenwald et al. (2024) substantiates extensive variations (10.5–20.1 kg CO_2-eq/kg) that are susceptible to productivity and calving interval. Furthermore, when the boundaries extend “beyond farm gate”, the order of magnitude may be subject to alteration. For example, Zhang et al. (2024) documents a transition from 8.12 kg CO_2 eq/kg in the agricultural phase to 33.88 kg CO_2 eq/kg including transport, slaughter and sale. Similarly, Mazzetto et al. (2016) reports have indicated higher values when considering a cradle-to-grave perspective (e.g., 14.8 kg CO_2 eq/kg of edible meat). Additionally, certain ‘macro’ estimates that are not directly comparable with farm LCA can yield remarkably high values, as evidenced in the case of Trasca et al. (2024) on a global average. Finally, in order to contextualise the “climate message” in a manner that extends beyond the confines of GWP100, Ridoutt et al. As demonstrated in 2021, the introduction of metrics based on radiative forcing has shown that, while estimating 5.73 kg CO_2 eq/kg LW with GWP100, certain sector configurations may approach a reading of “climate neutrality”, depending on the metric adopted. The field of geography has a direct influence on key agricultural parameters such as productivity, the quality and quantity of forage, and the use of external inputs. This leads to a shift in the relative importance of two significant factors: enteric CH_4 (CH_4) and soil N_2O. A pertinent example of this phenomenon can be observed in

Canada, where the wetter regions in the east tend to generate higher levels of N_2O from soil and fertilisation activities in comparison to the drier regions in the west (Dyer et al., 2014). In Australia, divergent rainfall and agro-ecological conditions give rise to differing emission profiles between pastoral areas, sheep-wheat systems and high rainfall areas (Biswas et al., 2010; Wiedemann et al., 2015; Wiedemann et al., 2015). Topography introduces an additional gradient: agricultural enterprises located on hill or mountain land frequently demonstrate higher levels of Condition Factor (CF) per kg of lamb meat in the context of harsh climates, less fertile pastures, and slower livestock growth (Jones et al., 2014; In accordance with the findings reported by Hyland et al. (2016), net CF may potentially be diminished by the incorporation of sequestration in extensive soils, as evidenced by O'Brien et al. (2016). In the Mediterranean region, a trade-off is evident between less efficient alpine/pastoral systems per unit of product and more efficient industrial plains. Research findings suggest that alpine grazing can reduce purchased inputs and enhance performance (Ripoll-Bosch et al., 2011; Ripoll-Bosch et al., 2013; Verduna et al., 2020). In arid and marginal contexts, water scarcity has been shown to increase hay purchases/transport (Wang et al., 2025), whilst overgrazing has been evidenced to transform the soil from a carbon sink to a carbon source (Schonbach et al., 2012). As Mujica et al. (2023) note, rainfall variability therefore modulates the need for supplements. As Toro-Mujica et al. (2022) note, microclimatic differences influence CH_4 emission factors. Moreover, as Argun et al. (2024) assert, transhumance may be more efficient than sedentary systems. Ultimately, within the context of export supply chains, maritime transport frequently constitutes a negligible portion of the overall composition, often being marginalised by efficiencies realised within the warehouse environment (Ledgard et al., 2011; Wiedemann et al., 2015).

From a temporal perspective, a discernible progression in the sophistication of the models has been documented. Initial studies (O'Brien et al., 2016; As stated by Ibidhi et al., (2017) and Dougherty et al. (2018), research was generally based on IPCC level 1 or 2 factors, with CF being the only factor reported. More recent studies, however, such as those by Ridoutt et al. (2021), have expanded the scope of factors examined. As asserted by Shrivastava et al. (2025) and McNicol et al. (2024), there is merit in the employment of dynamic metrics and the integration of uncertainty analysis, incorporating techniques such as Monte Carlo and sensitivity analysis. Moreover, there is value in broadening the scope to encompass biodiversity, water use, and socio-economic indicators, as Cerrato et al. (2023). This is indicative of both methodological maturation and increasing alignment with EU policy needs and global reporting frameworks.

Conclusion

An analysis of the existing literature reveals considerable heterogeneity among LCA studies on sheep farming systems, which makes it difficult to compare results directly (FAO 2013). The main differences and similarities identified relate to the following aspects: System boundaries: most studies define the system boundaries from production to the farm gate (from ‘cradle to farm gate’). However, some studies extend the scope of analysis to include the point of sale (from cradle to shop) or even the entire life cycle (from cradle to grave); however, these approaches are less common and are associated with greater data uncertainties; the definition of system boundaries can significantly influence the results.

Functional units (FU), i.e. greenhouse gas emissions and CF, are expressed in units of CO_2 equivalent (CO_2-eq). Functional units exhibit significant variability, frequently contingent on carcass weight (CW), live weight (LW) of the product (e.g., 1 kg LW of sheep, ram, or lamb at the barn), or fat and protein corrected milk (FPCM) for dairy production (e.g., 1 kg FPCM). In the context of wool, the methodology entails the utilisation of either 1 kg of raw wool or 1 kg of a wool-based product. It is imperative to recognise that the selection of the functional unit exerts a substantial influence on the outcomes and their degree of comparability. A number of studies advocate for a more holistic approach, entailing the evaluation of the comprehensive agricultural activity spanning a period of one year, whilst taking into account the entirety of products and services without any allocation.

With regard to the allocation methods employed in order to distribute emissions among agricultural products in co-production systems (e.g. meat and wool), the most common methods are economic allocation (based on the market value of co-products) and biophysical allocation (based on mass, protein or energy). Economic allocation is frequently employed; however, it is contingent on price fluctuations. In contrast, biophysical approaches are more consistent with the principles of LCA. Additionally, certain studies have investigated system expansion as an alternative to allocation, deeming it to be more representative. The necessity for a robust methodology with which to manage co-production has been emphasised, with the recommendation that studies should present results for both products rather than simplifying them.

Impact categories and data inventory: The majority of studies concentrate on GWP; however, there has been a recent increase in the number of studies that examine a broader representation of environmental impact, including eutrophication, acidification, water and soil use, and ecosystem services. The release of ammonia from fertilisers and manure is the primary contributor to acidification, while the loss of nitrate and phosphorus from the use of artificial fertilisers is the main source of eutrophication. The majority of fossil fuels are consumed during the pre-agricultural stage for the production of fertilisers and concentrated feed. The variability of inventory data is attributable to a number of factors, including differences in management practices, soil types, climates and seasonality. There is a clear need to improve the completeness and consistency of the selection of impact categories.

Critical emission points: It is universally acknowledged within the field of ruminant livestock farming that enteric fermentation is the most significant source of emissions, contributing substantially to total greenhouse gas emissions. Other critical points of relevance include manure management (particularly N_2O emissions), feed production and procurement (particularly soy and maize), and energy consumption. Recent studies have emphasized the necessity to enhance methodologies for calculating soil carbon sinks, particularly within the context of grazing-based systems, as their integration can exert a substantial influence on the final CF values. Indirect methods for estimating soil carbon sequestration, such as that proposed by Petersen et al. (2013), can be regarded as a valid alternative to direct methods, thus facilitating comparison between studies.

Geographical variability and intensification: according to the FAO estimates, emissions intensity for small ruminant milk is higher in developing regions due to suboptimal production conditions, while it is lower in industrialised countries due to production specialisation. Studies comparing extensive and intensive systems yield conflicting results with regard to their environmental performance. Although more intensive systems with higher productivity per animal tend to exhibit lower LC values per unit of product, extensive systems have the potential to offer advantages in terms of soil carbon sequestration, biodiversity conservation and the provision of other ecosystem services. Studies of extensive organic farms have demonstrated lower emissions than conventional farms, with significant carbon sequestration. It has been demonstrated that transhumant livestock farming, a practice which maximises the utilisation of local forage resources and concomitantly reduces the necessity for external feed, engenders a reduced CF in comparison with sedentary systems. This is further substantiated by reductions in emissions when the natural baseline emissions of displaced wild herbivores are taken into account. It is imperative that manure management and the utilisation of fertilisers, which are frequently scarce in certain regions, are conducted in an efficient manner in order to mitigate emissions. Sustainable intensification, which encompasses the augmentation of both production and efficiency, has the potential to enhance environmental performance. Notwithstanding the advances that have been made, the ability to compare studies remains problematic due to the divergence in the methodologies and assumptions employed. Meaningful comparison is principally possible within homogeneous areas or between studies utilising similar methodological approaches. The necessity to standardise LCA methodologies and to consider a broader range of environmental impacts, including socio-economic aspects and animal welfare, is becoming increasingly evident in order to provide a holistic assessment of sustainability.

Future perspectives:

The integration of animal welfare and LCA: studies that combine animal welfare assessment with LCA remain limited and require methodological standardisation. Recent work proposes integrated approaches or links animal welfare scores to the functional unit of LCA, considering physiological or behavioural indicators. (e.g. cortisol in fur).

Assessment of ecosystem services: conventional LCA faces challenges in capturing the multiple environmental benefits (e.g., biodiversity, landscape maintenance, fire prevention) provided by extensive agricultural systems. There is a need for studies that develop or apply methodologies to include the quantification of these ecosystem services in LCA assessments, particularly for high nature value (HNV) systems.

Sensitivity and uncertainty analysis: further insights into the use of sensitivity and Monte Carlo analysis to manage data variability and uncertainty in LCA studies.

Cost-effectiveness of mitigation strategies at the territorial level: quantifying the costs and benefits of mitigation actions from an economic perspective is essential for planning effective strategies.

Implications of dietary changes and technological innovation: recent studies on food additives, genetic selection for efficiency, and precision management in sheep farming to reduce emissions, such as precision feeding.

Integrated systems: LCA investigations of integrated systems, such as sheep farming with olive cultivation, which offer mitigation opportunities through synergies.

An example of research is da Silva et al. (2024). LCA of integrated olive cultivation and sheep farming: a Brazilian case study.

Contribution of agrivoltaics: emerging research on the integration of agrivoltaic systems with sheep farming and their environmental and economic implications.

The quality of the data and its accessibility: particular attention must be paid to the absence of quality inventory data and the difficulty of accessing data in languages other than English, which hinders international research.

The purpose of this review is to synthesise the complex network of existing information, provide an in-depth analysis of methodological trends and results, and identify knowledge gaps so as to guide future research towards more sustainable sheep farming on a global scale.

It is imperative that LCA studies be conducted with the objective of providing a foundation for the planning of efficacious mitigation actions. Meticulous attention must be allocated to the precise estimation of emissions from animals, crops, purchased feed, energy consumption, and soil carbon sinks, which were regarded as the most consequential quantitative factors influencing the environmental performance of agricultural operations.

It is imperative that the environmental indicators provided by inventories and LCA studies are evaluated and ranked according to mitigation effectiveness, in order to test their feasibility at farm and regional level. At regional level, when organising large-scale mitigation plans, actions must target the critical points of inefficient farms rather than efficient farms. It is imperative that the costs and benefits of mitigation actions are also quantified from an economic perspective.

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Appendix Chapter 1

Table 2. Summary of LCA studies in terms of the main topic analysed

Study (Autho & Year)	Main study subject	Study (Autho & Year)	Main study subject	Study (Author & Year)	Main study subject
Arca et al (2021)	LCA study of the transitio from semi-intensive to semi extensive Mediterranean dair sheep farming, focusing on so carbon sequestration.	**Escribano et al (2020)**	Analysis of carbon footprint i semi-arid rangeland dair sheep farms comparin intensification versus land based grazing.	**Sabia et al (2020)**	Investigation of dairy shee carbon footprint and relate damages using a simplifie LCA based on the ReCiPe End point method.
Atzori et al (2015)	Assessment of economic an environmental sustainability o extensive dairy sheep farmin in Sardinia using a case stud approach.	**Franca et al (2019)**	Comparison of environmenta performances between semi intensive and semi-extensiv sheep milk production system in a Sardinian farm.	**Salcedo et al (2022)**	Assessment of GHG emission reduction potential in Castilla La Mancha dairy smal ruminant farms using th ManleCO2 model.
Atzori et al (2022)	Systems perspective analysi for developing a territoria GHG mitigation plan in th Sardinian dairy sheep suppl chain (SheepToShip LIFE).	**Ghinea et al (2022)**	Life cycle assessment of shee cheese production in a sma dairy factory in a Romania rural area.	**Sintori et al (2019)**	Estimation of technica efficiency and GHG emission of Greek dairy sheep farm using Data Envelopmen Analysis.
Batalla et al (2014)	Description of GHG emission using different functional unit to include social and economi factors in sheep dairy farr assessment.	**Laliotis et al (2025)**	Assessment of GHG emission and carbon footprint i mountainous semi-extensiv dairy sheep and goat farms i Greece.	**Sodi et al (2024)**	Comparison of th environmental impact of mil production among Massese Sarda, and Lacaune shee breeds in Tuscany.
Batalla et al (2015)	Estimation of the carbo footprint of sheep milk i Northern Spain including so carbon sequestration i grasslands.	**Lunesu et al (2025)**	Application of an indirec method to assess the net carbo footprint of dairy sheep farm focusing on suckling lamb.	**Vagnoni et al (2014)**	Comparison of environmenta impacts of sheep mil production from thre Sardinian dairy farms wit different input levels.

Battacone e al.,(2021)	Estimation of the CH4-relate carbon footprint of sucklin lamb meat in Sardinian dair sheep farming.	**Meza-Herrera et al., (2022)**	Regionalization and combine productive, socio-economi and ecological footprin quantification of sma ruminant systems in Lati America.	**Vagnoni et al (2015)**	Evaluation of environmenta performances of Sardinia dairy sheep production system at low, mid, and high inpu levels.
Bosco et al (2021)	Assessment of environmenta impact reduction of ewe mil by introducing precisio feeding strategies in Tuscany.	**Miralles et al (2024)**	Environmental impact an biodiversity assessment c European High Nature Valu farming systems via LCA.	**Vagnoni et al., 2017)**	Characterization of th environmental profile o Sardinian sheep milk chees chain comparing industrial v artisanal systems.
Ceyhan et al (2020)	Estimation of greenhouse ga emissions and carbon footprin from a dairy sheep farm in th Nigde region (Turkey).	**Nunes et al (2020)**	Life-cycle assessment of regional sheep cheese produce in Portugal using a cradle-to gate approach.	**Vagnoni et al (2018)**	Analysis of environmenta implications of the transitio from semi-intensive to semi extensive production in Sardinian farm.
Cossu et al (2024)	Experimental implementatio of the "Made Green in Italy ecolabelling scheme on th hard sheep milk cheese suppl chain.	**Plaza et al (2021)**	Assessment of grazing leve influence on milk quality an carbon footprint indicators t identify management system in Spain.	**Vagnoni et al (2019)**	Definition of the SheepToShi LIFE strategy for GH mitigation and efficienc improvement in the Sardinia sheep supply chain.
Eldesouky e al.,(2018)	Assessment of carbo footprint in Spanis agroforestry systems t determine if extensificatio compensates for livestoc GHG emissions.	**Ravani et al (2024)**	Life cycle analysis compariso of semi-intensive and intensiv sheep milk production i Western Macedonia, Greece.	**Vagnoni et al (2024)**	Characterization o environmental performanc drivers of Sardinian shee farming systems including soi carbon sequestration.
Åby et a (2024)	Evaluation of GHG emission from Norwegian sheep mea production using a whole-far model.	**Cottle & Cowi (2016)**	Analysis of allocation method for GHG emissions betwee wool and meat in Australia sheep production.	**Yñez-Ruiz e al.,(2016)**	Review and analysis of GH emissions from specific non cow milk supply chain (buffalo, sheep, goats).
Ahlgren et a (2024)	Assessment of climate an biodiversity impacts o Swedish beef and lam production.	**Dakpo et a (2017)**	Assessment of GHG emission and eco-efficiency in Frenc sheep meat farming using DE and LCA.	**Zhang et al (2022)**	Study on the relationshi between low-carbon circula farming/animal husbandr

					models and human well-bein in China.
Argun & Çakmakcı (2024)	Determination of the carbo footprint of animal waste i Karaman province, Turkey.	**Davies et a (2021)**	Comparison of labou profitability, and carbo footprint of precision vs traditional sheep management	**Gill et al. (2009)**	Review of the role of domesti livestock in climate chang mitigation and global foo security.
Atzori et a (2015)	Economic and environmenta sustainability assessment o extensive dairy sheep farmin in Sardinia.	**Dougherty et a (2019)**	Quantification of carbon an blue water footprints of variou California sheep productio systems.	**Handler & Pearce (2022)**	LCA of agrivoltaic system integrating solar power wit pasture-based sheep and rabbi farming.
Audsley & Wilkinson (2014)	Analysis of the potential fo reducing national GH emissions from crop an livestock systems in the UK.	**Dyer et a (2014)**	Review and evaluation of foss energy use and GHG emission in Canadian agriculture (bee focus).	**Harrison et a (2014)**	Simulation of pastur management and ewe fecundit interventions to reduce GH emissions intensities.
Battacone et a (2021)	Effect of suckling managemen and ewe concentrate level o lamb meat carbon footprint i Sardinia.	**Eldesouky et a (2018)**	Comparison of carbo footprints between intensiv and extensive (Dehesa) bee and dairy sheep systems i Spain.	**Horrillo et a (2020)**	Analysis of organic farming a a strategy to reduce carbo footprint in Dehes agroecosystems.
Bhatt et a (2022)	Life cycle assessment (LCA) o the environmental performanc of the sheep sector in Ontario Canada.	**Farrell et a (2022)**	Modelling production, profi and GHG emissions of Iris sheep flocks with divergen genetic merit.	**Horrillo et a (2021)**	Assessment of GHG emissions carbon sequestration, an economic indicators in organi Dehesa farms.
Biswas et a (2010)	Comparison of global warmin contributions from whea sheep meat, and woo production in Victoria Australia.	**Geß et al. (2020**	LCA evaluation of lamb mea production in semi-extensiv vs. semi-intensive systems i Northern Italy.	**Hyland et a (2016)**	Evaluation of livestoc production efficienc improvements for reducin sectoral GHG emissions.
Cerrato et a (2023)	Evaluation of economic an environmental sustainability o livestock farms (sheep, goats cattle) in inland Italy.	**Geß et al. (2022**	Comparative life cycl perspective of lamb mea production systems in Turke and the EU.	**Ibidhi et a (2017)**	Assessment of water, land, an carbon footprints of sheep an chicken meat in Tunisia.

Ceyhan Sezgin (2020)	Estimation of the carbo footprint of a dairy shee farming enterprise in Niğd Turkey.	**Geß et al. (2023**	Circular economy an sustainability assessment c European lamb mea production systems.	**Jones et a (2014)**	Analysis of the carbon footprin of lamb in Wales, identifyin sources of variation an mitigation opportunities.
Lal et al. (2022	Life cycle assessment of shee production systems in semi arid Rajasthan, India.	**Mundus (Sarhan) (2013)**	Review of whole-farm GH models and LCA studies fo beef and dairy productio systems.	**Jones et a (2015)**	Development of farm-specifi marginal abatement cost curve (MACC) for sheep GH mitigation.
Ledgard et a (2011)	Carbon footprinting of Nev Zealand lamb from th perspective of an exportin nation.	**Nsabiyeze et a (2024)**	Integrated approach (DEA LCA) to mitigate GH emissions from shee production in China.	**Kilcline et a (2024)**	Integrated assessment of shee production systems and th agricultural value chain i Ireland.
Lin et al. (2015	Review comparin environmental impacts o cultured meat versu conventional livestock (bee sheep, pork).	**O’Brien et a (2016)**	LCA of the effect c intensification o environmental impacts c grass-based sheep farming.	**Ripoll-Bosch e al. (2013)**	Accounting for multi functionality in the carbo footprint of lamb i Mediterranean systems.
Lunesu et a (2025)	Estimation of net carbo footprint of dairy sheep farm using an indirect method fo soil C sequestration.	**Palomo et a (2024)**	Carbon footprint assessment c an extensively raised, low productivity sheep populatio (Segureña).	**Sarkar et a (2024)**	Estimation of the carbon cost o sheep grazing systems in semi arid India.
Mazzetto et a (2023)	Calculation of the carbo footprint of New Zealand bee and sheep meat exported t different markets.	**Pardo et a (2024)**	Carbon footprint c transhumant sheep farm accounting for natural baselin emissions.	**Schönbach et a (2012)**	Investigation of grazing effect on the GHG balance of temperate steppe ecosystem i Inner Mongolia.
McNicol et a (2024)	Prioritization of greenhous gas mitigation measures for th Welsh red meat secto (MACC).	**Patra (2017)**	Accounting of CH_4, nitrou oxide emissions, and carbo footprints of livestock in India states.	**Sharma et a (2018)**	Assessment of the effect o local climate and soil drainag on the environmental impact o grass-based milk.
McNicol et a (2024)	Analysis of the nutritiona value of meat in carbo footprint comparisons of lamb on different diets.	**Peri et al. (2020**	Carbon footprint assessment c lamb and wool production i Southern Patagonia.	**Shrivastava e al. (2025)**	Comprehensive LCA o Icelandic lamb productio focusing on global warmin and land use.

Meza-Herrera et al. (2022)	Review of small ruminar production, sustainability, an climate adaptability in th Americas.	**Recktenwald e al. (2024)**	LCA of GHG emissions fror diverse sheep productio systems (intensive t extensive) in the US.	**Silva et al. (2024**	Evaluation of carbon footprir mitigation potential i integrated olive and shee farming in Brazil.
Miralles et a (2024)	Assessment of environmenta impact and biodiversity c High Nature Value (HNV farming in Europe.	**Ridoutt (2021)**	Proposal of a radiative forcing based climate footprir approach for climate-neutra livestock.	**Thomas et a (2025)**	Assessment of the potential o seaweed feed supplements t reduce enteric CH4.
Mujica et a (2023)	Simulation-based approach t determine the carbon footprir of sheep systems in semi-ari Chile.	**Ripoll-Bosch e al. (2011)**	Comparison of GHG emission throughout the life cycle c three Spanish lamb-mea production systems.	**Toro-Mujica e al. (2017)**	Carbon footprint of shee production systems in semi arid Chile under differer rainfall scenarios.
Verduna et a (2020)	Sustainability assessmer (LCA & LCC) of four dair farming scenarios for Toma c Lanzo cheese.	**Study (Autho & Year)**	**Main Study Subject**	**Trasca et a (2024)**	Analysis of meat consumptio impact on climate change an the effect of consume awareness.
Villarreal-Ornelas (2022)	Review of environmental an socio-economic sustainabilit of small ruminants in Lati America.	**Åby et al. (2024**	Evaluation of GHG emission from Norwegian sheep mea production using a whole-farr model.	**Tsakiridis et a (2020)**	Environmental assessment o marine and agri-food sector using EIO-LCA.
Wang et a (2024)	Analysis of GHG emission from meat sheep production vs household consumption i Eurasian steppe.	**Ahlgren et a (2024)**	Assessment of climate an biodiversity impacts c Swedish beef and lam production.	**Dakpo et a (2017)**	Assessment of GHG emission and eco-efficiency in Frenc sheep meat farming using DE and LCA.
Wang et a (2025)	Investigation of GH emissions contributions fror sheep production in meado steppe regions.	**Argun & Çakmakcı (2024)**	Determination of the carbo footprint of animal waste i Karaman province, Turkey.	**Davies et a (2021)**	Comparison of labou profitability, and carbo footprint of precision vs traditional sheep management.
Wheeler et a (2013)	Technical manual fo calculating nutrient budget and GHG emissions in th OVERSEER model.	**Atzori et a (2015)**	Economic and environmenta sustainability assessment c extensive dairy sheep farmin in Sardinia.	**Dougherty et a (2019)**	Quantification of carbon an blue water footprints of variou California sheep productio systems.
Wiedemann e al. (2015)	LCA of sheep productio investigating co-production c	**Audsley & Wilkinson (2014)**	Analysis of the potential fo reducing national GH	**Dyer et al. (2014**	Review and evaluation of fossi energy use and GHG emission

	wool and meat in major globa producers.		emissions from crop an livestock systems in the UK.		in Canadian agriculture (bee focus).
Wiedemann e al. (2015)	Resource use an environmental impacts fror Australian beef and lam production (LCA).	**Battacone et a (2021)**	Effect of suckling managemer and ewe concentrate level o lamb meat carbon footprint i Sardinia.	**Eldesouky et al (2018)**	Comparison of carbo footprints between intensiv and extensive (Dehesa) bee and dairy sheep systems i Spain.
Worrall et a (2012)	Study of the carbon budget o peatlands under sheep grazin and managed burning.	**Bhatt et a (2022)**	Life cycle assessment (LCA) c the environmental performanc of the sheep sector in Ontaric Canada.	**Farrell et al (2022)**	Modelling production, profi and GHG emissions of Iris sheep flocks with divergen genetic merit.
Yetişgin et a (2022)	Comparison of farm-leve GHG emissions i transhumance and semi intensive sheep systems i Turkey.	**Biswas et a (2010)**	Comparison of global warmin contributions from whea sheep meat, and woc production in Victoria Australia.	**Geß et al. (2020**	LCA evaluation of lamb mea production in semi-extensiv vs. semi-intensive systems i Northern Italy.
Zervas & Tsiplakou (2016)	Assessment of GHG emission from small ruminant compared to large ruminant and monogastrics.	**Cerrato et a (2023)**	Evaluation of economic an environmental sustainability c livestock farms (sheep, goats cattle) in inland Italy.	**Geß et al. (2022**	Comparative life cycl perspective of lamb mea production systems in Turke and the EU.
Zhang et a (2024)	Modeling cost and carbo emission of shee transportation using pat optimization (Geneti Algorithm).	**Ceyhan & Sezgin (2020)**	Estimation of the carbo footprint of a dairy shee farming enterprise in Niğde Turkey.	**Geß et al. (2023**	Circular economy an sustainability assessment o European lamb mea production systems.
Zhang et a (2025)	Case study on implications o environmental constraints an opportunities for NZ livestock	**Cottle & Cowi (2016)**	Analysis of allocation method for GHG emissions betwee wool and meat in Australia sheep production.	**Gill et al. (2009)**	Review of the role of domesti livestock in climate chang mitigation and global foo security.
Horrillo et a (2020)	Analysis of organic farming a a strategy to reduce carbo footprint in Dehes agroecosystems.	**Ledgard et a (2011)**	Carbon footprinting of Nev Zealand lamb from th perspective of an exportin nation.	**Handler & Pearce (2022)**	LCA of agrivoltaic system integrating solar power wit pasture-based sheep and rabbi farming.

Horrillo et a (2021)	Assessment of GHG emissions carbon sequestration, an economic indicators in organi Dehesa farms.	**Lin et al. (2015)**	Review comparin environmental impacts c cultured meat versu conventional livestock (bee sheep, pork).	**Harrison et a (2014)**	Simulation of pastur management and ewe fecundit interventions to reduce GHG emissions intensities.
Hyland et a (2016)	Evaluation of livestoc production efficienc improvements for reducin sectoral GHG emissions.	**Lunesu et a (2025)**	Estimation of net carbo footprint of dairy sheep farm using an indirect method fc soil C sequestration.	**Mujica et a (2023)**	Simulation-based approach t determine the carbon footprin of sheep systems in semi-ari Chile.
Ibidhi et a (2017)	Assessment of water, land, an carbon footprints of sheep an chicken meat in Tunisia.	**Mazzetto et a (2023)**	Calculation of the carbo footprint of New Zealand bee and sheep meat exported t different markets.	**Mundus (Sarhan) (2013)**	Review of whole-farm GHG models and LCA studies fo beef and dairy productio systems.
Jones et a (2014)	Analysis of the carbon footprin of lamb in Wales, identifyin sources of variation an mitigation opportunities.	**McNicol et a (2024)**	Prioritization of greenhous gas mitigation measures for th Welsh red meat secto (MACC).	**Nsabiyeze et a (2024)**	Integrated approach (DEA - LCA) to mitigate GHG emissions from shee production in China.
Jones et a (2015)	Development of farm-specifi marginal abatement cost curve (MACC) for sheep GHG mitigation.	**McNicol et a (2024)**	Analysis of the nutritiona value of meat in carbo footprint comparisons of lamb on different diets.	**O'Brien et a (2016)**	LCA of the effect o intensification o environmental impacts o grass-based sheep farming.
Kilcline et a (2024)	Integrated assessment of shee production systems and th agricultural value chain i Ireland.	**Meza-Herrera et al. (2022)**	Review of small ruminan production, sustainability, an climate adaptability in th Americas.	**Palomo et a (2024)**	Carbon footprint assessment o an extensively raised, low productivity sheep populatio (Segureña).
Lal et al. (2022	Life cycle assessment of shee production systems in semi arid Rajasthan, India.	**Miralles et a (2024)**	Assessment of environmenta impact and biodiversity o High Nature Value (HNV farming in Europe.	**Pardo et a (2024)**	Carbon footprint o transhumant sheep farm accounting for natural baselin emissions.
Ridoutt (2021)	Proposal of a radiative forcing based climate footprin approach for climate-neutra livestock.	**Toro-Mujica e al. (2017)**	Carbon footprint of shee production systems in semi arid Chile under differen rainfall scenarios.	**Patra (2017)**	Accounting of CH4, nitrou oxide emissions, and carbo footprints of livestock in India states.

Ripoll-Bosch e al. (2011)	Comparison of GHG emission throughout the life cycle o three Spanish lamb-mea production systems.	**Trasca et a (2024)**	Analysis of meat consumptio impact on climate change an the effect of consume awareness.	**Peri et al. (2020**	Carbon footprint assessment o lamb and wool production i Southern Patagonia.
Ripoll-Bosch e al. (2013)	Accounting for multi functionality in the carbo footprint of lamb i Mediterranean systems.	**Tsakiridis et a (2020)**	Environmental assessment o marine and agri-food sector using EIO-LCA.	**Recktenwald e al. (2024)**	LCA of GHG emissions fron diverse sheep productio systems (intensive t extensive) in the US.
Sarkar et a (2024)	Estimation of the carbon cost o sheep grazing systems in semi arid India.	**Verduna et a (2020)**	Sustainability assessmen (LCA & LCC) of four dair farming scenarios for Toma c Lanzo cheese.	**Wiedemann e al. (2015)**	LCA of sheep productio investigating co-production o wool and meat in major globa producers.
Schönbach e al. (2012)	Investigation of grazing effect on the GHG balance of temperate steppe ecosystem i Inner Mongolia.	**Villarreal-Ornelas (2022)**	Review of environmental an socio-economic sustainabilit of small ruminants in Lati America.	**Wiedemann e al. (2015)**	Resource use an environmental impacts fron Australian beef and laml production (LCA).
Sharma et a (2018)	Assessment of the effect o local climate and soil drainag on the environmental impact o grass-based milk.	**Wang et a (2024)**	Analysis of GHG emission from meat sheep production vs household consumption i Eurasian steppe.	**Worrall et a (2012)**	Study of the carbon budget o peatlands under sheep grazin and managed burning.
Shrivastava e al. (2025)	Comprehensive LCA o Icelandic lamb productio focusing on global warmin and land use.	**Wang et a (2025)**	Investigation of GH emissions contributions fror sheep production in meadov steppe regions.	**Yetişgin et a (2022)**	Comparison of farm-leve GHG emissions i transhumance and semi intensive sheep systems i Turkey.
Silva et a (2024)	Evaluation of carbon footprir mitigation potential i integrated olive and shee farming in Brazil.	**Wheeler et a (2013)**	Technical manual fo calculating nutrient budget and GHG emissions in th OVERSEER model.	**Zervas & Tsiplakou (2016**	Assessment of GHG emission from small ruminant compared to large ruminant and monogastrics.
Thomas et a (2025)	Assessment of the potential o seaweed feed supplements t reduce enteric CH4.			**Zhang et a (2024)**	Modeling cost and carbo emission of shee transportation using pat optimization (Geneti Algorithm).

Zhang et a **(2025)**	Case study on implications o environmental constraints an opportunities for NZ livestock

CHAPTER 2

Carbon Footprint Benchmarking in European Sheep Farming: The LIFE Green Sheep Framework and Farm Profiling Approach

Abstract

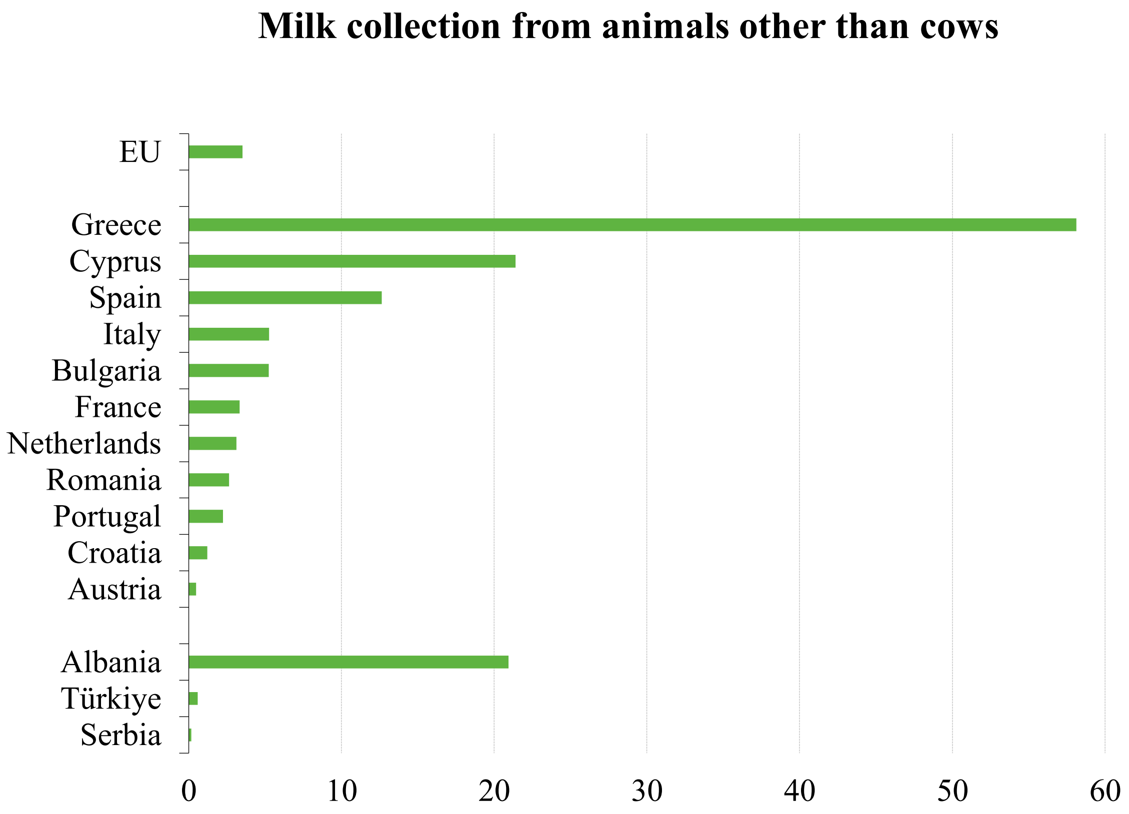
This chapter frames carbon footprint (CF) assessment as a decision-support asset for European sheep farming within the LIFE Green Sheep framework, where comparability and actionability are prerequisites for scalable mitigation. The analysis adopts a harmonised benchmarking logic across tools and countries, using kg FPCM (milk) and kg CW (meat) as functional units, and operationalises an intra-national profiling approach to translate emission heterogeneity into farm-level levers. For French dairy sheep farms, emission intensity (Total GHG emissions, CO_2 kg FPCM) was profiled via k-means clustering on the response variable, supported by nonparametric mean comparisons, correlation analysis, and PLSR with VIP to handle collinearity and prioritise drivers. Results show that low- vs high-intensity farms are primarily differentiated by production efficiency, with markedly higher FPCM output per ewe in the low-intensity cluster and higher pasture days and purchased concentrate share in the high-intensity cluster. Correlation and PLSR consistently identify FPCM (kg/yr/ewe) as the dominant predictor (strong negative association), with additional contributions from concentrate use, lambing rate, and grazing pattern. Within-system analyses (extensive and intensive) confirm that, even under the same production-system label, emission intensity depends on the ability to convert inputs into output. Finally, a residual-based approach (controlling for herd size and production level) indicates that differences persist beyond scale and production, highlighting additional management signals linked to milk composition, forage purchasing, pasture, and nitrogen management.

Keywords

Carbon footprint; Life Cycle Assessment (LCA); dairy sheep; benchmarking; emission intensity; FPCM; k-means clustering; partial least squares regression (PLSR); variable importance in projection (VIP).

Introduction

In the context of the contemporary debate on the sustainability of agricultural and livestock systems, reducing climate-changing emissions is not only a policy objective but also an operational requirement that directly affects farm management and the competitiveness of supply chains (Atzori et al., 2022). In this context, the carbon footprint (CF) is emerging as a synthetic indicator increasingly used to identify areas of higher emissions along the production process, guiding improvement strategies based on empirical evidence (Eldesouky et al., 2018). This approach is particularly relevant in the sheep sector, as European farms operate in highly heterogeneous conditions: there are systems strongly linked to grazing and marginal and mountain areas, but also more structured farms, with different levels of intensification, purchased inputs and productivity. The direct consequence of this phenomenon is that emission intensity (kg CO_2eq per unit of product) can vary significantly not only between countries, but also within the same country, depending on the combination of available resources, feed choices, stocking density, grazing management, energy consumption and production performance (Morgan and Davies et al., 2021). The variability of sheep farming systems in the European Union is clearly evident from a joint analysis of products and markets, as the supply chain is divided into two main outputs, meat and milk, associated with distinct production and territorial models, The production of meat, milk and sheep's cheese for the countries participating in the project are shown in Figures 3, 4 and 5. At EU level, the meat supply chain has different orientations that reflect distinct production models. The "heavy lamb" segment is typically associated with Irish systems, characterised by high slaughter weights of around 45 kg (O'Brien et al., 2016). "Light lamb”, on the other hand, is more common in southern regions, with weights of around 10 kg (e.g. in Italy) (Battacone et al., 2021). Spain and France have more mixed configurations, with average weights of 22 kg (Ripoll-Bosch et al., 2013). This element does not concern terminology, but translates into different practices, such as age and slaughter weight, seasonality of births, diet composition and land management. These factors can potentially generate different emission profiles. As highlighted by Ripoll-Bosch et al. (2013) and Battacone et al. (2021), these structural differences make it difficult to directly compare environmental impacts, as emission efficiency per kg of meat tends to vary significantly between light Mediterranean lamb and heavy continental lamb. In the case of milk, geographical specialisation is particularly evident: production from small ruminants is of considerable importance in Mediterranean regions and in some key countries. According to Eurostat (2026), countries such as Spain, Greece, France and Italy are among the main EU producers of sheep's and goat's milk, confirming the centrality of these contexts for the dairy supply chains. In line with this trend, a review of the relevant literature indicates that dairy farms are mainly located in the Mediterranean (and Black Sea) regions, as shown in Figure 1. In addition, a significant percentage of sheep's milk is supplied to the processing industry, giving rise to traditional cheeses, often with protected designation of origin (PDO), which have a direct impact on the organisation of the supply chain and on management decisions at farm level (Pulina et al., 2018). In this context, differences in market position translate into technical variations, such as the role of grazing during the year, the degree of integration with concentrated feed, decisions regarding reproductive management and productivity per head, with possible consequences on the emission intensity expressed per kg of corrected milk (FPCM) (Batalla et al., 2015; Vagnoni et al., 2015). In this context, the meat sector confirms the concentration of production in a few countries, as shown in Figure 2, confirming the need for a multinational comparative analysis to interpret the differences in production systems and, potentially, the differences in emission intensity (Eurostat, 2026). The European Commission (2026) provides an explicit description of this product and market differentiation in its sector documentation, establishing a useful reference for understanding the diversity of systems on which the LIFE Green Sheep project (LIFE19 CCM/FR/001245) is based.



Source: Eurostat (online data code: apro_mk_pobta)

Figure 2. Milk collection from animals other than cows (% of total milk delivered to dairies, 2024)

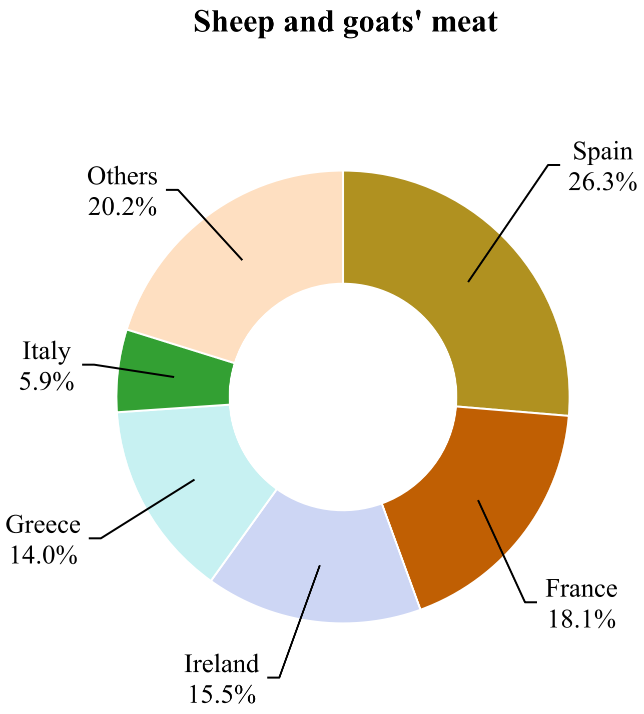


Figure 3. Source: Eurostat 2026 (online data code: apro_mt_pann)

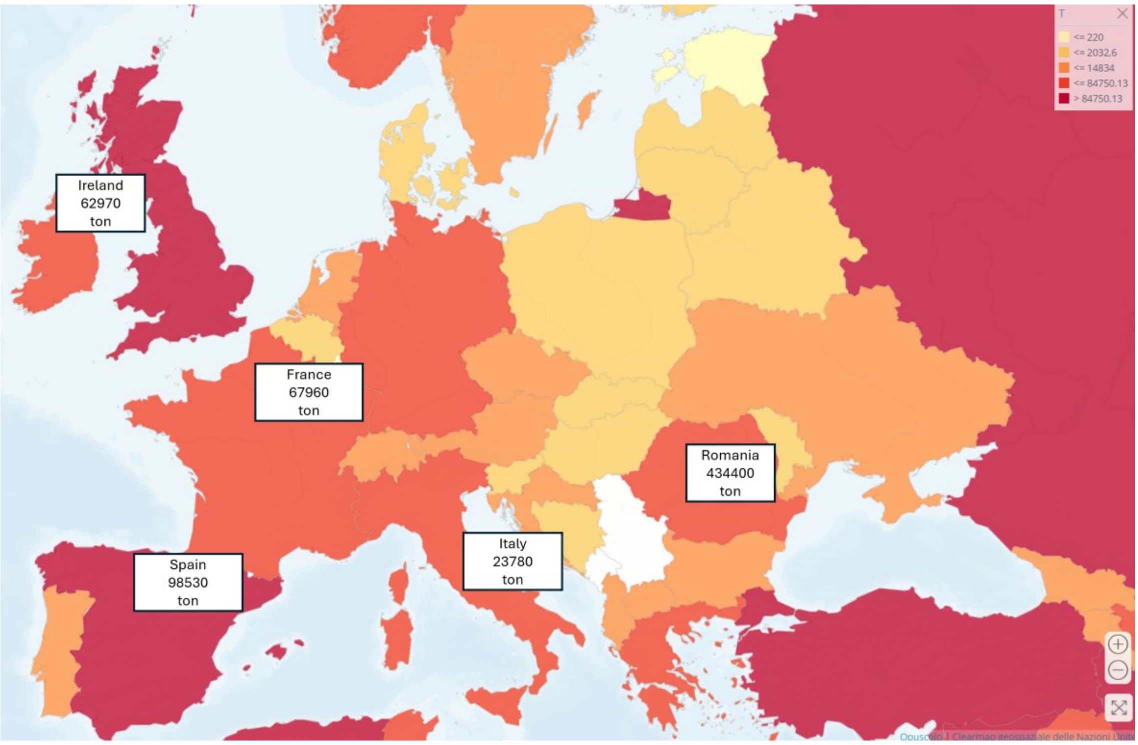


Figure 4. Quantity of sheep meat production, fresh or chilled by country 2024, FAOSTAT 2026

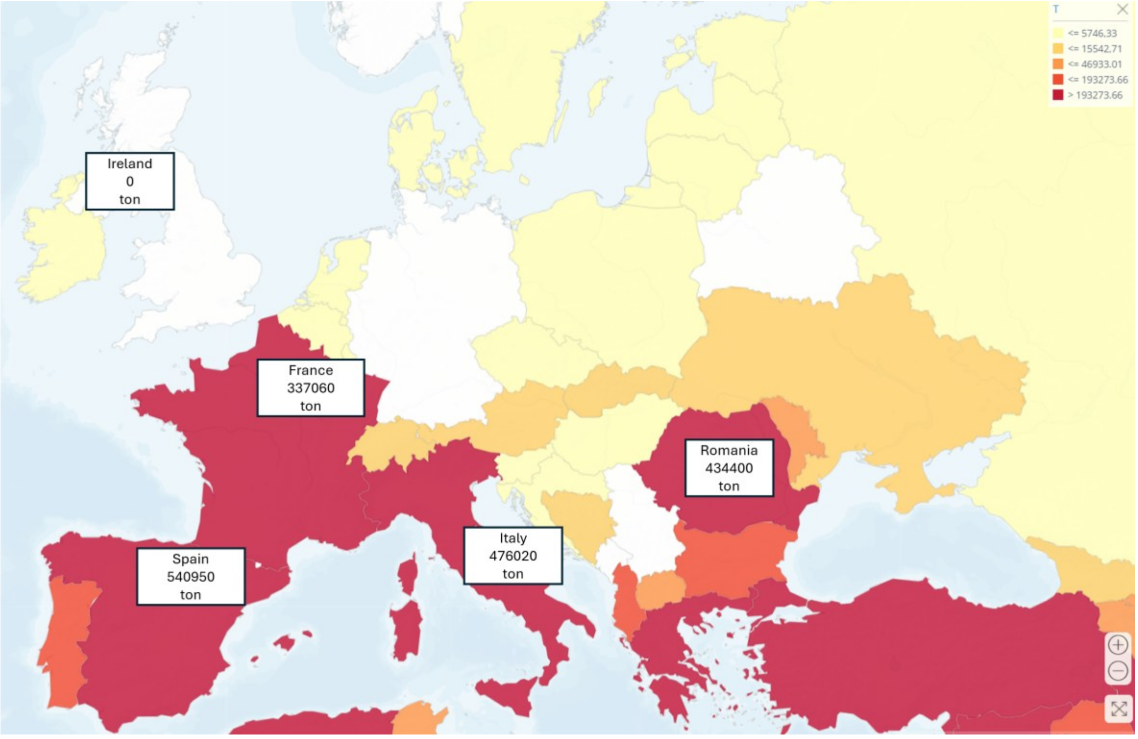


Figure 5. Quantity of raw sheep milk production by country 2024, FAOSTAT 2026

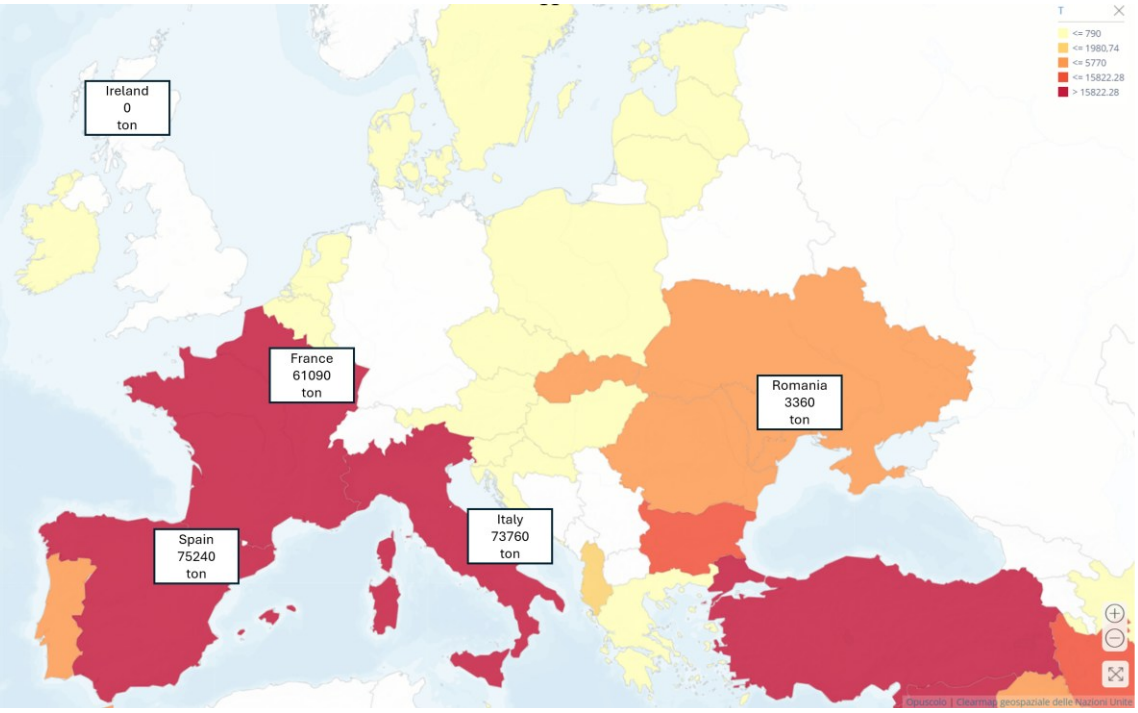


Figure 6. Production quantities of sheep milk cheese, fresh or processed by country 2023 – 2024, FAOSTAT 2026

In this context, the issue is not only the quantity of emissions generated by livestock farming, but also the ability to assess these emissions in a comparable way across different production contexts. In recent years, simplified tools (ST) have emerged precisely to balance scientific rigor with large-scale applicability, particularly for broad mitigation planning, benchmarking, and farm-level decision support (Arulnathan et al., 2020; MacPherson et al., 2020). These tools generally rely on secondary or aggregated farm data, such as herd size, milk deliveries, simplified diets, and total fuel and fertilizer use, and in some cases also allow direct farmer data entry (Hillier et al., 2011; Pirlo and Carè, 2013; Tuomisto et al., 2015; Aguirre-Villegas and Larson, 2017). Their main focus is typically on the major emission hotspots of livestock systems, particularly enteric fermentation, manure management, feed production, feed purchasing, and direct energy and fuel use, which together account for the largest share of total emissions (Sykes, 2019; Tamilselvan and Tyagi, 2024; Gislon et al., 2025). As a result, ST are now widely used to provide rapid farm-level diagnoses, support "what-if" analyses and decision support systems, and enable relatively low-cost benchmarking (Murphy et al., 2013; Sykes et al., 2017; Alexandropoulos et al., 2021; Thumba et al., 2022). At the same time, alignment with internationally recognized frameworks such as ISO 14067 and PAS 2050 remains essential, especially where results are intended to support Environmental Product Declarations or carbon market applications (Savva et al., 2025; Samad et al., 2025).

The development of these tools has followed a progressive evolution. Early ST, particularly after 2011, were mainly designed for policy support and global-scale modelling. Among the best-known examples, the Cool Farm Tool integrates greenhouse gas, biodiversity, and water indicators for cattle, sheep, and goats using IPCC Tier 1–2 approaches (Hillier et al., 2011). Between 2015 and 2025, a second generation of consultancy-oriented platforms expanded the scope of analysis through Tier 2-based approaches. AgRE Calc, for example, estimates GHG emissions together with nutrient efficiency and carbon sequestration, while CAP'2ER in France and ARDICARBON in Spain apply dual-level diagnostics to assess GHG emissions, nitrogen losses, energy use, soil condition, and ecosystem services (Sykes et al., 2017; Atzori et al., 2022a). At the global level, GLEAM-I provides a standardized cradle-to-retail LCA framework based on IPCC Tier 2, covering multiple livestock species and expressing emissions per kilogram of protein (FAO, 2022).

However, despite this progress, several tools remain partial in terms of species coverage or analytical scope. LatteGHG, LATT€CO_2, and HerdUp are mainly focused on dairy cattle, Carbon Navigator targets beef and dairy systems, and Holos includes cattle and sheep but lacks goat modules (Pirlo and Carè, 2013; Murphy et al., 2013; Thumba et al., 2022; Gislon et al., 2025). In contrast, CarbonSheep, CarbonGoat, and the sheep net method were developed specifically for small ruminants, alongside more recent approaches tailored to pastoral systems (Atzori et al., 2021; Ocak Yetişgin et al., 2022; Lunesu et al., 2025; Tziolas et al., 2025). More recent digital developments have further encouraged the diffusion of ST, as shown by platforms such as FARMBENV, which integrates real-time sensors with Ecoinvent-based inventories, Farmanagers®, an RFID-based management system for dairy sheep and goats, and FarmLCA, which applies a cradle-to-farm gate approach integrating Impact World+ and Ecological Scarcity 2021 (Savva et al., 2025; Moakes et al., 2026; Fotiadis et al., 2026).

Nevertheless, the growing diffusion of ST does not automatically solve the problem of comparability. Many tools are still based on settings, databases, and assumptions adapted to specific national or regional contexts. It can therefore be inferred that, even when starting from the same emission processes—such as enteric CH_4, manure management, fertilization and nitrogen flows, feed production and purchase, and direct energy use—the results may not be fully comparable if system boundaries, emission factors, data granularity, allocation rules, and functional units differ, as extensively documented in the literature (Eldesouky et al., 2018; Mundus et al., 2013). Furthermore, the use of methodologies with different levels of detail, such as Tier 1 versus Tier 2, can generate substantial discrepancies in final estimates even when analysing the same biological and technical processes (Argun et al., 2024). This limitation is particularly relevant for small ruminants, for which validation remains scarcer than for cattle, and where physiological and dietary differences affecting parameters such as Ym are still not always adequately captured (Atzori et al., 2017; Atzori et al., 2022a; Gras and Dragomir, 2024; Reyes-Palomo et al., 2025). In addition, most currently available tools still lack automated mitigation recommendation engines and only partially account for the effects of feed additives, thereby limiting their direct utility for farm-level management (Alexandropoulos et al., 2023; Thumba et al., 2022). In other words, comparability depends not only on actual differences among production systems, but also on the way in which such differences are represented and calculated. The LIFE Green Sheep project was designed with the specific aim of addressing this critical issue. According to the European Commission's LIFE Public Database, the project is designed as a demonstration and dissemination action with the aim of reducing the CF of sheep farming. The project develops a common approach applicable to both milk and meat production and supports the adoption of mitigation practices. The project is based on an operational framework that includes monitoring, training and action plans. The LIFE documentation sets out the overall objective of reducing the CF by 12% in the five target countries (France, Ireland, Italy, Romania and Spain) and outlines an implementation model that integrates an observatory, demonstration farms and innovative farms, advisor training and activities to compare the available tools. A key component of this analysis is the comparison and harmonisation of tools, highlighting how calculators, while converging in principle, are still partly adapted to national contexts. (Life Green Sheep, 2026). LIFE Green Sheep should not be interpreted as a simple “calculation project”, but as an initiative that attempts to transform CF assessment into an effective management tool: the diagnosis must generate measurable actions and these actions must be monitored. However, for this logic to be applied at European level, the differences between systems need to be made explicit and the technical and structural factors driving emission intensity need to be understood. The preliminary results of the project already show preliminary evidence at European level, revealing marked variability between countries and, in particular, substantial variability within countries, as well as a significant effect of the choice of functional unit and level of intensification in the comparative reading of performance (Life Green Sheep, 2026). This result is relevant from both a methodological and operational point of view: if the systems are not homogeneous, reasoning exclusively in terms of “national averages” is ineffective, as there is a risk of losing the extreme profiles, precisely those on which it is most effective to intervene. In light of this, this chapter aims to verify whether there are structural and managerial similarities and differences in the farming systems of the participating countries, and to what extent these differences may influence emission intensity. In order to ensure consistency with the multi-output nature of the sheep sector and the comparability of the supply chain, the analysis considers two main functional units: kg of FPCM for systems with milk output (kg of milk corrected for fat and protein) and kg of CW for systems with meat output (carcass weight). This choice allows the results to be interpreted in a way that is directly linked to farm decisions and actual outputs, avoiding the flattening of different systems into a single metric and maintaining readability for both production components.

The objective is to identify which inputs enable emissions reduction for each system, classifying farms according to their emissions intensity in order to obtain precise operational indications on “what to mitigate” and “how to do it”, distinguishing between generalisable measures and measures that must be adapted to the production profile, considering:

1. What are the characteristics of high- and low-intensity farms?
2. What factors explain why some farms have high or low emissions and which variables (inputs) are most decisive in terms of intensity?
3. Given the same production system, why do some farms have high emissions and others low emissions, and which inputs determine these differences within the same type?
4. Given the same level of production, which inputs determine emissions and how are they linked to yields (who emits a lot with low yields; who emits little with high yields)?

To answer these questions, an intra-national profiling approach was adopted, which aims to identify clusters of emission intensity and link them to structural and technical indicators that can be measured in the farm (e.g. animal load and surface area, days at pasture, purchase of concentrates, fodder self-sufficiency, direct energy consumption, nitrogen pressure, productivity per head). This approach has two added values. On the one hand, it allows for the identification of “common core” mitigation levers, i.e.

interventions that tend to be robust and transferable to multiple contexts. On the other hand, it allows us to identify when the heterogeneity of systems requires customised solutions: not all farms have the same structure, the same land constraints or the same room for manoeuvre, and therefore effective mitigation must be compatible with the actual conditions in which the farm operates.

Materials and methods

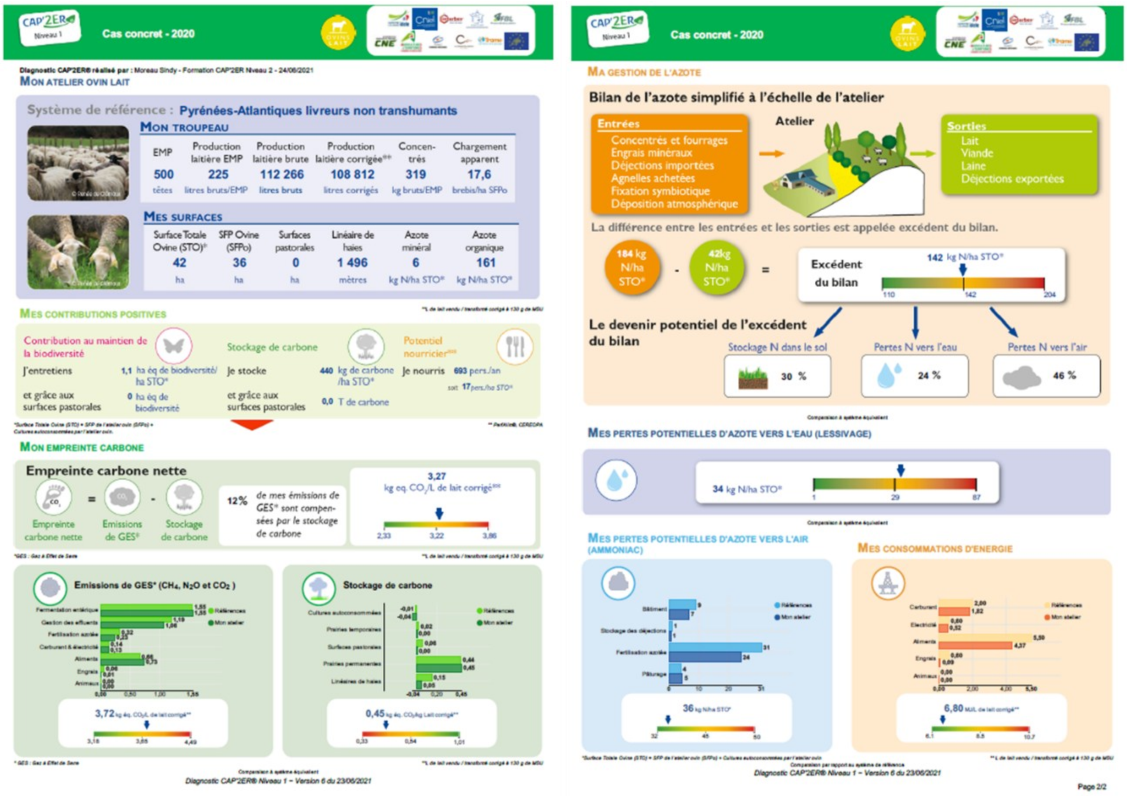
Among the initiatives aimed at harmonising the assessment of the carbon footprint in European sheep farming, the LIFE Green Sheep project (LIFE19 CCM/FR/001245) provides a useful framework for comparing the various national calculation approaches. This chapter examines four tools: CAP’2ER/DEO (France), Sheep LCA (Ireland), ArdiCarbon (Spain) and CarbonSheep (Italy). All tools are based on greenhouse gas estimation approaches consistent with the IPCC (2006) guidelines for livestock systems, and have been updated to account for subsequent refinements by the IPCC (2019). Furthermore, each tool includes country-specific algorithms and equations to represent national production conditions and farm structures. The comparison focused on the following methodological components: operational scale (territorial, farm-level or other), input data requirements (livestock, crops/land and farm management), system boundaries, emissions quantification approach (including IPCC reference and tier), impact categories considered, outputs generated, functional units adopted and inclusion of carbon sequestration. The main characteristics of the four tools are summarised in Table 1.

CAP'2ER®/DEO (France)

Sheep farming in France is organised around a grazing model, with production concentrated mainly in three southern regions (Pyrénées-Atlantiques, Aveyron and Corsica) and a supply chain strongly oriented towards cheese production: around 90% of the milk collected is used to make cheese, including PDO products. (FranceAgriMer, 2026) The cycle is structurally seasonal (lambing and grazing dynamics), and this seasonality is also reflected in the rules of the supply chain, for example in the specifications (Roquefort), (INAO, 2026). Alongside grazing-centred systems, there are more intensive variants with greater use of winter stabling and preserved fodder (silage/hay), with a return to grazing in spring, (Idele, 2026)

For meat, the French system remains strongly grazing-based and territorial, also for the enhancement of "difficult" areas. At sector level, it is characterised by high forage (~96%) and energy (~88%) autonomy, with grass as the main resource (~82% of the average ration of suckling ewes), (FranceAgriMer, 2026). Operationally, systems geared towards the enhancement of grasslands coexist with systems for the production of lambs in barns ("agneaux en bergeries") (FranceAgriMer, 2026).

CAP'2ER® is a calculation tool developed to quantify the environmental footprint of livestock farms, with a primary focus on the CF of sheep production (milk and meat) according to a cradle-to-farm-gate approach. The model in question allows both the gross footprint and the net footprint (gross footprint minus carbon sequestration) to be estimated, and broadens the reading to include additional impact categories and performance indicators (e.g. energy consumption, air and water quality, biodiversity). Within the application context, CAP'2ER® is not limited to acting as a calculator, but is configured as a decision-making framework that assists farms in positioning themselves with respect to reference standards and in identifying levers for improvement, ensuring an integrated reading of environmental, economic and social dimensions. From an operational point of view, CAP'2ER® is divided into two levels of assessment. Level 1 is a simplified web version designed for rapid and scalable diagnosis (target audience: farmers, consultants, students), while Level 2 is a more "decision-support" tool for consultants, geared towards detailed assessment and the definition of improvement measures. In the context of the LIFE Green Sheep project, Level 1 is associated with demonstration farms, as illustrated in Figure 6, while Level 2 is associated with innovative farms, in line with an approach of increasing information intensity. In terms of input, CAP'2ER® collects technical data on flock structure and animal categories, milk and meat production, housing and grazing times, crop and grazing areas and destinations, feed purchases (forage and concentrates), fertilisation (mineral and organic) and energy consumption (fuel and electricity). Level 1 operates on a more compact set of inputs (sheep unit scale), while Level 2 significantly increases the level of detail (farm scale, with more modules and a more detailed description of animals, crops, waste and agroecological infrastructure). From a methodological point of view, the tool is based on the IPCC guidelines (2006) and subsequent refinements (2019), integrating algorithms and equations adapted to the French context. The emissions estimate includes: enteric CH_4, CH_4 and N_2O from waste management, emissions related to fertilisation and cultivation practices, as well as emissions associated with external inputs (purchased feed, energy). With regard to “upstream” factors and the emission profiles of purchased inputs, the tool uses specific databases (e.g. Ecoalim and Ecoinvent), while for some emission components (e.g. ammonia) it refers to estimation systems such as EMEP. The allocation of emissions is determined on the basis of biophysical considerations, in order to distribute the impact among co-products (milk/meat, and where applicable wool). For the milk component, the functional unit is expressed as corrected milk (FPCM), while for meat, the functional unit is referred to kg of CW.



CAP'2ER Niveau 1 — Cas concret - 2020

Diagnostic CAP'2ER® réalisé par : Moreau Sindy - Formation CAP'2ER Niveau 2 - 24/06/2021

MON ATELIER OVIN LAIT

Système de référence : **Pyrénées-Atlantiques livreurs non transhumants**

MON TROUPEAU

EMP	Production laitière EMP	Production laitière brute	Production laitière corrigée**	Concen-trés	Chargement apparent
500	225	112 266	108 812	319	17,6
têtes	litres bruts/EMP	litres bruts	litres corrigés	kg bruts/EMP	brebis/ha SFPo

MES SURFACES

Surface Totale Ovine (STO)*	SFP Ovine (SFPo)	Surfaces pastorales	Linéaire de haies	Azote minéral	Azote organique
42	36	0	1 496	6	161
ha	ha	ha	mètres	kg N/ha STO*	kg N/ha STO*

MES CONTRIBUTIONS POSITIVES

Contribution au maintien de la biodiversité
J'entretiens 1,1 ha éq de biodiversité/ha STO*
et grâce aux surfaces pastorales 0 ha éq de biodiversité

Stockage de carbone
Je stocke 440 kg de carbone /ha STO*
et grâce aux surfaces pastorales 0,0 T de carbone

Potentiel nourricier***
Je nourris 693 pers./an
soit 17 pers./ha STO*

*Surface Totale Ovine (STO) = SFP de l'atelier ovin (SFPo) + Cultures autoconsommées par l'atelier ovin.

MON EMPREINTE CARBONE

Empreinte carbone nette

Empreinte carbone nette = Emissions de GES* - Stockage de carbone

12% de mes émissions de GES* sont compensées par le stockage de carbone

3,27 kg eq. CO$_2$/L de lait corrigé**

*GES : Gaz à Effet de Serre

*GES : Gaz à Effet de Serre

Comparaison à système équivalent

Diagnostic CAP'2ER® Niveau 1 – Version 6 du 23/06/2021

CAP'2ER Niveau 1 — Cas concret - 2020

MA GESTION DE L'AZOTE

Bilan de l'azote simplifié à l'échelle de l'atelier

Entrées
Concentrés et fourrages
Engrais minéraux
Déjections importées
Agnelles achetées
Fixation symbiotique
Déposition atmosphérique

Atelier

Sorties
Lait
Viande
Laine
Déjections exportées

La différence entre les entrées et les sorties est appelée excédent du bilan.

184 kg N/ha STO* - 42kg N/ha STO* = Excédent du bilan 142 kg N/ha STO*

Le devenir potentiel de l'excédent du bilan

Stockage N dans le sol 30 %

Pertes N vers l'eau 24 %

Pertes N vers l'air 46 %

Comparaison à système équivalent

MES PERTES POTENTIELLES D'AZOTE VERS L'EAU (LESSIVAGE)

34 kg N/ha STO*

Comparaison à système équivalent

MES PERTES POTENTIELLES D'AZOTE VERS L'AIR (AMMONIAC)

MES CONSOMMATIONS D'ENERGIE

*Surface Totale Ovine (STO) = SFP de l'atelier ovin (SFPo) + Cultures autoconsommées par l'atelier ovin

**L de lait vendu / transformé corrigé à 130 g de MSU

Comparaison par rapport au système de référence

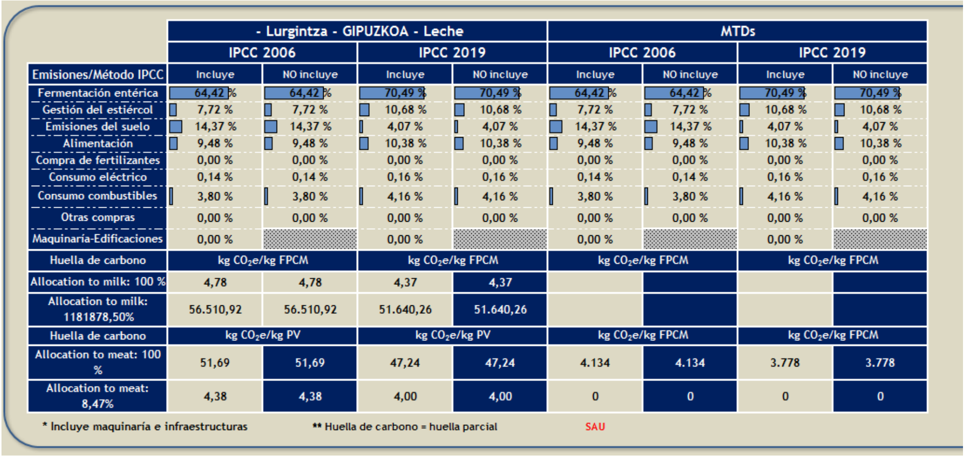
Diagnostic CAP'2ER® Niveau 1 – Version 6 du 23/06/2021

Page 2/2

Figure 7. CAP'2ER® Level 1: Results presentation

ArdiCarbon (Spain – NEIKER)

Sheep farming in Spain is strongly linked to local grazing resources and is commonly managed according to semi-extensive to extensive schemes, in which grazing is the fundamental pillar of nutrition and is supplemented, when necessary, by preserved fodder and concentrated supplements, especially in the advanced stages of gestation and during milk production, with a gradual shift towards a higher percentage of grazing as spring progresses. The production cycle is structurally seasonal: official monitoring shows a clear cyclical/seasonal trend in sheep milk production, with higher production volumes from March to July and reduced supply in autumn-winter (which is also reflected in price trends). At the regional level, dairy sheep are heavily concentrated in a few regions, particularly Castilla-La Mancha and Castilla y León, which effectively serve as the main operational centres of the Spanish sheep milk production chain (Herrera et al., 2017). ArdiCarbon is a calculator developed to estimate the CF of sheep farms using a cradle-to-farm-gate approach. It is designed to work with realistic farm data and return results that can be read in both ‘quick diagnosis’ and more analytical modes. From an operational point of view, the interface is configured as a spreadsheet and the results are displayed via a dashboard at various levels of disaggregation (from summary level to “investigation” level), in order to make the major contribution of each component to the overall impact immediately apparent. In terms of inputs, ArdiCarbon requires information on the location of livestock (to characterise the climatic context), its size and dynamics (beginning/end of year, categories and weights), the days on the farm and the periods of stabling, the management of excrement (including the proportion in yards and on pasture), the crop plan and areas, milk and meat production, purchases of fodder and concentrates, fertilisation and energy consumption. A distinctive feature relevant to its applicability “in the field” is the dual mode of feed management: when total intake is known, it can be entered directly (Method 1), otherwise the tool allows it to be reconstructed from feed purchases (Method 2), maintaining a single consistent line of compilation. From a methodological point of view, the tool integrates IPCC references (2006/2019) with national parameters and documentation, and includes explicit modules for the management of nitrogen and waste system emissions (e.g. NH_3 and N_2O throughout the various stages), in addition to upstream components (feed, fertilisers, energy) based on dedicated databases. With a view to European comparability, ArdiCarbon explicitly allows for the estimation of a “net” CF, including carbon sequestration. The structured logic considers changes in C stocks (20-year horizon) and distinguishes the contributions of natural infrastructure (trees, shrubs and low elements). The tool calculates the CF per 1 kg of FPCM milk or per 1 kg of meat (live weight) and, on request, can also include additional contributions relating to machinery and infrastructure, as shown in Figure 7.



	- Lurgintza - GIPUZKOA - Leche				MTDs			
	IPCC 2006		IPCC 2019		IPCC 2006		IPCC 2019	
Emisiones/Método IPCC	Incluye	NO incluye	Incluye	NO incluye	Incluye	NO incluye	Incluye	NO incluye
Fermentación entérica	64,42 %	64,42 %	70,49 %	70,49 %	64,42 %	64,42 %	70,49 %	70,49 %
Gestión del estiércol	7,72 %	7,72 %	10,68 %	10,68 %	7,72 %	7,72 %	10,68 %	10,68 %
Emisiones del suelo	14,37 %	14,37 %	4,07 %	4,07 %	14,37 %	14,37 %	4,07 %	4,07 %
Alimentación	9,48 %	9,48 %	10,38 %	10,38 %	9,48 %	9,48 %	10,38 %	10,38 %
Compra de fertilizantes	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %
Consumo eléctrico	0,14 %	0,14 %	0,16 %	0,16 %	0,14 %	0,14 %	0,16 %	0,16 %
Consumo combustibles	3,80 %	3,80 %	4,16 %	4,16 %	3,80 %	3,80 %	4,16 %	4,16 %
Otras compras	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %
Maquinaría-Edificaciones	0,00 %		0,00 %		0,00 %		0,00 %	
Huella de carbono	kg CO_2e/kg FPCM		kg CO_2e/kg FPCM		kg CO_2e/kg FPCM		kg CO_2e/kg FPCM	
Allocation to milk: 100 %	4,78	4,78	4,37	4,37				
Allocation to milk: 1181878,50%	56.510,92	56.510,92	51.640,26	51.640,26				
Huella de carbono	kg CO_2e/kg PV		kg CO_2e/kg PV		kg CO_2e/kg FPCM		kg CO_2e/kg FPCM	
Allocation to meat: 100 %	51,69	51,69	47,24	47,24	4.134	4.134	3.778	3.778
Allocation to meat: 8,47%	4,38	4,38	4,00	4,00	0	0	0	0

* Incluye maquinaría e infraestructuras

** Huella de carbono = huella parcial

SAU

Figure 8. Ardicarbon main output.

Sheep LCA (Ireland – Teagasc)

Irish sheep farmers rely mainly on grass as their primary source of feed and try to match grass production to the nutritional requirements of their sheep. Lowland farmers breed their ewes in October and November, and the lambs are born in the spring. Breeding ewes are brought indoors a few weeks before lambing, between late February and early March, and fed silage and/or hay, supplemented with concentrated feed. After lambing, the ewes and their lambs are returned to pasture and fed concentrated feed for a short period. Lambs are usually weaned at 12 weeks of age and sold between four and six months of age, when they reach a target live weight of around 45 kg. Mountain sheep farmers have a similar operating system, although they breed their sheep a few weeks later than lowland sheep farmers and the lambs are born in mid-April, as grass growth in mountain areas starts later (O'Brien et al., 2016). Sheep LCA is an LCA model designed to consistently describe Irish sheep farming systems, which are typically grass-based, over a production year and with cradle-to-farm-gate boundaries that include both emissions generated by breeding and feeding, and indirect emissions associated with the production and transport of purchased inputs (fertilisers, lime, pesticides, concentrates, chemicals, fuels and energy). In terms of application, the tool is configured to transform farm management into a robust impact estimate by calculating emissions across five animal subcategories (adult ewes, lambs, replacement ewes, hoggets, rams) and aggregating the contributions to obtain a CF per functional unit and the total footprint of the farm. This system makes the model particularly suitable for highlighting the management levers typical of seasonal systems (grazing/housing) and for operationally linking reproductive and productive performance with emission intensity. In terms of data requirements, Sheep LCA has a relatively high demand for information, as it operates with detailed information on farm structure (size, grazing and housing dates, winter conditions), performance and reproduction (number of mated ewes, barren rates, lambing/weaning rates, lambing patterns, replacement ewes), animal movements (purchases/sales), inputs (fertilisers, feed, fuel, third-party services) and main outputs (meat and wool) on a monthly basis. The equations applied are derived from IPCC recommendations and national studies, with an approach consistent with decision-making at farm level. The output indicator for meat is typically expressed in terms of kg CO_2 eq/kg live weight, kg CO_2 eq/kg cull weight, in addition to total farm emissions. In the context of the project, Sheep LCA is one of a number of tools which, in addition to CF, include a more extensive set of indicators and carbon sequestration estimates (unlike tools focused exclusively on CF, Figure 8).

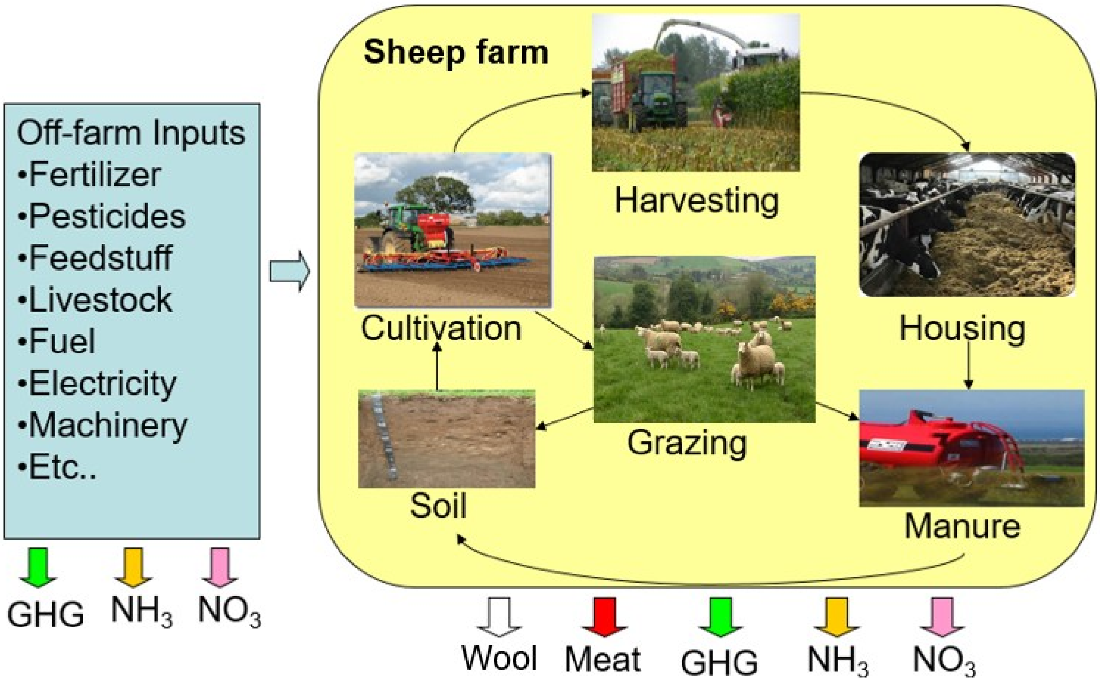
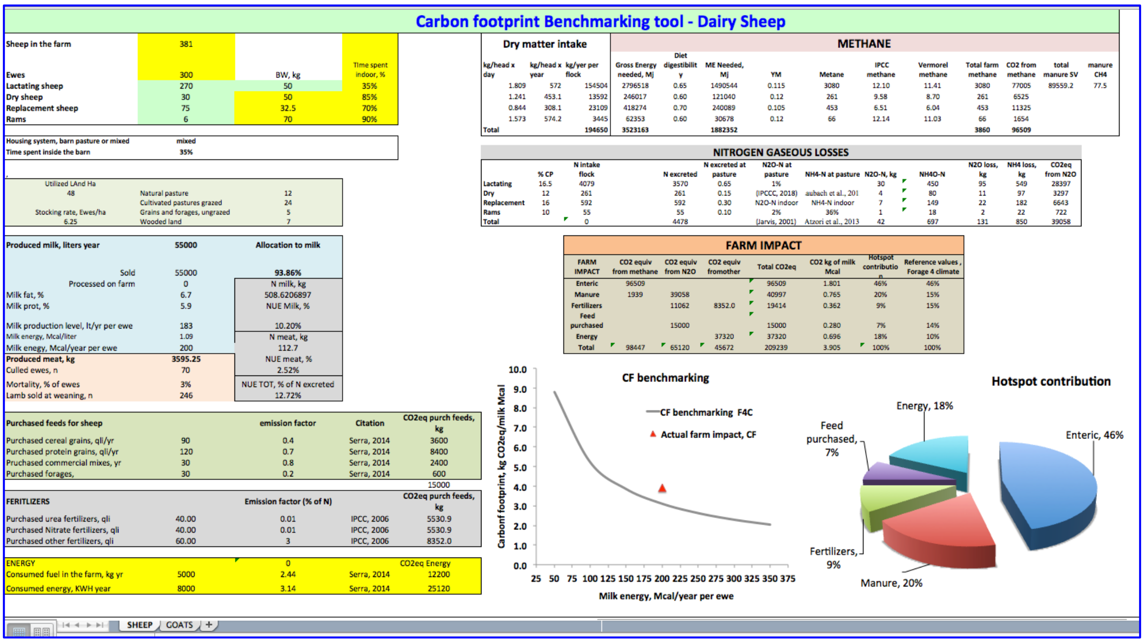


Figure 9. Cradle to farm gate system boundary for sheep meat production in Sheep LCA

CarbonSheep (Italy – University of Sassari)

Sheep farming in Italy, particularly in the main production areas, remains largely based on grazing and is often organised according to a semi-extensive management system, in which grazing is the backbone of the feeding strategy and is supplemented, when necessary, by preserved fodder and targeted supplementation of concentrates to stabilise performance. The production cycle is structurally seasonal, as the dynamics of lambing and grazing concentrate milk availability in a limited period, with production typically peaking in winter and spring; "off-season" milk production programmes are mainly reported in specific irrigated lowland contexts as an adaptation of the traditional system. At the policy/operational level, Italian institutional frameworks explicitly recognise grazing-oriented and movement-based management (e.g., semi-wild, wild/transhumant systems), including requirements for grazing and animal movement management, where relevant, and definitions of modalities such as free grazing. Contrasting technical models coexist within this landscape (semi-extensive variants vs. more input-dependent variants), and downstream processing calendars also reflect seasonality (e.g., traditional PDO production windows reported for Pecorino Romano), (Piras et al., 2007). CarbonSheep is a simplified calculator developed as part of the LIFE+ Forage4Climate project (CCM/IT/000039) to estimate greenhouse gas emissions from sheep farming using a limited set of variables considered to be decisive for the CF of small ruminants. The tool has been implemented as a spreadsheet and the estimate is based on easily available farm inputs, including: flock size by category (lactating ewes, dry ewes, replacement ewes and breeding rams), average weight of categories, time spent in the barn (useful for estimating excrement deposition), housing system, crop plan and areas, milk produced (sold or processed on the farm) with composition, meat produced (lambs and culls), purchased feed, fertilisers and energy consumption (fuel and electricity). Starting from the data collected, CarbonSheep applies a set of equations, including some locally developed procedures, to obtain the functional quantities for emission calculation (e.g., dry matter intake per category and energy content of milk) and estimate the main sources of emissions. These sources include enteric and waste CH_4 (with references to IPCC 2006/2019 and additional bibliographic sources listed in the document), nitrogen excretion and its distribution between faeces and urine, direct and indirect N_2O emissions, and ammonia losses from grazing excreta and litter. The tool also includes CO_2 equivalent contributions related to purchased inputs (feed, fertilisers and energy) through specific factors, and converts gases to COeq using global warming potentials of 28 for CH_4, 265 for N_2O and 1 for CO_2 (IPCC, 2013). A distinctive feature of CarbonSheep is the integration of an "expected vs actual" benchmarking approach, which consists of comparing the values calculated for a single farm ("actual") with expected values estimated using regressions (linear and non-linear) built on a dataset of farms surveyed in Forage4Climate. In this dataset, the relationship between impact intensity and production level (in particular milk production) is used to define a reference threshold. In this way, the difference between "actual" and "expected" indicates whether the farm has a higher or lower impact than the average expected for that production level. To support data collection and reporting, the tool has been translated into a GIS system on the ArcGIS platform, with a survey module for inputting data and a dashboard for viewing the CF, the breakdown by hotspot and the comparison with the benchmark (Figure 9).



Carbon footprint Benchmarking tool - Dairy Sheep

Sheep in the farm	381		
Ewes	300	BW, kg	Time spent indoor, %
Lactating sheep	270	50	35%
Dry sheep	30	50	85%
Replacement sheep	75	32.5	70%
Rams	6	70	90%

Housing system, barn pasture or mixed	mixed
Time spent inside the barn	35%

Utilized LAnd Ha		
48	Natural pasture	12
	Cultivated pastures grazed	24
Stocking rate, Ewes/ha	Grains and forages, ungrazed	5
6.25	Wooded land	7

Produced milk, liters year	55000	Allocation to milk
Sold	55000	93.86%
Processed on farm	0	N milk, kg
Milk fat, %	6.7	508.6206897
Milk prot, %	5.9	NUE Milk, %
Milk production level, lt/yr per ewe	183	10.20%
Milk energy, Mcal/liter	1.09	N meat, kg
Milk enegy, Mcal/year per ewe	200	112.7
Produced meat, kg	3595.25	NUE meat, %
Culled ewes, n	70	2.52%
Mortality, % of ewes	3%	NUE TOT, % of N excreted
Lamb sold at weaning, n	246	12.72%

Purchased feeds for sheep		emission factor	Citation	CO2eq purch feeds, kg
Purchased cereal grains, qli/yr	90	0.4	Serra, 2014	3600
Purchased protein grains, qli/yr	120	0.7	Serra, 2014	8400
Pruchased commercial mixes, yr	30	0.8	Serra, 2014	2400
Purchased forages,	30	0.2	Serra, 2014	600
				15000

FERITLIZERS		Emission factor (% of N)		CO2eq purch feeds, kg
Purchased urea fertilizers, qli	40.00	0.01	IPCC, 2006	5530.9
Purchased Nitrate fertilizers, qli	40.00	0.01	IPCC, 2006	5530.9
Purchased other fertilizers, qli	60.00	3	IPCC, 2006	8352.0

ENERGY		0		CO2eq Energy
Consumed fuel in the farm, kg yr	5000	2.44	Serra, 2014	12200
Consumed energy, KWH year	8000	3.14	Serra, 2014	25120

Dry matter intake			METHANE											
	kg/head x day	kg/head x year	kg/yer per flock	Gross Energy needed, Mj	Diet digestibility	ME Needed, Mj	YM	Metane	IPCC methane	Vermorel methane	Total farm methane	CO2 from methane	total manure SV	manure CH4
	1.809	572	154504	2796518	0.65	1490544	0.115	3080	12.10	11.41	3080	77005	89559.2	77.5
	1.241	453.1	13592	246017	0.60	121040	0.12	261	9.58	8.70	261	6525		
	0.844	308.1	23109	418274	0.70	240089	0.105	453	6.51	6.04	453	11325		
	1.573	574.2	3445	62353	0.60	30678	0.12	66	12.14	11.03	66	1654		
Total			194650	3523163		1882352					3860	96509		

NITROGEN GASEOUS LOSSES

	% CP	N intake flock	N excreted	N excreted at pasture	N2O-N at pasture	NH4-N at pasture	N2O-N, kg	NH4O-N	N2O loss, kg	NH4 loss, kg	CO2eq from N2O
Lactating	16.5	4079	3570	0.65	1%		30	450	95	549	28397
Dry	12	261	261	0.15	(IPCCC, 2018)	aubach et al., 201	4	80	11	97	3297
Replacement	16	592	592	0.30	N2O-N indoor	NH4-N indoor	7	149	22	182	6643
Rams	10	55	55	0.10	2%	36%	1	18	2	22	722
Total		0	4478		(Jarvis, 2001)	Atzori et al., 2013	42	697	131	850	39058

FARM IMPACT

FARM IMPACT	CO2 equiv from methane	CO2 equiv from N2O	CO2 equiv fromother	Total CO2eq	CO2 kg of milk Mcal	Hotspot contribution	Reference values , Forage 4 climate
Enteric	96509			96509	1.801	46%	46%
Manure	1939	39058		40997	0.765	20%	15%
Fertilizers		11062	8352.0	19414	0.362	9%	15%
Feed purchased		15000		15000	0.280	7%	14%
Energy			37320	37320	0.696	18%	10%
Total	98447	65120	45672	209239	3.905	100%	100%

Figure 10. CarbonSheep, a simplified tool for Sheep carbon footprint estimation and benchmarking

Sheep farming in Romania is deeply rooted in rural areas, particularly in disadvantaged and mountainous areas where grazing is a structural resource for management. The sector is also characterised by a highly fragmented business base (high incidence of farms <5 ha), which tends to favour small-scale models and extensive use of local fodder resources; in this context, seasonal pastoral mobility (transhumance) is still a relevant practice and is formally recognised as cultural heritage (European Commission, 2026). Statistical analyses for Total GHG emissions CO_2 kg FPCM were conducted in R (version 4.5.1), with methods selected according to the specific aims of each research question. To limit the influence of skewed distributions, skewness was computed for each numeric variable and, when appropriate, data were transformed using a square-root transformation for moderate skewness or a log(x + 1) transformation for more pronounced skewness. Farms were then clustered solely on the response variable Total GHG emissions CO_2 kg FPCM using k-means clustering (kmeans); the number of clusters was evaluated for k = 2 to 6, and the optimal k was chosen as the value maximizing the mean silhouette coefficient using the cluster package. After clustering, differences in input variables among clusters were assessed using nonparametric procedures: Mann–Whitney (Wilcoxon rank-sum) tests were used when 2 clusters were present (wilcox.test), whereas Kruskal–Wallis tests were used when more than 2 clusters were present (kruskal.test). When the overall test was significant, pairwise contrasts were performed using Dunn's test (package FSA) with Benjamini–Hochberg adjustment for multiple comparisons, and results were summarized using letter groupings (package multcompView). Pairwise associations between Total GHG emissions CO_2 kg FPCM and numeric input variables were evaluated using Pearson and Spearman correlation coefficients with corresponding P-values (package Hmisc; rcorr). To identify drivers of variation in Total GHG emissions CO_2 kg FPCM in the presence of collinearity among explanatory variables, partial least squares regression (PLSR) was fitted using the pls package (plsr); models were validated by cross-validation with up to 10 segments, and the optimal number of components was selected based on the minimum RMSEP. The contribution of each predictor was evaluated using regression coefficients and the variable importance in projection (VIP) statistic, and, following Wold et al. (1994), base predictors with VIP < 0.8 were removed; the final model was then reported using the retained predictors, and loadings were used to aid interpretation. Statistical significance was declared at $P < 0.05$.

Results and Discussion

The results for each question are reported for French dairy milk farms.

Q 1 For French dairy farms what are the characteristics of high- and low-intensity farms?

Results showed that clustering on the output variable Total GHG emissions CO_2 kg FPCM produced two clusters, where Cluster 1 (n=128) had a lower level and Cluster 2 (n=63) had a higher level (Table 2).

Cluster 1 (low intensity) had a significantly higher FC (Mj/y/ewe), PC (Mj/y/ewe), UAA (ha), MFP (kg/ha), ewes (hd), LR (%), MFP (%), MPP (%), FPCM (kg FPCM/yr/ewe), CONC (kg/yr/ewe) compared with Cluster 2 (high intensity). Also, in Cluster 2, Part of PCON (%) and PAS (d/yr) were higher than in Cluster 1. No significant differences were observed for part of PFOR (%) and ONP (ha) (Table 3). Separating emission intensity into low- and high-intensity clusters indicates that emission intensity declines as FPCM (kg FPCM/yr/ewe) increases. The contrast between clusters is therefore better interpreted in terms of differences in efficiency and the level of FPCM output, rather than being attributed solely to the production-system label (Gerber et al., 2011). From a management perspective, this pattern suggests that strategies aimed at improving productive performance and feed-use efficiency, together with effective grazing management, can align with lower emission intensity (Gerber et al., 2011; Guerci et al., 2014).

Q 2 What factors explain why some dairy sheep French farms have high or low emissions and which variables (inputs) are most decisive in terms of intensity?

The strongest and most significant correlations were observed for FPCM (kg FPCM/yr/ewe) (Pearson r = -0.84; Spearman r = -0.95; P < 0.001), CONC, (kg/yr/ewe) (Pearson r = -0.62; Spearman r = -0.63; P < 0.001), PAS (d/yr) (Pearson r = 0.60; Spearman r = 0.60; P < 0.001), and LR (%) (Pearson r = -0.57; Spearman r = -0.68; both P < 0.001). Additional significant correlations with |r| ≥ 0.50 were detected for part of PCON (%) (Spearman r = 0.57; P < 0.001), MFP (%) (Spearman r = -0.60; P < 0.001), MPP (%) (Spearman r = -0.59; P < 0.001), and FC (Mj/y/ewe) (Spearman r = -0.54; P < 0.001). No significant correlations were observed for ONP (ha) (Pearson r = -0.08, P = 0.260; Spearman r = -0.06, P = 0.380), part of PFOR (%) (Pearson r = 0.04, P = 0.604; Spearman r = 0.13, P = 0.063), and SR (Lu/ha) (Pearson r = 0.03, P = 0.720; Spearman r = 0.05, P = 0.502)

(Table 4).

Variable importance in projection (VIP) identified FPCM (kg FPCM/yr/ewe) (VIP = 1.99) as the most influential predictor of Total GHG emissions CO_2kgFPCM, followed by CONC (kg/yr/ewe) (VIP = 1.40), LR (%) (VIP = 1.28), and PAS, (d/yr) (VIP = 1.27). Additional predictors retained in the final model were MPP (%) (VIP = 1.07), FC (Mj/y/ewe) (VIP = 1.02), MFP (%) (VIP = 1.02), part of PCON (%) (VIP = 0.98), and PC (Mj/y/ewe) (VIP = 0.86). Regression coefficients from the final PLSR model were negative for FPCM (kg FPCM/yr/ewe) (−0.0126), LR (%) (−0.0319), and part of PCON (%) (−0.1073), and positive for CONC (kg/yr/ewe) (0.0007), PAS (d/yr) (0.0032), MPP (%) (0.8201), FC (Mj/y/ewe) (0.0003), MFP (%) (0.3969), and PC (Mj/y/ewe)

(0.0012). In other words, the VIP indicates that, in the PLSR model developed to predict Total GHG emissions CO_2 kg FPCM, FPCM (kg FPCM/yr/ewe) contributed the most to the predictive structure, followed by CONC (kg/yr/ewe), LR (%), and PAS (d/yr) as the next most influential predictors. The signs of the regression coefficients indicate the direction of the relationships within the model: FPCM (kg FPCM/yr/ewe), LR (%), and part of PCON (%) were associated with lower predicted Total GHG emissions CO_2kgFPCM, whereas MPP (%) and MFP (%) were associated with higher predicted values. The remaining predictors retained in the model (CONC, (kg/yr/ewe), PAS (d/yr), FC (Mj/y/ewe), and PC (Mj/y/ewe) had positive but relatively small coefficients, indicating a more limited directional contribution on the fitted scale (Table 5).

Further examination of predictor structure using PLSR indicated that the first 3 orthogonal prediction components summarized the main patterns of covariance between the predictor set and Total GHG emissions CO_2 kgFPCM (Figure 10). Component 1 was primarily characterized by high absolute loadings for FPCM (kg FPCM/yr/ewe), PAS (d/yr), and CONC (kg/yr/ewe). Component 2 showed high absolute loadings for LR (%), MPP (%), and MFP (%), with additional contribution from part of PCON (%). Component 3 was mainly characterized by high absolute loadings for PC (Mj/y/ewe) and LR (%), with secondary contributions from MFP (%) and MPP (%). The observed correlations are consistent with the view that milk output per animal is a key driver of emission intensity, in line with Gerber et al. (2011), who reported lower emission intensity per unit of FPCM with greater output per animal. This interpretation is further supported by Wilkes et al. (2020), who showed at the animal level that variation in milk yield can account for a large share of the variation in emission intensity. With respect to concentrate feeding, evidence indicates that increasing concentrate supplementation can raise milk yield and reduce emission intensity per FPCM (Dida et al., 2024). In the multivariable analysis, the VIP results from the present study identify which inputs contribute most to the predictive structure and can therefore be discussed as key variables alongside the correlation results. Accordingly, the discussion should emphasize the central role of FPCM output per animal, with feeding practices and grazing patterns considered as concurrent factors associated with differences in emission intensity.

Q 3 Given the same production system in dairy sheep French farms, why do some farms have high emissions and others low emissions, and which inputs determine these differences within the same type?

Results showed that clustering on the output variable Total GHG emissions CO_2 kg FPCM (Figure 11). in extensive system produced two clusters, where Cluster 1 (n=64) had a lower level and Cluster 2 (n=38) had a higher level (Table 6). Cluster 1 (low intensity) had significantly higher FC (Mj/y/ewe), ONP (kg/ha), ewes, (hd), LR (%), FPCM (kg FPCM/yr/ewe), and CONC (kg/yr/ewe) than Cluster 2 (high intensity) within the extensive system (all $P \leq 0.04$). In contrast, PAS (d/yr) was higher in Cluster 2 than in Cluster 1 ($P < 0.001$). No significant differences were detected for PC (Mj/y/ewe), UAA (ha), MFP (kg/ha), MFP (%), MPP (%), part of PCON (%), part of PFOR (%), or SR (Lu/ha) (Table 7).

Results showed that clustering on Total GHG emissions CO_2 kg FPCM within the intensive system yielded 3 clusters (Figure 12). Cluster C1 (n = 42) had the lowest mean (mean ± SD = 2.69 ± 0.26, Cluster C3 (n = 39) showed an intermediate level (3.41 ± 0.24), and Cluster C2 (n = 8) had the highest level (4.89 ± 0.49) (Table 8).

In the extensive system, emission differentiation is mainly linked to the ability to enhance grazing. Low-emission farms (C1) show much higher levels of FPCM (kg FPCM/yr/ewe) LR (%) and CONC (kg/yr/ewe), as well as higher FC (Mj/y/ewe), indicating an extensive system that is nevertheless actively managed. High-emission farms (C2), on the other hand, have a greater amount of PAS (d/yr), but without a corresponding increase in yields, suggesting inefficient use of pasture (Escribano et al., 2020; Bosco et al., 2021).

In the intensive system, mean comparisons across clusters identified significant differences for PC (Mj/y/ewe), LR (%), MFP (%), FPCM (kg FPCM/yr/ewe), CONC (kg/yr/ewe), and SR (Lu/ha) ($P \leq 0.05$). Specifically, PC, (Mj/y/ewe) was higher in C1 than in C2 and C3 ($P < 0.001$), and LR (%) was higher in C1 than in C2 and C3 ($P < 0.001$). MFP (%) differed among all clusters ($C1 > C3 > C2$; $P < 0.001$). FPCM (kg FPCM/yr/ewe) also differed among all clusters ($C1 > C3 > C2$; $P < 0.001$). CONC (kg/yr/ewe) was higher in C1 and C3 than in C2 ($P = 0.02$), and SR (Lu/ha) was higher in C2 than in C1 and C3 ($P = 0.02$). No significant differences were detected for FC (Mj/y/ewe), UAA (ha), MNF (kg/ha), ONP (kg N/ha), ewes, (hd), MPP (%), part of PCON (%), part of PFOR (%), or PAS (d/yr) ($P \geq 0.05$) (Table 9).

In the intensive system, the presence of three clusters reveals a more articulated gradation: the least emission-intensive cluster (C1) has the best technical performance FPCM (kg FPCM/yr/ewe) LR (%), MFP (%) and FC (Mj/y/ewe), while the most emission-intensive (C2) shows much lower yields and a higher SR (LU/ha), a sign of production pressure that is not adequately compensated. The intermediate cluster (C3) represents a moderate management condition in terms of both production and emissions. The intra-system differences show that, regardless of the system adopted, emission intensity depends on the ability to translate inputs into production efficiently, through technical choices specific to each context.

Q 4. Given the same level of production in dairy sheep French farms, which inputs determine emissions and how are they linked to yields (who emits a lot with low yields; who emits little with high yields)?

At comparable herd scale and production level, the effects of herd size and milk production level were controlled for separately from y. Table 10 summarizes adjusted (residual) emission intensity, rather than the raw response, where residuals were obtained after accounting for herd size and production level. Cluster C1 had positive residuals on average, indicating higher adjusted emission intensity than expected given herd size and production, whereas cluster C2 had negative residuals on average, indicating lower adjusted emission intensity than expected under the same adjustments (Figure 13).

Clusters derived from the adjusted (residual) Total GHG emissions CO_2 kg FPCM differed for several input variables (Table 11). Cluster C1 had higher FC (Mj/y/ewe), PC (Mj/y/ewe), MNF (kg /ha), LR (%), MFP (%), MPP (%), FPCM (kg FPCM/yr/ewe), and CONC (kg/yr/ewe) than Cluster C2 ($P \leq 0.03$). In contrast, Cluster C2 had higher part of PCON (%) and PAS (d/yr) than Cluster C1 ($P \leq 0.02$). No significant differences were observed for UAA (ha), ONP (kg/ha), ewes, (hd), part of PFOR (%), or SR (Lu/ha) ($P \geq 0.12$).

Variable importance in projection (VIP) for the PLSR model fitted to the adjusted outcome (Total GHG emissions CO_2 kg FPCM residuals) indicated that MPP (%) (VIP = 1.47) and part of PFOR (%) (VIP = 1.27) were the most influential predictors, followed by FPCM (kg FPCM/yr/ewe) (VIP = 1.26), PAS (d/yr) (VIP = 1.15), MNF (kg/ha) (VIP = 1.06), MFP (%) (VIP = 1.05), SR (Lu/ha) (VIP = 1.02), and ONP, (kg N/ha) (VIP = 1.02). Predictors with VIP values < 1 but retained in the final model included UAA (ha) (VIP = 0.96), FC (Mj/y/ewe) (VIP = 0.95), part of PCON, (%) (VIP = 0.93), CONC (kg/yr/ewe) (VIP = 0.88), and LR (%) (VIP = 0.81).

Regression coefficients were positive for MPP (0.779%), PAS (0.003 d/yr), MNF (0.005 kg/ha), MFP (0.278%), part of PCON (%) (0.096), CONC (kg/yr/ewe) (0.001), and FC (Mj/y/ewe), and negative for part of PFOR (%) (−0.352), FPCM (kg FPCM/yr/ewe) (-0.003), SR (Lu/ha) (-0.114), ONP (kg N/ha) (-0.001), UAA (ha) (-0.072), and LR (%) (-0.012) (Table 12).

The adjusted analysis indicates that, after jointly controlling for ewe size and FPCM output per animal, differences in emission intensity persist, pointing to the potential influence of management factors beyond scale and production level. Chen et al. (2026) reported that potential benefits of management changes such as grazing can be offset by increased emissions associated with nitrogen fertilization, such that the net outcome reflects the balance among multiple management drivers. Within this context, observed differences in mineral nitrogen inputs can be discussed as further evidence that nitrogen management is relevant to variation in emission intensity (Chen et al., 2026). In the multivariable analysis of the adjusted outcome, VIP indicates which variables contribute most to the predictive structure once the effects of production and scale are removed, and thus provides a basis for discussing drivers "beyond production". Taken together, after standardizing for production and scale, the remaining differences can be interpreted as being associated with input-management practices and characteristics linked to feeding and milk composition, without implying causality.

Conclusion

This chapter positions the CF not as a "reporting" output, but as a governance tool: a diagnosis that must translate into measurable actions and a cycle of monitoring–training–action plan, consistent with the operational framework of the LIFE Green Sheep project, including the overall objective of reducing the CF by 12% in the five target countries. Methodologically, the key message is that comparability between contexts depends not only on the actual differences between systems, but also on the "way" in which processes are accounted for (system boundaries, assumptions, level of detail/tier, allocation rules and functional units). To avoid misleading interpretations and make the comparison replicable, the chapter adopts kg of FPCM com FU for milk output systems and proposes a "structured" reading of national tools (CAP'2ER/DEO, ArdiCarbon, Sheep LCA, CarbonSheep) based on IPCC 2006 and 2019 updates, highlighting national convergences and adaptations. Operationally, the chapter demonstrates the value of the intra-national profiling approach: classifying farms by emission intensity to obtain precise indications on "what to mitigate" and "how to do it", distinguishing between generalisable levers and solutions to be adapted to the production profile, because reasoning solely in terms of "national averages" risks losing sight of the extreme profiles, i.e. those with the greatest potential for intervention. Within this framework, empirical results (e.g., French dairy farms) confirm that the variability of Total GHG emissions CO_2 kg FPCM can be interpreted as a combination of production and management factors that can be measured at the farm level. In the predictive structure, FPCM (kg FPCM/yr/ewe) emerges as a priority driver, together with feeding and supply indicators (CONC (kg/yr/ewe), PCON (%), PFOR (%)), pasture management (PAS (d/yr)), reproductive performance (LR (%)), milk composition (MFP (%), MPP (%)), direct consumption (FC (Mj/y/ewe), PC (Mj/y/ewe)) and nitrogen management signals (MNF (kg/ha), ONP (kg N/ha)), with differentiated readings when working "within-system" (e.g. extensive vs intensive) and when controlling for scale and production level via Total GHG emissions CO_2 kg FPCM residuals. In the latter case, the persistence of differences after adjustment supports the discussion of drivers beyond production in particular MPP (%) and PFOR (%) among the most influential in the PLSR on the adjusted outcome, without implying causality. The chapter therefore shows that CF only becomes truly useful when it is part of a structured process of methodological harmonisation and company profiling, capable of transforming indicators such as Total GHG emissions CO_2 kg FPCM into technical priorities and mitigation actions that can be monitored over time, consistent with the operational framework of LIFE Green Sheep.

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https://webgate.ec.europa.eu/life/publicWebsite/project/LIFE19-CCM-FR-001245/demonstration-and-dissemination-actions-to-reduce-the-carbon-footprint-in-sheep-farming

https://webgate.ec.europa.eu/life/publicWebsite/project/LIFE19-CCM-FR-001245/demonstration-and-dissemination-actions-to-reduce-the-carbon-footprint-in-sheep-farming

https://www.fao.org/faostat/en/#data/QCL/visualize

https://www.franceagrimer.fr/

Tables and Figures

Table 1. Qualitative scheme of tools description and aims and methodological approaches.

Item	**CAP'2ER/DEO**	**ARDICARBON**	**Sheep LCA**	**CARBONSHEEP**
Country/ Developer	France/INSTITUTE DE L'ELEVAGE	Spain/NEIKER	Ireland/ TEAGASC	ITALY/University o Sassari
Species	Sheep, Goat, Dairy and Bee cattle	Sheep	Sheep - Cattle	Sheep - Goats
Approach	LCA and mitigation plan		Simplified LCA	Simplified LCA
Levels o complexity	Lev.1: impact calculation Lev.2: action plan			Lev.1: simplified impac calculation
Prod. systems	Milk/meat		Meat	Milk
Target	Farmers/advisors/Policy Makers		Farmers/advisors/Policy Makers	Farmers/advisors
Data collectio	30 min to 3 hours	30 min to 2 hours	30 min to 2 hours	30 minutes
Inputs, n	82	83	100	52
Impact categories	Climate change, Acidification, eutrophication, Energy consumption, Economics, Labour			Climate Change
Carbon seque	Yes	YES	YES	NO
Enteric CH_4 estimates	IPCC, 2019; Modified Tier 2 with local equations		IPCC, 2006 Tier 2	IPCC, 2019; Modified Tier 2 wit local equations
Digestibility	Variable	FIxed	Fixed values (IPCC, 2006)	Fixed value per anima category
Manure CH_4	IPCC, 2019			
N. emission coeff.	IPCC, 2019 and local developed equations		National values	Local develope equation
Purchased feeds coeff.	Ecoinvent		-	Local Values an Ecoinvent
Produced feeds coeff.	LCA and IPCC 2019		-	LCA and IPCC 2019
Energy emission coeff.	National values or ecoinvent			Serra et al., 2012
Spatial data on GIS layers		NO		YES

Table 2. Cluster results for Total GHG emissions CO_2 kg FPCM

Cluster	n	mean	sd	min	max
C1	128	3.20	0.51	2.02	4.10
C2	63	5.41	1.39	4.15	13.03

Table 3. Mean comparison of input variables across clusters from Total GHG emissions CO_2 kg FPCM (mean ± SE)

Variable[1]	C 1	C 2	p value
FC, Mj/y/ewe	820.69 ± 27.84 ^{a}	540.83 ± 34.14 ^{b}	<0.001
PC, Mj/y/ewe	584.85 ± 42.00 ^{a}	372.66 ± 44.49 ^{b}	<0.001
UAA, ha	85.69 ± 5.64 ^{a}	72.71 ± 13.78 ^{b}	<0.001
MNF, kg/ha	34.48 ± 2.33 ^{a}	25.44 ± 3.40 ^{b}	0.013
ONP, ha	91.53 ± 3.55	83.48 ± 5.49	0.108
Ewes, hd	419.93 ± 14.36 ^{a}	339.49 ± 14.98 ^{b}	<0.001
LR, %	1.50 ± 0.01 ^{a}	1.29 ± 0.03 ^{b}	<0.001
MFP, %	7.17 ± 0.03 ^{a}	6.74 ± 0.05 ^{b}	<0.001
MPP, %	5.36 ± 0.03 ^{a}	5.12 ± 0.04 ^{b}	<0.001
FPCM, kg FPCM/yr/ewe	335.33 ± 7.56 ^{a}	156.71 ± 6.02 ^{b}	<0.001
CONC, kg/yr/ewe	244.66 ± 5.59 ^{a}	156.21 ± 7.83 ^{b}	<0.001
PCON, %	0.65 ± 0.02 ^{a}	0.90 ± 0.02 ^{b}	<0.001
PFOR, %	0.12 ± 0.01	0.16 ± 0.02	<0.117
PAS, d/yr	65.60 ± 3.59 ^{a}	128.34 ± 6.08 ^{b}	<0.001
SR, Lu/ha	6.24 ± 0.25	6.63 ± 0.45	0.665

[1] FC, fuel consumption (mega joule/year/ewe); PC, power consumption (mega joule/year/ewe); UAA, utilised agricultural area (ha); MNF, mineral nitrogen fertilizer (kg/ha); ONP, organic nitrogen pressure (kg/ha); Ewes, ewes (per head); LR, lambing rate (%); MFP, milk fat percentage (%); MPP, milk protein percentage (%); FPCM, fat and protein corrected milk (kg FPCM/yr/ewe); CONC, concentrates consumption (kg/yr/ewe); PCON, purchased concentrates (%); PFOR, purchased forages (%); PAS, pasture (d/yr); SR, stocking rate (Lu/ha).

Table 4. Pearson and Spearman correlation coefficients between input variables and Total GHG emissions CO_2 kg FPCM

Variable[1]	**Pearson**		**Spearman**	
	r	**p value**	**r**	**p value**
FC, Mj/y/ewe	-0.44	<0.001	-0.54	<0.001
PC, Mj/y/ewe	-0.31	<0.001	-0.45	<0.001
UAA, ha	-0.10	0.178	-0.19	0.007
MNF, kg/ha	-0.22	0.002	-0.25	0.001
ONP, ha	-0.08	0.260	-0.06	0.380
Ewes, hd	-0.22	0.002	-0.23	0.002
LR, %	-0.57	<0.001	-0.68	<0.001
MFP, %	-0.44	<0.001	-0.60	<0.001
MPP, %	-0.39	<0.001	-0.59	<0.001
FPCM, kg FPCM/yr/ewe	-0.84	<0.001	-0.95	<0.001
CONC, kg/yr/ewe	-0.62	<0.001	-0.63	<0.001
PCON, %	0.44	<0.001	0.57	<0.001
PFOR, %	0.04	0.604	0.13	0.063
PAS, d/yr	0.60	<0.001	0.60	<0.001
SR, Lu/ha	0.03	0.720	0.05	0.502

[1] FC, fuel consumption (mega joule/year/ewe); PC, power consumption (mega joule/year/ewe); UAA, utilised agricultural area (ha); MNF, mineral nitrogen fertilizer (kg/ha); ONP, organic nitrogen pressure (kg/ha); Ewes, ewes (per head); LR, lambing rate (%); MFP, milk fat percentage (%); MPP, milk protein percentage (%); FPCM, fat and protein corrected milk (kg FPCM/yr/ewe); CONC, concentrates consumption (kg/yr/ewe); PCON, purchased concentrates (%); PFOR, purchased forages (%); PAS, pasture (d/yr); SR, stocking rate (Lu/ha).

Table 5. Variable importance for projection (VIP) statistics and regression coefficients of a partial least squares regression (PLSR) model fitted to Total GHG emissions CO_2 kg FPCM using input variables.

Variable[1]	VIP Statistic	coefficient
FPCM, kg FPCM/yr/ewe	1.99	-0.0126
CONC, kg/yr/ewe	1.40	0.0007
LR, %	1.28	-0.0319
PAS, d/yr	1.27	0.0032
MPP, %	1.07	0.8201
FC, Mj/y/ewe	1.02	0.0003
MFP, %	1.02	0.3969
PCON, %	0.98	-0.1073
PC, Mj/y/ewe	0.86	0.0012

[1] FC, fuel consumption (mega joule/year/ewe); PC, power consumption (mega joule/year/ewe); LR, lambing rate (%); MFP, milk fat percentage (%); MPP, milk protein percentage (%); FPCM, fat and protein corrected milk (kg FPCM/yr/ewe); CONC, concentrates consumption (kg/yr/ewe); PCON, purchased concentrates (%);PAS, pasture (d/yr).

[2] predictors were transformed (if skewed) and standardized; coefficients are reported on the preprocessed scale.

Table 6. Cluster results for Total GHG emissions CO_2 kg FPCM in extensive system

Cluster	n	mean	sd	min	max
C1	64	3.72	0.57	2.46	4.62
C2	38	5.99	1.51	4.76	13.03

Table 7. Mean comparison of input variables across clusters from Total GHG emissions CO_2 kg FPCM in extensive system (mean ± SE)

Variable[1]	C 1	C 2	p value
FC, Mj/y/ewe	642.65 ± 35.14 ^{a}	447.12 ± 29.22 ^{b}	<0.001
PC, Mj/y/ewe	416.74 ± 48.46	360.45 ± 48.71	0.08
UAA, ha	83.08 ± 15.18	65.04 ± 6.43	0.88
MNF, kg/ha	24.89 ± 3.34	18.75 ± 3.58	0.13
ONP, ha	94.90 ± 6.47 ^{a}	72.99 ± 6.00 ^{b}	0.04
Ewes, hd	376.20 ± 14.84 ^{a}	305.82 ± 14.18 ^{b}	<0.001
LR, %	1.42 ± 0.02 ^{a}	1.22 ± 0.04 ^{b}	<0.001
MFP, %	6.81 ± 0.04	6.78 ± 0.05	0.59
MPP, %	5.09 ± 0.03	5.08 ± 0.02	0.54
FPCM, kg FPCM/yr/ewe	249.23 ± 8.39 ^{a}	129.21 ± 5.53 ^{b}	<0.001
CONC, kg/yr/ewe	206.65 ± 7.64 ^{a}	134.11 ± 9.31 ^{b}	<0.001
PCON, %	0.85 ± 0.03	0.91 ± 0.03	0.26
PFOR, %	0.16 ± 0.01	0.14 ± 0.02	0.18
PAS, d/yr	113.22 ± 4.69 ^{a}	147.12 ± 6.05 ^{b}	<0.001
SR, Lu/ha	7.23 ± 0.50	5.81 ± 0.47	0.10

1 FC, fuel consumption (mega joule/year/ewe); PC, power consumption (mega joule/year/ewe); UAA, utilised agricultural area (ha); MNF, mineral nitrogen fertilizer (kg/ha); ONP, organic nitrogen pressure (kg/ha); Ewes, ewes (per head); LR, lambing rate (%); MFP, milk fat percentage (%); MPP, milk protein percentage (%); FPCM, fat and protein corrected milk (kg FPCM/yr/ewe); CONC, concentrates consumption (kg/yr/ewe); PCON, purchased concentrates (%); PFOR, purchased forages (%); PAS, pasture (d/yr); SR, stocking rate (Lu/ha).

Table 8. Cluster results for Total GHG emissions CO_2 kg FPCM in intensive system

Cluster	n	mean	sd	min	max
C1	42	2.69	0.26	2.02	2.99
C2	8	4.89	0.49	4.22	5.76
C3	39	3.41	0.24	3.07	3.90

Table 9. Mean comparison of input variables across clusters from Total GHG emissions CO_2 kg FPCM in intensive system (mean ± SE)

Variable[1]	C 1	C 2	C3	p value
FC, Mj/y/ewe	949.01 ± 42.68	764.39 ± 105.97	898.14 ± 51.04	0.38
PC, Mj/y/ewe	871.04 ± 87.59 ^{a}	405.63 ± 121.88 ^{b}	465.18 ± 54.60^b	<0.001
UAA, ha	83.29 ± 8.25	54.41 ± 7.73	98.11 ± 9.39	0.08
MNF, kg/ha	42.33 ± 4.01	31.24 ± 7.47	43.17 ± 4.05	0.50
ONP, ha	87.92 ± 4.24	112.38 ± 14.30	90.67 ± 5.64	0.30
Ewes, hd	422.40 ± 25.00	430.38 ± 43.59	468.13 ± 32.61	0.62
LR, %	1.59 ± 0.02 ^{a}	1.42 ± 0.04 ^{b}	1.50 ± 0.02 ^{b}	<0.001
MFP, %	7.44 ± 0.04 ^{a}	6.76 ± 0.27 ^{b}	7.26 ± 0.05 ^{c}	<0.001
MPP, %	5.55 ± 0.02	5.56 ± 0.24	5.46 ± 0.03	0.06
FPCM, kg FPCM/yr/ewe	420.57 ± 7.74 ^{a}	190.63 ± 12.77 ^{b}	326.79 ± 7.16 ^{c}	<0.001
CONC, kg/yr/ewe	268.16 ± 9.12 ^{a}	204.18 ± 15.64 ^{b}	254.85 ± 9.33 ^{a}	0.02

Variable[1]	**C 1**	**C 2**	**C3**	**p value**
PCON, %	0.53 ± 0.03	0.73 ± 0.09	0.58 ± 0.03	0.13
PFOR, %	0.12 ± 0.02	0.16 ± 0.05	0.10 ± 0.01	0.41
PAS, d/yr	42.53 ± 1.66	41.90 ± 5.10	39.09 ± 1.67	0.20
SR, Lu/ha	5.94 ± 0.29 ^{a}	8.42 ± 0.97 ^{b}	5.55 ± 0.31 ^{a}	0.02

[1] FC, fuel consumption (mega joule/year/ewe); PC, power consumption (mega joule/year/ewe); UAA, utilised agricultural area (ha); MNF, mineral nitrogen fertilizer (kg/ha); ONP, organic nitrogen pressure (kg/ha); Ewes, ewes (per head); LR, lambing rate (%); MFP, milk fat percentage (%); MPP, milk protein percentage (%); FPCM, fat and protein corrected milk (kg FPCM/yr/ewe); CONC, concentrates consumption (kg/yr/ewe); PCON, purchased concentrates (%); PFOR, purchased forages (%); PAS, pasture (d/yr); SR, stocking rate (Lu/ha)

Table 10. Descriptive statistics of adjusted emission intensity (residuals) by clusters derived from the residual-based analysis.

Cluster	n	mean	sd	min	max
C1	55	0.76	0.92	0.25	0.75
C2	136	-0.31	0.33	-1.14	0.21

Table 11. Mean comparison of input variables across clusters from Total GHG emissions CO_2 kg FPCM adjusted (mean ± SE)

Variable[1]	C 1	C 2	p value
FC, Mj/y/ewe	832.67 ± 49.60 ^{a}	686.21 ± 25.90 ^{b}	0.01
PC, Mj/y/ewe	633.67 ± 67.76 ^{a}	466.82 ± 35.84 ^{b}	0.03
UAA, ha	89.77 ± 15.84	78.02 ± 5.30	0.51
MNF, kg/ha	41.19 ± 4.00 ^{a}	27.58 ± 2.12 ^{b}	<0.001
ONP, ha	84.53 ± 4.49	90.63 ± 3.79	0.67
Ewes, hd	390.09 ± 23.65	394.74 ± 12.44	0.29
LR, %	1.47 ± 0.03 ^{a}	1.42 ± 0.02 ^{b}	0.03
MFP, %	7.17 ± 0.05 ^{a}	6.97 ± 0.04 ^{b}	<0.001
MPP, %	5.41 ± 0.04 ^{a}	5.23 ± 0.03 ^{b}	<0.001
FPCM, kg FPCM/yr/ewe	309.55 ± 20.77 ^{a}	263.01 ± 7.56 ^{b}	0.02
CONC, kg/yr/ewe	245.28 ± 13.31 ^{a}	203.43 ± 5.13 ^{b}	<0.001
PCON, %	0.67 ± 0.03 ^{a}	0.76 ± 0.02 ^{b}	0.02
PFOR, %	0.12 ± 0.01	0.14 ± 0.01	0.50
PAS, d/yr	75.25 ± 7.40 ^{a}	90.76 ± 4.36 ^{b}	0.01
SR, Lu/ha	5.65 ± 0.26	6.66 ± 0.29	0.12

[1] FC, fuel consumption (mega joule/year/ewe); PC, power consumption (mega joule/year/ewe); UAA, utilised agricultural area (ha); MNF, mineral nitrogen fertilizer (kg/ha); ONP, organic nitrogen pressure (kg/ha); Ewes, ewes (per head); LR, lambing rate (%); MFP, milk fat percentage (%); MPP, milk protein percentage (%); FPCM, fat and protein corrected milk (kg FPCM/yr/ewe); CONC, concentrates consumption (kg/yr/ewe); PCON, purchased concentrates (%); PFOR, purchased forages (%); PAS, pasture (d/yr); SR, stocking rate (Lu/ha).

Table 12. Variable importance for projection (VIP) statistics and regression coefficients of a partial least squares regression (PLSR) model fitted to Total GHG emissions CO_2 kg FPCM adjusted using input variables.

Variable[1]	**VIP Statistic**	**coefficient**
MPP, %	1.47	0.779
PFOR, %	1.27	-0.352
FPCM, kg/yr/ewe	1.26	-0.003
PAS, d/yr	1.15	0.003
MNF, kg/ha	1.06	0.005
MFP, %	1.05	0.278
SR, Lu/ha	1.02	-0.114
ONP, kg/ha	1.02	-0.001
UAA, ha	0.96	-0.072
PC, Mj/y/ewe	0.95	0.000
PCON, %	0.93	0.096
CONC, kg/yr/ewe	0.88	0.001
LR, %	0.81	-0.012

[1] UAA, utilised agricultural area (ha); MNF, mineral nitrogen fertilizer (kg/ha); ONP, organic nitrogen pressure (kg/ha); LR, lambing rate (%); MFP, milk fat percentage (%); MPP, milk protein percentage (%); FPCM, fat and protein corrected milk (kg FPCM/yr/ewe); CONC, concentrates consumption (kg/yr/ewe); PCON, purchased concentrates (%); PFOR, purchased forages (%); PAS, pasture (d/yr); SR, stocking rate (Lu/ha).

[2] predictors were transformed (if skewed) and standardized; coefficients are reported on the preprocessed scale.

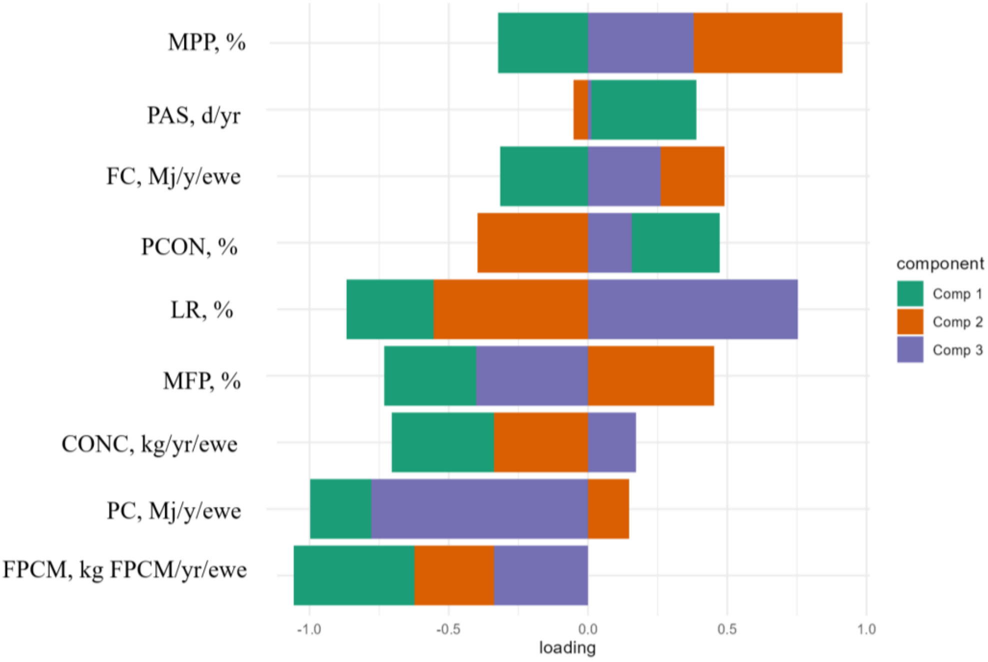

Figure 10. Loading values for the first 3 orthogonal components of a partial least squares regression (PLSR) model fitted to Total GHG emissions CO2 kg FPCM using selected input variables. Loading values indicate which predictors contributed most strongly to each orthogonal c component and therefore define the main predictor patterns captured by the model.

[1] FC, fuel consumption (mega joule/year/ewe); PC, power consumption (mega joule/year/ewe); LR, lambing rate (%); MFP, milk fat percentage (%); MPP, milk protein percentage (%); FPCM, fat and protein corrected milk (kg FPCM/yr/ewe); CONC, concentrates consumption (kg/yr/ewe); PCON, purchased concentrates (%); PAS, pasture (d/yr).

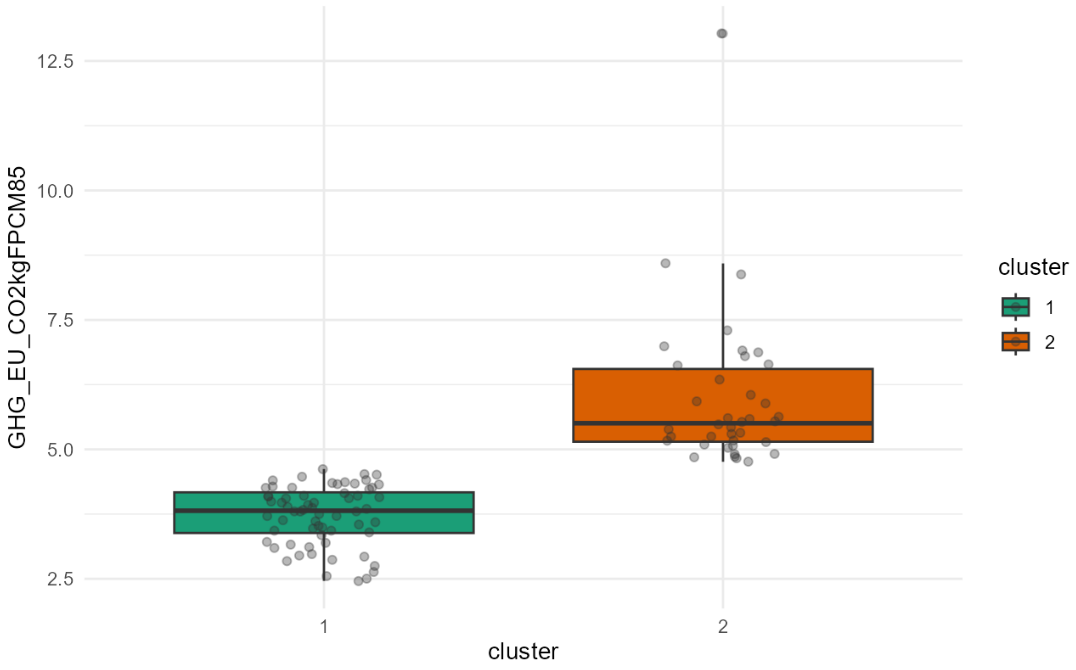

Figure 11. Distribution of Total GHG emissions CO₂ kg FPCM by cluster within the extensive system.

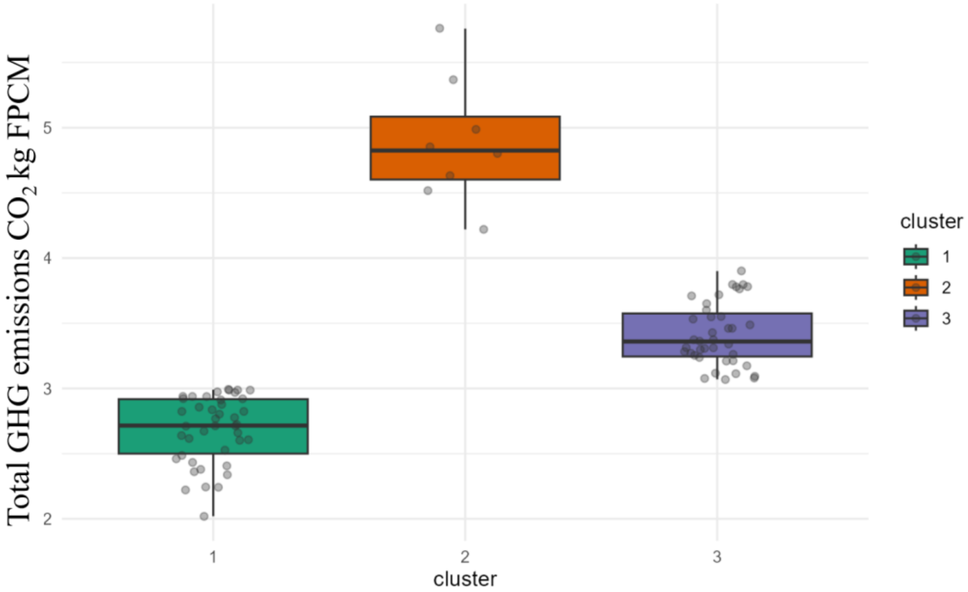

Figure 12. Distribution of Total GHG emissions CO₂ kg FPCM by cluster within the intensive system

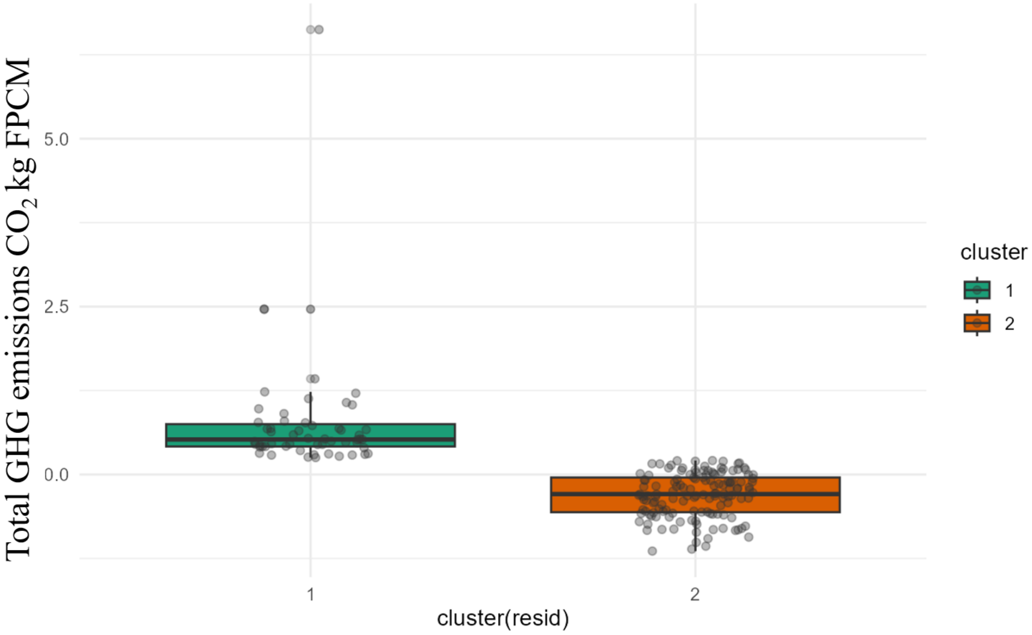

Figure 13. Distribution of adjusted emission intensity (residuals) by residual-based clusters for Total GHG emissions CO_2 kg FPCM.

CHAPTER 3

From Data Collection to Environmental KPIs: The APPàre Platform and an Integrated Carbon Footprint Calculator for Dairy Sheep Systems

Abstract

Digital infrastructures capable of integrating multi-domain agricultural data (health, production, nutrition, environmental impact) remain limited for sheep dairy farming systems, and existing solutions often lack interoperability between operational datasets. This chapter presents the design and implementation of a climate-altering gas emissions calculator integrated into the APPàre platform, with the aim of (i) formulating guidelines for the application of LCA, (ii) quantify CF indicators on a sample of Sardinian dairy sheep, and (iii) support a protocol for technical-environmental indicators for the regional livestock sector. The environmental module was designed to maximise data reusability and minimise user burden by leveraging variables available on the platform and requiring only targeted additions (e.g., details on manure management, energy consumption, completion parameters). The platform requirements and calculation rules were structured through user stories and data flow analysis to ensure traceability, consistency and verifiability. The calculator applies an LCA framework with cradle-to-farm boundaries and uses 1 kg of FPCM as the functional unit; a simplified allocation assigns 100% of the farm's impact to milk (allocation factor = 1). Emissions are estimated using IPCC equations (enteric, manure, managed soils) and activity data-based approaches for energy and feed supply; results are reported as total annual footprint (kg CO_2eq·yr^{-1}), emission intensity (kg CO_2 eq·kg FPCM^{-1}) and percentage contribution per macro-source. Validation data were collected through interviews/questionnaires in 10 dairy sheep farms in Sardinia. The farms had an average area of 136.98 ha (50-450) and 702 lactating ewes (260-1450; ±471.76), with an average production level of 261.33 kg FPCM/ewe/yr (150.78-350.68; ±79.67). The CF was 2.94 kg CO_2 eq/kg FPCM (1.84-5.13; ±1.5). In relative terms, enteric emissions dominated the inventory (53.35%; 37.88-70.78%; ±0.10), followed by purchased feed (22.81%; 4.07-44.12%; ±0.11) and energy (15.00%; 6.46-27.24%; ±0.07). Emissions intensity was strongly and negatively associated with production level ($r = -0.892$). APPàre makes environmental accounting operational by transforming it into a decision-making support tool with a traceable and verifiable process that standardises KPIs, enables benchmarking and accelerates the identification of priority levers at farm level (production efficiency as the main factor; purchased feed and energy as secondary levers depending on production yield). At the system level, the platform provides a replicable information architecture to strengthen sector governance, monitor progress over time and support evidence-based calibration of incentives and interventions.

Keywords

APPàre; Life Cycle Assessment (LCA); carbon footprint; decision support system; dairy sheep farms; hotspot analysis; benchmarking

Introduction

The Sardinian agricultural and livestock sector is therefore required to make a qualitative leap in terms of technological innovation, particularly with regard to data collection and management, which is now an essential factor in combating the structural crisis in the sector (Vagnoni et al., 2018). Failure to do so may result in being left behind by a transformation that is already enabling companies to make more effective decisions, optimise processes and maintain their competitiveness (Bosco et al., 2021). Within the European Union, data, innovation in production systems and increased efficiency are recognised as key strategic drivers (Vagnoni et al., 2019). However, in extensive and semi-extensive systems based on grazing and access to pastures, digitalisation remains limited and there are substantial gaps in the acquisition, sharing and analysis of information. This delay is frequently attributable to objective barriers to innovation, including structural limitations such as company size, which retard the adoption of new tools (Atzori et al., 2022). Despite its historical roots, the agricultural sector in Italy is undergoing a gradual process of digitisation. The Ministry of Health has been instrumental in promoting digital traceability and health monitoring through a range of tools and programmes. These include the National Livestock Database (BDN), VetInfo (2026), ClassyFarm (2026) and the Electronic Veterinary Prescription platform (REV, 2026). SI@lleva (2026), a software developed by the Italian Breeders' Association, integrates genetic and production data to support herd management. Furthermore, there has been a notable increase in the utilisation of precision instruments within this domain, including DeLaval milk meters equipped with DelPro software

(DDW, 2026). Despite the evident necessity to optimise supply chains in order to reduce their environmental impact and enhance their performance through the collection and management of data, it is evident that many of the current platforms designed for data collection and management are primarily tailored towards the dairy cattle sector (e.g. UNIFORM), whilst solutions specifically dedicated to sheep farming remain limited in scope (Bosco et al., 2021). In certain contexts, applications developed for goats, such as App Democapra (2026) and Cynomys Agritech, have also been adapted for sheep. However, there remains a conspicuous absence of comprehensive tools designed specifically for dairy sheep farming. Among the limited options available are the modular software programmes "ALLEVAMENTO OVINI" and "ISAOVINI", which are designed to meet the specific management requirements of the sector, and "Sementusa Tech", which is primarily utilised for data collection during ultrasound examinations. The primary issue with current tools pertains to their constrained capacity to amalgamate data from disparate production domains in a manner that is conducive to interoperability. This necessity gave rise to the project "APPàre: smart and secure applications in the livestock sector to promote digital innovation along the food supply chain". The initiative constitutes one of ten chapters of the "e.INS - Innovation Ecosystem for Next Generation Sardinia" programme, which is funded by the PNRR. The overarching aim of the programme is threefold: firstly, to strengthen the link between business and research; secondly, to mitigate the social impacts associated with the crisis; and thirdly, to increase territorial inclusion. The coordination of the project is the responsibility of the Experimental Zooprophylactic Institute of Sardinia (IZS), with involvement from the Universities of Sassari and Cagliari, the company Abinsula and the National Interuniversity Consortium for Telecommunications (CNIT). The e.INS ecosystem has been meticulously designed to facilitate innovation processes and expedite their dissemination. It is also intended to encourage technology transfer to the production system, promote the involvement of local communities in the challenges of sustainable innovation, and support the territory in transitioning to an economy based effectively on knowledge. The programme is developed around the specialisation "Humanistic culture, creativity, social transformations, inclusive society" and enhances regional scientific vocations.

Within the e.INS initiative, the APPàre project endeavours to effect a transformation of the Sardinian sheep sector through the adoption of digital technologies and the analysis of large data sets. The operational hub constitutes an integrated digital platform, the purpose of which is twofold: firstly, to collect farm data, and secondly, to process and correlate this data to generate key performance indicators in different production areas. Consequently, farmers are empowered to make data-driven decisions for integrated farm management, utilising data that encompasses health, production, nutrition and environmental impact. The platform constitutes the inaugural integrated digital solution to have been designed specifically with Italian sheep farmers in mind. The objective of the platform is twofold: firstly, to facilitate decision-making and, secondly, to enhance efficiency, profitability and sustainability. The farms involved constitute the foundation of APPàre's cascade calls for proposals, assuming a dual function. Firstly, they serve to test and validate the platform, thereby providing multi-sector data (production, health, nutrition). Secondly, thanks to the funding received, they have procured advanced tools and equipment for precision farming, which are instrumental in the digitisation of processes. This is accompanied by participation in dedicated training courses, with the aim of creating a network of "smart" companies based on the sharing of knowledge and data. Finally, within the framework of e.INS, APPàre (Spoke 03) has activated synergies with other Spokes (Sustainable Mobility, Finance and Credit, Environmental Protection and Enhancement) to enable network economies and involve different actors, such as companies, cooperatives and trade associations, thus strengthening a truly collaborative ecosystem. The APPARÈ project is an initiative that focuses on the development of indicators that are designed to assist companies in achieving environmental sustainability.

This is the context for the specific contribution of this research, which involved the design and implementation of a calculator of climate-changing gas emissions to be integrated into the platform. The objective was to estimate the environmental impact associated with sheep farming for meat and milk production through the application of the LCA methodology:

- Formulate guidelines for the application of the LCA methodology.
- Quantify the efficiency of natural resource use (land, biomass, water, energy) and the environmental impact (in terms of CF) of a sample of livestock farms in Sardinia.

Develop a protocol for the development of indicators for the technical and environmental assessment of the livestock sector in Sardinia.

Materials and methods

The module dedicated to environmental impact assessment has been designed as an integrated component of the APPàre platform, with the aim of maximising data reusability and reducing the burden of data collection on the user. From an operational perspective, the calculator primarily utilises data already present on the platform, including company details, herd size and structure, milk production, feed management, and supplies. The calculator necessitates specific additions for variables that are not available in the reference databases. These include particular details on the waste management system, energy consumption and, when necessary, completion parameters for certain emission items. This architectural approach facilitates consistent management of information flows, ensuring traceability, consistency and auditability of the calculation throughout the entire process, from the collection of inputs to the return of indicators. The technical activities involved in the design of the APPàre platform commenced with an analysis of user needs, which was undertaken through an approach based on the creation of a series of user stories. These were then refined with the analysis of indices, through an approach based on the creation and analysis of data flows.

User story-based approach

The user requirements were analysed using a user story-based approach, a technique that is commonly utilised in the context of agile project management. A user story, as defined by Atlassian et al. (2025), constitutes an informal, high-level explanation of a software feature from the perspective of the end user. The purpose of this text is to articulate how a software feature will provide value to the customer. This structured approach has been demonstrated to facilitate the refinement and alignment of features and services, thereby ensuring that the platform effectively addresses real-world challenges.

Data flow analysis

The definition of data flows and calculation processes played a pivotal role in ensuring the accuracy and consistency of the indicators developed within the project. This structured approach enabled the systematic mapping of data sources, the establishment of calculation procedures, and the validation of the integration of different variables. This facilitated a thorough evaluation, thereby guaranteeing the appropriate utilisation of variables, as well as the assessment of data availability and the uniformity of calculations.

This approach enabled the clear definition of all relevant parameters, thus facilitating their seamless integration into the platform's user interface. Furthermore, continuous verification was undertaken in order to ascertain the availability of the requisite data within the reference databases or its obtainability from reliable sources.

Collection of Data

In order to validate the environmental calculation model, a survey was conducted at ten sheep dairy farms in the Sardinia region. The data was collected through direct interviews with farmers or through the administration of questionnaires, with the objective of gathering information on crop management, the number of animals present and the relative farming methods employed, gross saleable production, feed supply methods and diesel and energy consumption.

Spatial and temporal boundaries of the system

In the environmental assessment module of the calculator, the boundaries of the system are defined according to a cradle-to-farm-gate approach. Consequently, the analysis encompasses upstream processes pertaining to the production and procurement of pivotal inputs (e.g. feed and raw materials, fertilisers, energy and other technical means), in addition to processes executed within the farm environment (animal management, enteric fermentation emissions, manure management and storage, energy consumption and farm operations) and the associated direct and indirect emissions emanating from these processes. However, it should be noted that all stages subsequent to the product's departure from the farm, including post-farm transport, industrial processing, distribution, utilisation, and end-of-life management, are excluded from the scope of this study. In terms of the time frame, the average agricultural year from 1 September to 30 August is utilised as a reference point, as substantiated by numerous studies including Lunesu et al. (2025) and Vagnoni et al. (2015).

Allocation and Functional Unit

This calculator employs a simplified allocation rule, whereby the total environmental impact of the farm is attributed to milk production. Consequently, any co-products (e.g. meat, wool) are excluded from the impact allocation and do not contribute to the definition of the functional unit. Operationally, this is equivalent to setting an allocation factor for milk equal to 1 (100%), so that the total emissions estimated at farm level coincide with the emissions allocated to milk, as reported in numerous studies such as that by Atzori et al. (2015). The emissions intensity is thus calculated as the ratio between total emissions and corrected milk production (FPCM). In accordance with international guidelines and scientific literature in the field for environmental assessments of dairy production, the functional unit (FU) adopted is 1 kg of fat and protein corrected milk (FPCM). The utilisation of FPCM facilitates the standardisation of raw milk production, accounting for variations in energy content attributable to fat and protein percentages, thereby ensuring the comparability of results. The quantity of milk was converted to FPCM using the reference equation that has been commonly adopted for dairy sheep (e.g. Pulina et al., 2005).

Global warming potential

The CF is calculated from the sum of various emission sources, including enteric CH_4, CH_4 from waste, N_2O from waste, and CO_2 from energy and food. These are expressed in kg CO_2 equivalent according to the Global Warming Potential (GWP100) equivalence scale over a 100-year time frame.

The following conversions are applicable:

1 kg of CO_2 = 1 kg of CO_2 equivalent

1 kg of CH_4 = 27.9 kg of CO_2 equivalent

1 kg of N_2O = 273 kg of CO_2 equivalent

Model structure and formalisation of the equations implemented

The study was carried out following ISO 14040 and ISO 14044. The estimation of the CF is based on the guidelines for the AFOLU sector as reported in the 2019 Refinement of Volume 4, Chapter 10 (livestock and manure management) and Chapter 11 (managed soils, indirect and partitioning factors) of the Intergovernmental Panel on Climate Change (IPCC).

CH_4 emissions from enteric fermentation

The calculation of annual enteric CH4 emissions is performed through the utilisation of equation 10.19 from the IPCC (2019) report. This equation serves as a tool for the aggregation of CH_4 emissions across various animal categories. The equation calculates the product of stocking density and emission factor, thereby providing a comprehensive measurement of CH4 emissions for each animal category.

$$CH_{4,\ enteric} = \sum_{i} EF_{T,P}\ \left(N_{T,P}\right)$$

where $N_{T,P}$is the number of head of livestock species / category T in the country classified as productivity system P, EF is the emission factor for the defined livestock population T and the productivity system P, in kg CH_4 head-1 yr-1, CH_4 emission factor for each category of livestock developed per head of animal kept in the specified productivity system (Table 10.10).

CH_4 emissions from manure management

CH_4 from manure is estimated using IPCC Equation 10.22 (Tier 1), which quantifies emissions as the product of: (i) number of animals per category, (ii) annual volatile solids (VS) excretion, (iii) proportion of VS managed in each management system (AWMS), and (iv) system-specific emission factor (EF), with final conversion from grams to kg.

$$CH_{4,mm} = \ \sum \left(N_{T,P} \cdot VS_{T,P} \cdot AWMS_{T,S,P} \cdot EF_{T,S,P}\right)/1000$$

con $EF_{T,S,P}$ emission factor for direct CH_4 emissions from manure management system *S,* by animal species/category *T*, in manure management system *S*, for productivity system *P*, when applicable (Table 10.14), g CH_4 kg VS-1

N_2O emissions from manure management (direct and indirect)

Direct N_2O from storage/waste management (IPCC Eq. 10.25, updated). Direct emissions are calculated based on nitrogen excreted and the amount managed in each system, applying the specific emission factor for the manure management system and the conversion from N_2O–N to N_2O:

$$N_2O_{D,mm} = \left[\sum_{T,P}\sum_{S}\left(N_{T,P} \cdot Nex_{T,P} \cdot AWMS_{T,S,P} \ + \ N_{cdg,s}\right) \cdot EF3(S)\right] \cdot \frac{44}{28}$$

where is the number of animals in the category (and any production class), is the annual nitrogen excretion per animal, is the share of nitrogen excretion allocated to the management system, emission factor for direct N_2O emissions from manure management system *S* in the country, kg N_2O-N/kg N in manure management system *S*, *S* manure management system, and represents any nitrogen input from co-digestates (assumed to be zero if not applicable).

N losses due to volatilization and indirect N_2O from deposition

The proportion of nitrogen that volatilizes as NH_3/NOx from management systems is estimated with (IPCC Eq. 10.26–10.28) as:

$$N_{volatilization,MMS} = \sum_{T,P}\sum_{S}\left(N_{T,P} \cdot Nex_{T,P}) \cdot AWMS_{T,S,P} +)N_{cdg,s}\right) \cdot FracGasMS_{T,S}$$

Indirect N_2O emissions due to atmospheric deposition of volatilized nitrogen are therefore calculated as:

$$N_2O_{G,mm} = N_{volatilization,MMS} \cdot EF4 \cdot \frac{44}{28}$$

where is the fraction of managed nitrogen that volatilizes in the system and emission factor for N_2O emissions from atmospheric deposition of nitrogen on soils and water surfaces, kg N_2O-N (kg NH_3-N + NOx-N volatilized)-1 ; given in Chapter 11, Table 11.3.

Indirect N_2O from leaching

$$N_2O_{L,mm} = N_{leaching,MMS} \cdot EF5 \cdot \frac{44}{28}$$

where is the fraction of managed nitrogen subject to leaching/runoff in the system, and emission factor for N_2O emissions from nitrogen leaching and runoff, kg N_2O-N/kg N leached and runoff, given in Chapter 11, Table 11.3 (IPCC Eq. 10.29).

Emissions from fertilizers (managed soils approach)

When data on nitrogen added to soils (e.g., fertilizers purchased/used) are available, the calculator quantifies direct N_2O emissions from managed soils using Tier 1 equation in Volume 4, Chapter 11, Equation 11.1, which considers the main sources of N input (mineral and organic fertilizers, crop residues, mineralization, etc.):

$$N_2O_{direct,\ soil} = N_2O\text{-}N_{direct} \cdot \frac{44}{28} \cdot 273$$

estimated according to IPCC formalization for managed soils; 273 is the conversion factor from N_2O to CO_2eq.

Emissions from energy and food supply

Emissions linked to energy consumption are calculated using an activity data approach multiplied by the emission factor, consumption for the relative emission coefficient equal to 0.44 kg CO_2 kWh^{-1} for electricity (ISPRA, 2011) and 3.54 kg CO_2 kg^{-1} for diesel fuel (3.15 kg CO_2 kg^{-1} resulting from fuel combustion and 0.39 kg CO_2 kg^{-1} resulting from its production; Rotz et al. (2010), consistent with the logic of the tool:

$$CO_{2,energy} = (Diesel\_L \cdot EF_{diesel}) + (Electricity\_kWh \cdot EF_{grid})$$

Emissions from feed procurement

Emissions linked to feed procurement are calculated using an activity data approach multiplied by the emission factor, consistent with the logic of the tool:

$$CO_{2eq,feed} = \sum_{j} (Q_j \cdot EF_j)$$

where represents the quantity purchased of the feed category and the relative emission factor (from bibliographic sources/databases selected and coded in the calculator), as shown in Table 1.

Aggregation in CO_2 equivalents and indicator per kg FPCM

Once emissions have been quantified for each source (enteric fermentation, waste management, energy consumption, feed procurement and, where applicable, fertilizers), applying equations and emission factors consistent with the Intergovernmental Panel on Climate Change guidelines, they are converted to CO_2 equivalents using the respective global warming potential (GWP) factors adopted by the model. The CO_2 eq components are then aggregated to obtain the overall footprint within the "cradle-to-farm-gate" boundaries. The results are reported in two ways, absolute and intensive, accompanied by a percentage breakdown:

Absolute emissions for each macro emission source, emissions are reported as kg CO_2eq·year^{-1}, i.e:

$$E_k = (\mathrm{kg\ CO_2eq\backslash FPCMyear^{-1}})$$

The total for the farm is calculated as:

$$E_{tot} = \sum_k E_k$$

Normalized emissions (/kg FPCM)

To enable comparison and benchmarking, emissions are also expressed as kg CO_2 eq kg FPCM^{-1}, normalizing each component (and the total) to annual FPCM production:

$$I_k = \frac{E_k}{FPCM}; I_{tot} = \frac{E_{tot}}{FPCM}$$

where is the total quantity of milk corrected for fat and protein produced during the reference period, calculated according to the formula by Pulina et al. (2005) for sheep's milk normalized for fat (6.5%) and protein (5.8%):

FPCM = Milk production x (0.25 + 0.085 x % fat + 0.035 x % protein)

Percentage contribution (%)

finally, the table shows the relative incidence of each macro-source on the total, calculated as:

$$\%_k = \frac{E_k}{E_{tot}} \times 100$$

This metric supports the identification of emission hotspots and the prioritization of improvement levers. In line with the calculator's setup, the summary results are therefore reported as: (i) total annual footprint (kg CO_2 eq·yr^{-1}), (ii) emission intensity per functional unit (kg CO_2 eq kg $FPCM^{-1}$), and (iii) percentage breakdown by macro-source, ensuring an integrated reading (total impact) and a comparative reading (performance per product unit).

Statistical analysis

The analysis was conducted on ten Sardinian dairy sheep farms. Data processing and statistical analyses were performed using Microsoft Excel. Descriptive statistics (mean, standard deviation, minimum and maximum) were calculated for the main structural, productive, input-use and emission variables. Correlation analyses were used to explore the relationships between carbon footprint intensity (kg CO_2 eq/kg FPCM) and selected technical-management variables. Simple linear regression was applied to assess the association between emission intensity and production level, while multiple linear regression models were used to evaluate the combined effect of production level and selected input-use variables on emission intensity and to estimate the coefficient of determination (R^2). Statistical significance was considered at $P < 0.05$.

Results and Discussion

Sample characteristics and production performance

The sample demonstrates significant heterogeneity in terms of size, with an average farm size of 137 hectares, ranging from 50 to 450 hectares. The average herd size is 702 lactating ewes (260–1,450; ± 47176). The production profile indicates an average milk sales production of 180,236 L/yr (43,133–453,344; ±171.20). The production level (expressed as kg FPCM/ewe/yr) averages 261.33 (150.78–350.68; ±79.67), confirming the presence of farms with very different performances and, consequently, with different potential for dilution of emissions per unit of product (Opio et al., 2013; Sodi et al., 2024), as shown in Figure 1.

On the input side, the average quantity of purchased feed amounts to 113.51 t/yr (41.30–255.00; ±67,91), corresponding to 147.12 kg/adult animal/yr (24.82–347.22; ±93.99). Energy consumption exhibited further variability: diesel fuel averaged 17,443 L/yr (6,000–65,000; ±17516,11), equating to 19.41 L/adult animal/yr (5.04–35.77; ±10.82); purchased electricity averaged 17,062 kWh/yr (1,190–52,000; ±15353,26), equating to 16.84 kWh/adult/yr (2.73–32.46; ±9.58). Electricity production from renewable sources is present in three farms, with values ranging from 1,525 to 13,000 kWh/yr, thus confirming that self-production solutions are not yet widespread, as shown in Table 2.

Carbon footprint: emission intensity and contributions by source

The total estimated emissions average at 457.22 t CO_2 eq/yr, with a range of 193.64–886.71 t CO_2 eq/yr. With regard to intensity, the mean CF is 2.94 kg CO_2 eq/kg FPCM (1.84–5.13, ±1.5), thus demonstrating a considerable disparity between the most efficient companies and those with higher emission intensity. Despite the considerable heterogeneity, these values are highly representative of the production reality in Sardinia and the Mediterranean basin, as reported in the studies by Lunesu et al. (2025), Vagnoni et al. (2018) and Atzori et al. (2022). The primary outcomes are delineated in Table 3. The breakdown of emission intensity (kg CO_2 eq/kg FPCM) indicates the following:

-The average contribution of enteric fermentation is 1.58 (0.91–3.05; ±0.74);

-Manure management contributes an average of 0.19 (0.11–0.35; ±0.08);

-Fertilizers account for an average of 0.05 (0.01–0.19; ±0.07);

-The supply of purchased feed contributes an average of 0.72 (0.07–2.27; ±0.59), with the most marked variability;

-The energy component accounts for an average of 0.40 (.21–0.64; ±0.14).

With regard to percentage share of the total, the average values correspond to those documented in the extant literature (Lunesu et al., 2025; Vagnoni et al., 2018). The emissions inventory is predominantly influenced by enteric fermentation (53.35%, range 37.88–70.78%; ±0.10), a finding that is indicative of the greater variability observed in more extensive farms, where a diet consisting primarily of grazing results in a higher percentage of enteric emissions compared to other factors (Vagnoni et al., 2018). This is followed by purchased feed (22.81%, 4.07–44.12%¸±0.11). The high variability observed reflects the different degrees of feed self-sufficiency of Sardinian farms, which is why reducing the use of external feed is a key strategic lever for mitigation, as reported in the study by Vagnoni et al. (2017), who estimate that soybean meal and purchased cereals together account for between 20% and 24% of the total footprint.

Energy, at 15.00% (6.46–27.24%; ±0.07), demonstrates that the utilisation of agricultural machinery or diesel generators can impact the environmental profile, particularly in farms equipped with oversized equipment or those engaging in inefficient milking and refrigeration practices, as also reported by Vagnoni et al. (2014). Manure management accounts for an average of 6.39% (4.63–8.21%; ±0.01), while fertilisers are marginal overall (2.45% on average), although there are cases where the share reaches higher values (up to about 10.56%), consistent with the different levels of nitrogen inputs observed. The low percentage of fertilizers (2.45%) is consistent with the characteristics of Mediterranean pastoral systems. However, the peak of 10.56% recorded reflects the results of Vagnoni et al. (2024), who associate higher emission values (Resource Use and Marine Eutrophication) with the use of nitrogen fertilisers to force arable crops on less extensive farms. The breakdown of these figures is illustrated in Figure 2.

Relationships between emission intensity and technical-management drivers

The analysis of the relationships indicates that the variable most closely associated with the CF is the production level (kg FPCM/sheep/yr), which demonstrates a very strong negative correlation with emission intensity ($r = -0.892$). This finding is in full accordance with the results of Lunesu et al. (2025). In terms of management interpretation, the data indicate that, as production is adjusted for fat and protein per head, the footprint per kg of product tends to decrease, likely due to the combined effect of efficiency and dilution of maintenance emissions (Opio et al., 2013), as shown in Figure 3. The relationship is confirmed by simple linear regression, in which emission intensity (kg CO_2 eq/kg FPCM) is explained by production level with $R^2 = 0.795$ and a negative slope ($\beta = -0.01285$; $p < 0.001$). Operationally, this implies that an increase of +10 kg FPCM/ewe/yr is associated, on average, with a reduction of approximately 0.13 kg CO_2 eq/kg FPCM (all other conditions being equal). This finding is in accordance with Vagnoni et al. (2024), who demonstrate that GWP (Global Warming Potential) values per kg of FPCM are negatively correlated with production performance. In addition to production, a moderate positive correlation is observed between emission intensity and feed purchased per adult animal ($r = 0.427$), indicating that elevated levels of external inputs (particularly commercial feed) can contribute to an augmentation of the CF, particularly when they do not result in a proportional increase in output. The validity of these results is further substantiated by Sodi et al. (2024), who emphasise that the environmental performance of farms is subject to significant penalties as the proportion of feed procured from external sources increases. However, the relationship between purchased feed and production level is weak ($r = -0.148$), indicating that in the sample, an increase in purchased inputs does not necessarily coincide with an improvement in performance per head, as discussed by Escribano et al. (2020), who note that in intensified systems, the proportion of emissions from feed increases, but this increase must be offset by a sharp increase in productivity to lower the unit impact (Escribano et al., 2020). The multiple regression model that incorporates production level and purchased feed demonstrates enhanced explanatory power ($R^2 = 0.884$). In this specification, production level maintains a robust and significant effect ($\beta = -0.01221$; $p < 0.001$), while the effect of purchased feed is positive but borderline ($\beta = +0.00368$; $p = 0.054$), consistent with a potential role of purchased inputs as a secondary driver of emission intensity, as shown in Figure 4. With regard to urea fertilisers (kg/ha), a negative correlation is observed with emission intensity ($r = -0.524$), yet concurrently, a positive correlation is evident with production levels ($r = +0.695$). The application of regression analysis (emission intensity with fertilisers + production level) indicates that, once production is controlled for, the effect of fertilisers is not statistically significant

($p > 0.4$), while production level remains the dominant driver. Vagnoni et al. (2024) also observe similar dynamics, noting that greater use of fertilisers per unit area to stimulate milk production results in greater total or per-hectare impacts, but improves efficiency per kg of milk. Finally, with regard to the CF (kg CO_2 eq/kg FPCM), diesel fuel demonstrates a moderate negative correlation in both absolute terms ($r = -0.484$; $p = 0.156$) and per adult animal ($r = -0.490$; $p = 0.151$). This suggests that higher consumption is characteristic of farms with greater scale and operations, and frequently, better output (structure effect). Purchased electricity demonstrates a weaker relationship ($r = -0.287$; $p = 0.421$ in annual terms; $r = -0.140$; $p = 0.700$ per adult head). When normalised per litre of milk sold, electricity demonstrates a moderate positive relationship ($r = 0.537$; $p = 0.109$), indicative of a potential penalty on emission intensity in the presence of high electricity consumption compared to reduced output, as also reported by Vagnoni et al. (2015). The empirical framework of the sample provides substantial support for a key data-driven conclusion: the variability of the footprint per kg of product is predominantly explained by the level of production, with inputs such as purchased feed and fertilisation acting as secondary or indirect factors, the impact of which is contingent on their return in terms of output.

Conclusion

In conclusion, this chapter has demonstrated how the APPàre platform was conceived as a means to augment corporate data collection as a strategic resource. This transformation of data collection from a purely descriptive activity into an operational infrastructure is a significant development, as it renders the measurement, comparison, and enhancement of performance in a traceable manner possible. The methodological framework, predicated on the definition of requirements through user stories, the mapping of information flows, and the formalisation of calculation rules, ensures consistency between input data, applied transformations, and returned indicators, thereby reducing interpretative ambiguity and increasing the overall robustness of the system. The platform's contribution is twofold and complementary. At the company level, APPàre facilitates concrete decision support through the standardisation of KPIs, the capacity to interpret performance in a comparative key, and the more immediate identification of priority areas for intervention. The outputs generated can be utilised for both internal management and for reporting and comparison purposes throughout the supply chain. At the political-institutional level, the establishment of a consistent, replicable and verifiable information architecture is imperative for enhancing governance within the sector. This architecture facilitates the monitoring of progress over time, enables territorial comparability, and enables the evaluation of the efficacy of implemented measures. Furthermore, it supports the planning and potential calibration of incentive tools grounded in empirical evidence. The chapter's significance lies not merely in its delineation of a technical solution, but in its establishment of a comprehensive framework that facilitates the quantifiable assessment of sustainability, thereby ensuring its effective management at both the corporate and public decision-making levels.

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https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch11_Soils_N2O_CO2.pdf#page=12.06

Tables and Figures

Table 1. Tabella coefficienti di emissione per alimenti acquistati (Fonte: Serra, 2014).

Feed	Emission factor, kg CO_2eq kg di DM^{-1}
Mixed hay (gramineous and leguminous plants)	0.20
Commercial product rich in protein	0.80
Commercial product	0.0
Cereal by-products	0.40

Table 2. Main characteristics of farms. (Data are presented as mean; SD; min; max).

Characteristics	Mean	SD	min	max
Farm area, ha	136.97	115.55	50	450
Days of lactation, days/yr	210	-	-	-
Average weight, kg	52	4.83	45	55
Lactating sheep, n	702.2	471.76	260	1450
Dry sheep, n	108.8	171.20	10	570
Replacement, n	164.3	90.74	60	300
Rams,n	26.5	16.75	10	59
Lambs, n	640.1	403.49	128	1500
Feed purchased, ton/anno	113.505	67.91	41.3	255
Urea fertilizers purchased, kg/anno	3692.85	3635.41	100	8250
Diesel, litri/anno	17443.1	17516.11	6000	65000
Purchased energy, kWh/anno	17061.8	15353.26	1190	52000
Energy produced, kWh/anno	7865	5831.63	1525	13000
Milk sold, l/anno	180236.4	141557.65	43133	453344

Characteristics	Mean	SD	min	max
Fat, %	6.425	0.25	5.85	6.74
Protein, %	5.531	0.26	5.2	5.97
Lactose, %	4.5	0.00	4.5	4.5
Fat/protein ratio, %	1.162	0.04	1.09	1.21
Stocking rate, capo/ha	7.39	6.25	2.00	23.52
Production level, kg FPCM/yr per ew	261.33	79.67	150.78	350.68
Daily production, kg FPCM/day per ewe	1.24	0.38	0.72	1.67
Feed purchased, kg/yr/sheep	147.12	93.99	24.82	347.22
Urea fertilizers purchased, kg/yr/ha	21.32	33.40	0.00	100.00
Diesel, l/yr per sheep	19.41	10.82	5.04	35.77
Purchased energy, kWh/yr per sheep	16.84	9.58	2.73	32.46

Table 3. Emission intensity and contributions by source (mean; SD; min; max)

Emissions	Mean	SD	Min	Max
CO_2eq from enteric CH_4	1.58	0.74	0.91	3.05
CO_2eq manure management	0.19	0.08	0.11	0.35
CO_2eq from fertilizers	0.05	0.07	0.00	0.19
CO_2eq from animal feed	0.72	0.59	0.07	2.27
CO_2eq from energy	0.40	0.14	0.21	0.64
CO_2eq kg of kgFPCM allocation	2.94	1.15	1.84	5.13

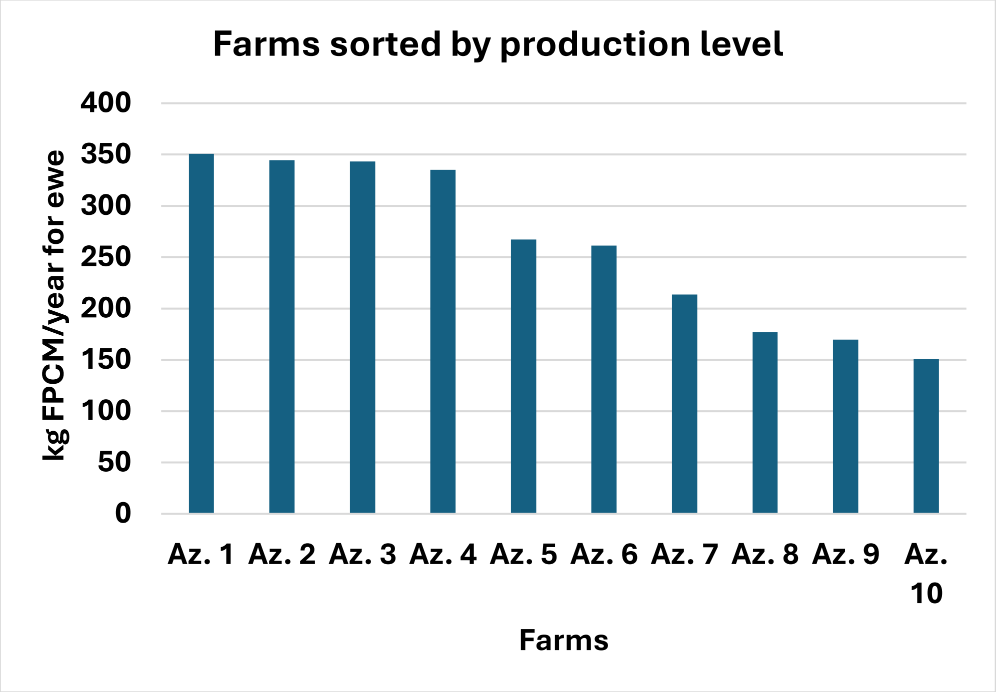

Figure 11. Companies sorted by production level

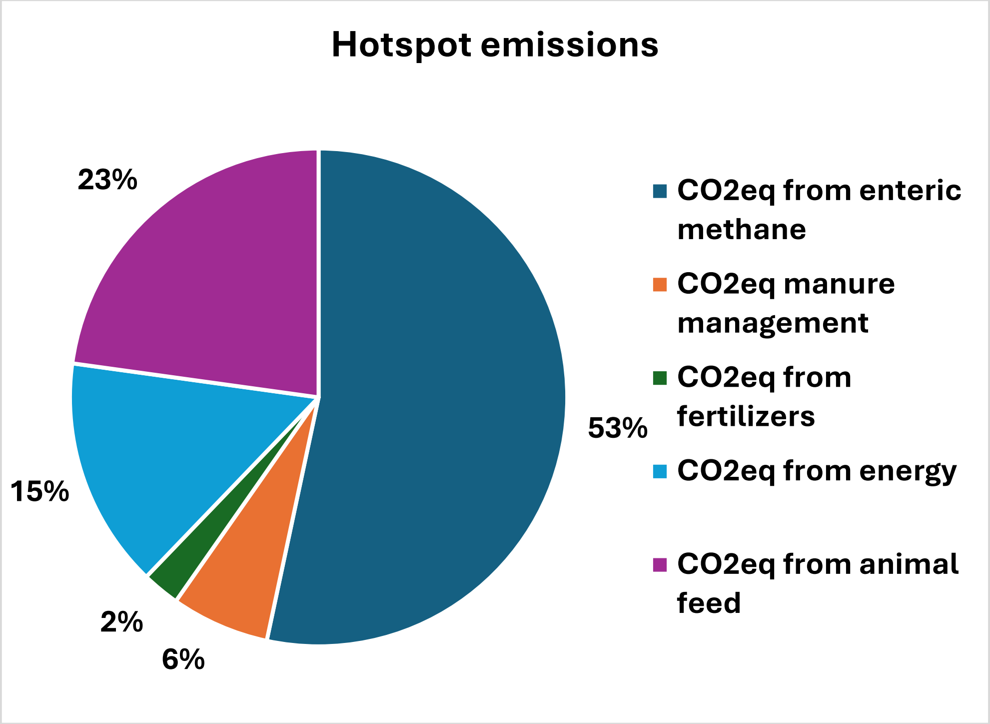

Figure 12. Emissions breakdown

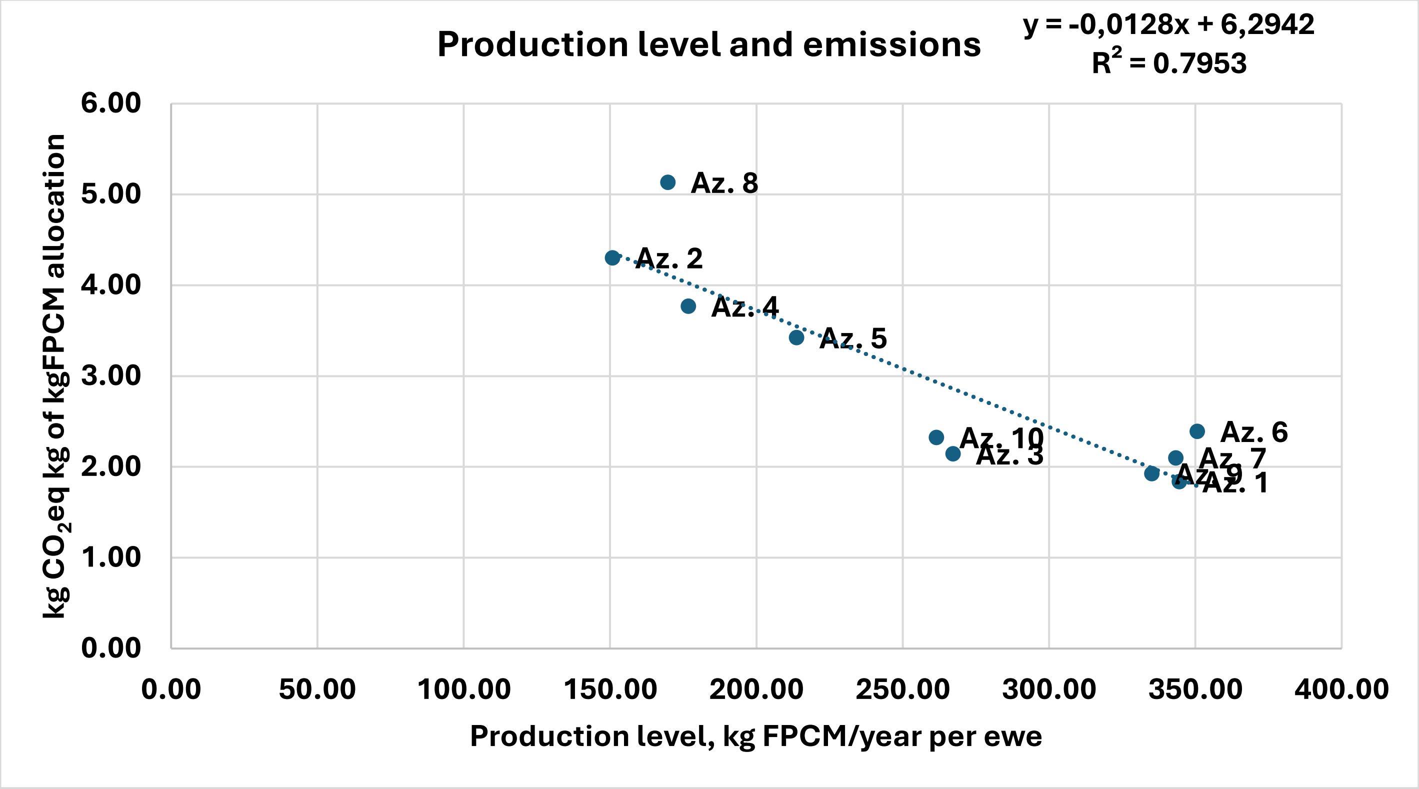

Figure 13. Production level and emissions

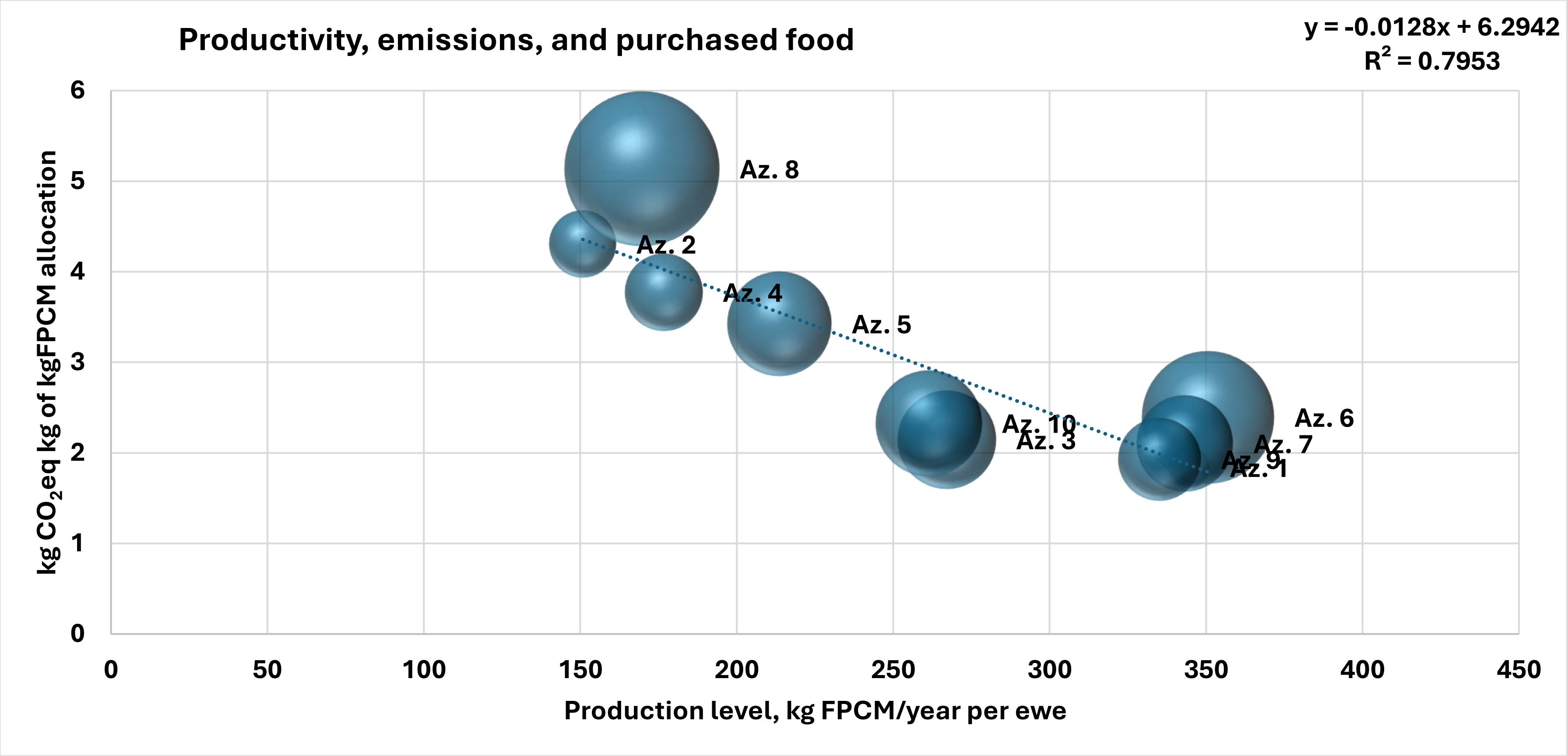

Figure 14. Productivity, emissions and purchased feed

CHAPTER 4

Quantifying the carbon footprint and environmental monitoring in the sheep milk supply chain: the CAO Cooperative's path to sustainability

Abstract

In sheep dairy supply chains organised into cooperatives, carbon footprint (CF) accounting can be leveraged as a governance resource: it standardises metrics, enables benchmarking among members, and transforms farm-level variability into a decision-ready dashboard useful for technical support and mitigation planning.

The aim of the chapter was to quantify the CF of the primary production phase of the Cooperativa Allevatori Ovini (CAO) in Oristano, Sardinia, using a standardised LCA approach to identify critical emission points and define a set of operational KPIs to support capacity building at the cooperative level and performance harmonisation. The assessment was conducted on 18 dairy sheep farms in Sardinia with boundaries from cradle to farm gate, focusing exclusively on the primary phase. The methodological framework followed ISO 14040/14044/14067 standards, in line with PEF Dairy 2018. The functional unit was 1 kg of milk corrected for fat and protein content (FPCM). Primary data were collected through interviews and questionnaires concerning livestock, feed used on and off the farm, and the farm's impact. Enteric emissions of CH_4 and N_2O were estimated following the 2006 IPCC, updated in 2019 (AFOLU), and converted to CO_2 eq using IPCC AR6 GWP100 (CO_2=1; non-fossil CH_4=27; N_2O=273). Upstream processes (feed, fertilisers and energy) were quantified using emission factors (Ecoinvent). The average emission intensity was 3.61 kg CO_2 eq/kg FPCM, with a wide range (1.74-5.67), indicating strong potential for cooperative benchmarking and the implementation of targeted technical actions. The emissions profile reflects the typical hierarchy of ruminants, with enteric fermentation as the dominant component, and shows farm-specific variability in manure, feed supply and energy. Productivity per sheep present emerged as the most relevant factor: simple linear regression showed a strong negative association between production level (kg FPCM/head/yr) and emissions intensity ($R^2 = 0.818$; adjusted $R^2 = 0.807$; $p = 2.55\times10^{-7}$). The case study posits CF measurement as an operational prerequisite for the CAO to align environmental performance with competitiveness. In fact, the cooperative can implement a KPI-based dashboard to prioritise interventions, structure capacity building and monitor progress over time. In management terms, productivity per head is confirmed as a first-level KPI for emissions efficiency governance.

Keywords

CAO cooperatives; dairy sheep farms; life cycle assessment (LCA); carbon footprint; cradle-to-farm-gate; benchmarking; emission hotspots; productivity per head

Introduction

In Sardinia, sheep farming is not simply a niche market, but a sector that plays an important economic and social role, supported by a network of specialised producers who also contribute to protecting the local area. ISMEA's analysis of BDN (National Database) data from the Livestock Registry indicates that over 93% of Italy's sheep population is concentrated in the centre-south, with a clear predominance in the region of Sardinia, which is home to approximately 49% of the total (2,658,122 sheep). Similarly, ISMEA's analysis highlights a prevalence of specialisation in milk production, with a percentage exceeding half of the total. This profile is directly reflected in production, as evidenced by data from 2023 showing a regional supply of approximately 315,000 tonnes of sheep's milk, corresponding to approximately 68% of national deliveries (Laore, 2026). In structural terms, there has been a reduction in the number of farms (over 30,000 fewer sheep and goat farms between 2019 and 2024, approximately -22%), with average flock sizes in the small-medium range (approximately 140-333 sheep per farm); farms with more than 300 head remain in the minority, but account for about half of the animals raised (Laore, 2026). Milk production is dominated by the Sardinian breed (about 80%), described as a high-yield breed with average production of around 201 L/ewe (Pulina et al., 2018); at regional level, more extensive contexts coexist in mountainous and silvopastoral areas (very low stocking densities) and lowland contexts with higher stocking densities and more intensive management (Atzori et al., 2022).

This structure is consistent with the biophysical context. The production profile of dairy sheep in Sardinia is a direct consequence of the Mediterranean climate, where hot, dry summers and mild, wet winters result in highly seasonal forage availability, with rainfall concentrated between autumn and winter and prolonged drought from May to October (Arca et al., 2021). In this context, seasonality plays a managerial role, with production cycles (calving and lactation) organised in accordance with periods of greater availability of biomass from natural pastures, in order to maximise the use of the system's most competitive resource, namely grass (Atzori et al., 2022). The Bioclimatic Map of Sardinia (30-year period 1971-2000) provides a useful territorial reference for interpreting the climate architecture and its local variability, which is reflected in the production opportunities and limitations of the different areas. In this context, farming diversity should not be interpreted as a mere difference in farming styles, but rather as a rational and measurable response to territorial constraints and access to resources. At the same time, farmers and processors operate in an environment characterised by three external factors that limit their ability to make autonomous decisions. The first model is economic and market-based, with margins depending on the balance between price and cost structure, resulting in exposure to volatility. With regard to Sardinia, ISMEA (2024) reports an average sheep's milk price of €135/100 L for 2024. In terms of demand, ISMEA (2026) noted an increase in agri-food exports in 2025, with cheese among the growing categories, consolidating opportunities but also exposure to cycles and shocks in the outlet markets. The second driver is climate-related and production-related: when the fodder base becomes unstable, decisions regarding the purchase of concentrates, the duration of lactation, replacement and health cease to be tactical optimisations and become levers that simultaneously influence costs, production and emission profiles (Marino et al., 2016). The third driver is regulatory and standards related. The CAP

2023-2027 integrates instruments such as eco-schemes to promote practices that generate environmental and climate benefits (EU Commission; MASAF).

The supply chain is called upon to maintain an operational structure in which competitiveness and social licence are not alternative objectives, but complementary drivers (Vagnoni et al., 2017; Atzori et al., 2015). Competitiveness supports economic sustainability and the solidity of the industrial sector; social licence protects operational continuity and access to markets, reducing the risk of reputational damage and regulation (Vagnoni et al., 2017). Given that uncertainty is no longer episodic but structural, the ability to measure, report and improve environmental and social performance becomes a lever for resilience and competitive positioning (Cossu et al., 2024; Pulina et al., 2018). In this context, the CF acts as a transition metric between reducing uncertainty and generating value, as it allows complexity to be managed by separating physiological variability from correctable inefficiencies (benchmarking), establishing links between technical decisions (feed, productivity, purchased inputs, energy, manure management) and a key performance indicator (KPI) that can be compared over time (monitoring), producing evidence that can be used for accountability and supply chain dialogue. In other words, measurement is not only a means of communication, but also a means of decision-making and ensuring the replicability of improvement (Pulina et al., 2018). In quantitative terms, the production of LCA studies relating to sheep dairy systems, with cradle-to-farm-gate boundaries and the functional unit set at 1 kg of fat and protein corrected milk (FPCM), indicates that the climate footprint associated with milk production tends to be limited. In particular, in representative farms with different levels of input, emissions vary depending on the farming system and geographical area, but the average is between 2.4 and 3.8 kg of equivalent. The overall range of studies is between 1.8 and 5.2 kg of CO_2 eq, with hotspots mainly attributable to enteric CH_4, followed by processing/cultivation operations, electricity and machinery (Lunesu et al., 2025). For sheep's milk cheeses with Protected Designation of Origin (PDO), evidence from LCA confirms the “farm-driven” nature of performance in terms of climate impact. In the specific case of Pecorino Romano PDO, whose study covered the entire cycle, from primary production to retail, the CF stands at 16.9 kg CO_2 eq per 1 kg of cheese. The milk production phase contributes approximately 92% of total emissions, while the cheese-making phase contributes approximately 7%, with residual contributions from harvesting and transport.

The process analysis identifies the following priority areas for improvement: enteric CH_4, which accounts for approximately 53.4% of the total, the optimisation of purchased feed, the rationalisation of purchases and the use of fuel and electricity offer a reading consistent with a supply chain governance approach based on benchmarks and technical support plans. In this context, the role of the CAO Sheep Farmers' Cooperative (based in Oristano, founded in 1966) takes on crucial importance. Numerous studies have shown that, in the sheep cheese production sector, environmental performance is significantly influenced by the primary phase and, in the cases examined, can account for over 90% of the overall contribution to environmental impact (Vagnoni et al., 2017). In this context, the cooperative can operate as a “reflective governance structure” (Atzori et al., 2022), standardising languages and metrics based on LCA (Vagnoni et al., 2019), building shared references and transforming scattered data into a useful dashboard. This makes it possible to provide the technical support needed to harmonise performance among members and make climate mitigation strategies feasible in a concrete way (Escribano et al., 2020; Atzori et al., 2022).

The main objective of this chapter is to quantify the CF of the supply chain linked to the Cooperativa Allevatori Ovini (CAO) in Oristano, applying the standardised LCA methodology (Vagnoni et al., 2017). Measuring the CF of the CAO is not merely an accounting exercise, but a diagnostic and strategic tool (Vagnoni et al., 2017). In particular, the chapter pursues the following specific objectives:

1. Identification of emission hotspots: Analyse the data inventory to identify critical points in the cooperative's supply chain
2. Definition of a dashboard for governance and capacity building: Transform the environmental data collected into standardised metrics that the Cooperative can use as a platform for territorial governance. Providing the CAO with the benchmarks necessary to implement technical support actions (capacity building) aimed at its members, filling information gaps and promoting the adoption of good practices (eco-innovations) capable of improving resource efficiency

The chapter aims to demonstrate how the CAO's measurement of the CF is the operational prerequisite for harmonising the economic profitability of farmers with environmental sustainability, guiding the ecological transition of the entire local production system, representing the first step towards possible adherence to ecological certification and environmental labelling schemes, transforming sustainability from a cost to a lever of competitiveness and resilience for the entire supply chain.

Materials and methods

The analysis was conducted on a sample of 18 dairy sheep farms located in Sardinia (n = 18), distributed across several municipalities and along a heterogeneous territorial gradient. For the purposes of describing the sample, the following data were recorded: average air temperature (16.0–19.5 °C; average 18.25; SD 0.88), altitude (7–670 m a.s.l.; mean 140.33; SD 181.48) The methodological approach followed ISO 14040, ISO 14044 and ISO 14067 standards and was aligned with PEF Dairy 2018. This case study concerns exclusively the primary phase of the CAO Cooperative members; the processing and distribution phases are not included. The system was modelled with cradle-to-farm-gate boundaries, including in the system boundaries all the input and output related to sheep milk production, Figure 1. Using 1 kg of sheep milk corrected for fat and protein (FPCM) as the functional unit; normalisation to FPCM was carried out according to the equation of Pulina et al. (2005). The inventory (LCI) was constructed through interviews following a questionnaire organised into the subsets of livestock, feed (farm and off-farm feed) and farm impacts (energy, fuels, water, materials used), ensuring consistency between primary data and calculations. The estimation of CH_4 and N_2O emissions is based on the IPCC Guidelines 2006 updated by the 2019 Refinement (Volume 4, AFOLU), with particular reference to the methods for enteric fermentation and manure management (Chapter 10) and for N_2O from managed soils and CO_2 from urea/lime (Chapter 11). The conversion to CO_2 eq adopts the IPCC AR6 GWP100 (CO_2=1; non-fossil CH_4=27; N_2O=273) as reported in the manual; "upstream" processes (feed, fertilisers, energy) are valued with emission factors from Ecoinvent according to the tables shown in Table .

The cradle-to-farm-gate approach and the use of FPCM as FU are in line with the LCA literature on sheep milk (Lunesu et al., 2025; Atzori et al., 2022).

Sheep milk normalised for fat (6.5%) and protein (5.8%):

FPCM = Milk production * (0.25 + 0.085 * % fat + 0.035 * % protein)

Formulas for enteric CH_4 emissions

Enteric CH_4 emissions are determined using the methodology proposed by Vermorel et al. 2008, and are calculated using the following formula:

$$Me = \frac{\text{ME} * \text{Ym} * 365}{55.65} N_i$$

where:

Me = enteric CH_4 emissions (kg CH_4 yr^{-1}); ME = metabolisable energy (MJ $head^{-1}$ d^{-1}); Ym = conversion factor, percentage of gross energy ingested by the animal converted into CH_4 (Table 1); 55.65 = energy contained in CH_4 (MJ kg CH_4^{-1}); Ni = number of heads.

Metabolisable energy, ME, is calculated as:

$$ME = GE * dig * 0.82$$

where:

ME = metabolisable energy (MJ $animal^{-1}$ d^{-1}); GE = gross energy intake (MJ $animal^{-1}$ d^{-1}); dig = diet digestibility (Table 2); 0.82 = conversion factor from digestible energy to metabolisable energy.

Gross energy intake, GE, is calculated using the following formula:

$$GE = DMI * 18.45$$

where:

GE = gross energy intake (MJ animal^{-1} day^{-1}); DMI = dry matter intake (kg animal^{-1} day^{-1}); 18.45 = standard value for energy density of feed (MJ kg DMI^{-1}).

For the calculation of dry matter intake (DMI), those proposed by Pulina et al. (1996) are used.

$\text{Lactating ewe} = (-0.545 + 0.095 \times \text{BW}^\wedge 0.75 + 0.65 \times \text{FPCM} + 0.0025 \times \text{BWchange}) \times \text{K}$

$\text{Dry ewe} = (-0.545 + 0.095\ \text{BW}^\wedge 0.75 + 0.005 \times \text{BWchange}) \times \text{K}$

$\text{Replacement ewe} = -0.124 + 0.0711\ \text{BW}^\wedge 0.75 + 0.0015 \times \text{BWchange}$

$\text{Reproductive ewe} = 0.065 \times \text{BW}^\wedge 0.75$

where:

DMI = dry matter intake (kg animal^{-1} d^{-1}); BW = live weight of the animal (kg);

FPCM = normalised milk (kg animal^{-1} d^{-1}); K = correction factor for pregnancy; BWchange = daily weight gain (kg).

CH_4 emissions from manure for sheep are determined using the methodology of the Intergovernmental Panel on Climate Change (IPCC), from: IPCC, 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Vol. 4 Agriculture, Forestry and Other Land Use-Ch.10-Emissions from livestock and manure management. CH_4 emissions from manure management are calculated using the following formula:

$$EMm_i = (N_i * VS_i * AWMS_i * EF_i)/1000$$

where:

EMmi = CH_4 emissions from manure per animal species (kg CH_4 yr^{-1}) Ni = number of animals; VSi = average value of volatile solids (VS) for each animal in each category (kg VS $animal^{-1}$ yr^{-1}); AWMSi = fraction of volatile solids present in the manure of each animal species, depending on the storage system used (dimensionless); EFi = emission factor for CH_4 from manure, for each animal species (g CH_4 kg VS^{-1}); (parameters indicated in Table 6)

The annual quantity of volatile solids (VS) produced is calculated using the following formula:

$$VS_i = \ (VS_{rate}\frac{TAMi}{1000}) * 365$$

where:

VSrate = standard VS excretion value (kg VS 1000 kg animal mass-1d-1) (Reference values are given in Table 3); TAMi = typical mass of each species (kg) (given in Table 6)

Formulas for nitrous oxide emissions from manure management

$$N_2O = \left(\left(N_2O - N * \frac{44}{28}\right) + NH_4 - N * 0.01 * \frac{44}{28}\right) * 365 * N$$

where:

N_2O = total nitrous oxide emissions from manure management (kg N_2O yr-1); N_2O-N = nitrous oxide emissions (kg N_2O-N head-1); 44/28 = conversion factor from nitrous oxide to nitrous oxide; NH_4-N = ammonium nitrogen emissions (kg NH_4-N head-1); 0.01 = percentage of nitrous oxide emissions from ammonium nitrogen; N = number of heads.

$$N_2O - N = N_{ex} * \%_{escp} * \%N_2O - N_p + N_{ex} * \%_{esc} - N_2O - N_s$$

where:

N$_2$O-N = nitrous oxide emissions (kg N$_2$O-N per head); Nes = nitrogen excreted (kg N head-1); %escp = percentage of nitrogen excreted at pasture; %N$_2$O-Np = % of nitrous oxide excreted at pasture (Table B.4.1); %escs = percentage of nitrogen excreted in the barn; %N$_2$O-Ns = % of nitrous oxide excreted in the barn (Table 4).

NH4-N emissions are calculated as follows

$$NH_4 - N = N_{ex} * \%_{escp} * \%NH_4Np + N_{ex} * \%_{esc} * \%NH_4 - N_s$$

where:

NH$_4$-N = ammonium nitrogen emissions (kg NH$_4$-N per head);Nes = nitrogen excreted (kg N per head);%escp = percentage of nitrogen excreted at pasture;% NH$_4$-Np = % of ammonium nitrogen excreted at pasture (Table B.4.2);%escs = percentage of nitrogen excreted in the barn;% NH$_4$-Ns = % ammonium nitrogen excreted in the barn (Table 4).

Emissions from fertilisers (managed soils approach)

When data on nitrogen added to soils (e.g. fertilisers purchased/used) are available, the calculator quantifies direct N$_2$O emissions from managed soils using the equation in Volume 4, Chapter 11, Equation 11.1, which considers the main sources of N input (mineral and organic fertilisers, crop residues, mineralisation, etc.): Table 5 shows the emission factors for the main fertilisers used in agriculture

$$N_2O_{direct,\ soil} = N_2O\text{-}N_{direct} \cdot \frac{44}{28} \cdot 273$$

estimated according to IPCC formalisation for managed soils; 265 is the conversion factor from N$_2$O to CO$_2$eq.

Emissions from food procurement

Emissions linked to food procurement are calculated using an activity data approach multiplied by the emission factor, consistent with the logic of the tool:

$$CO_{2eq,feed} = \sum_{j} \left(Q_j \cdot EF_j\right)$$

where represents the quantity purchased of the food category and the relative emission factor (from bibliographic sources/databases selected and coded in the calculator), as shown in Table 5.

Emissions from energy and food supply

Emissions linked to energy consumption are calculated using an activity data approach multiplied by the emission factor, consumption for the relative emission coefficient equal to 0.44 kg CO2 kWh^{-1} for electricity (ISPRA, 2011) and 3.54 kg CO_2 kg^{-1} for diesel (3.15 kg CO2 kg^{-1} from fuel combustion and 0.39 kg CO_2 kg^{-1} from its production; Rotz et al., 2010).

$$CO_{2,energy} = (Diesel\_L \cdot EF_{diesel}) + (Electricity\_kWh \cdot EF_{grid})$$

Aggregation in CO_2 equivalents and indicator per kg FPCM

Once emissions have been quantified for each source (enteric fermentation, waste management, energy consumption, feed procurement and, where applicable, fertilisers), applying equations and emission factors consistent with the Intergovernmental Panel on Climate Change guidelines, they are converted to CO_2 equivalents using the respective global warming potential (GWP) factors adopted by the model (Table 6). The CO_2 eq components are then aggregated to obtain the overall footprint within the "cradle-to-farm-gate" boundaries.

Statistical analysis

All data processing and statistical analyses were performed using Microsoft Excel. Descriptive statistics (mean, standard deviation, minimum and maximum) were calculated for the main structural, productive, input-use and emission variables of the farms. Correlation analyses were used to explore the relationships between carbon footprint intensity (kg CO_2 eq/kg FPCM) and selected production and input-use variables. Simple linear regression was applied to evaluate the relationship between emission intensity and production level. Multiple linear regression models were then used to assess whether purchased feed and fertiliser use retained explanatory power after accounting for production level, and to estimate the coefficient of determination (R^2). Statistical significance was considered at $P < 0.05$.

Results and Discussion

Table 1 summarises the main descriptive statistics (mean, minimum, maximum and standard deviation) of the structural, production and input use variables of the farms under study. Overall, the farms present a heterogeneous profile, with significant ranges, especially in terms of farm size, livestock scale, milk output and energy consumption, indicating high potential for benchmarking and identifying levers for improvement at farm and supply chain level. The sample falls within a relatively homogeneous climatic context in terms of average temperature (18.25 °C), while altitude is extremely variable (7–670 m above sea level). This combination is significant because it suggests that, at the same average temperature, the sample covers different production and agronomic contexts (exposure, slope, forage vocation and logistics), which may be reflected in the cost structure and input intensity.

The average farm size is 111.94 ha (45–450). The dispersion of the UAA is in itself an indicator that the sample does not represent a single type, but a portfolio of models with different capacities to sustain fodder self-sufficiency and rotation management. While flock size shows a wide dispersion (Flock size: 899.83 head; 231.00–1975.00; ± 585.03). The number of adult ewes (692.50; 160.00–1670.00; ± 487.21) and lactating ewes (616.22; 150.00–1450.00; ± 424.84) shows a production structure with marked differences in scale. The replacement rate averages 164.89 head (50.00–500.00; ± 118.19), suggesting different turnover management strategies. The stocking rate (Ewes/ha) averages 7.65 (2.00–23.52; ± 5.39), indicating substantial variability in livestock pressure on UAA, potentially associated with differences in forage availability and input intensity. Annual milk production is 151,746.28 L/yr (43,133.00–453,344.00; ± 114,232.16). Annual production in FPCM is 155,054.29 kg/yr (44,143.80–482,354.39; ± 116,932.45). The use of FPCM as a normalisation metric is consistent with the LCA approach in the dairy sector (FU frequently set at 1 kg FPCM) and allows for more consistent comparisons between farms with different compositional profiles (Sabia et al., 2020). The indicators per head show a heterogeneous production positioning, with production per lactating ewe averaging 254.73 kg FPCM/yr (143.25–377.61; ± 83.74). These ranges indicate significant differences in the ability to transform food and management resources into the final product, a key point also in the interpretation of environmental performance according to LCA literature (dominant hotspots and the role of productivity) (Vagnoni et al., 2018; Baldini et al., 2017). The literature on dairy sheep farms highlights that production efficiency (e.g. milk yield per ewe, feed efficiency) is frequently associated with a reduction in impacts per kg of milk; however, the effect is not mechanical and depends on the structure of inputs (e.g. share of purchases). Efficiency improvements can reduce the unit impact, while increases in purchased concentrates not offset by a more than proportional increase in production can worsen it (Finocchi et al., 2025; Bosco et al., 2021). The quality profile of milk appears relatively stable: fat 6.41% (5.85–6.74; ± 0.24), protein 5.55% (5.20–5.97; ± 0.21), fat/protein ratio 1.15 (1.10–1.22; ± 0.04). The energy content of milk is 1.08 Mcal (1.01–1.13; ± 0.03). The value “Energy from milk for milk produced” (Mcal/L) shows greater dispersion (1.36; 0.72–3.28; ± 0.63), which is useful as a summary indicator of compositional/management differences. The total amount of feed purchased is 129.76 t/yr (6.00–440.28; ± 113.82). Normalised per head: 184.89 kg/yr/ewe (5.83–430.56; ±

148.23). In the literature, feed purchases are frequently among the main contributors to impacts after enteric emissions, and are a key driver for differentiating farm types and margins for improvement (self-production of fodder, fodder quality, precision feeding) (Vagnoni et al., 2018; Finocchi et al., 2025). The total amount of fertilisers purchased is 16,708.89 kg/yr (0.00–95,000.00; ± 21,672.71), and 174.34 kg/ha (0.00–700.00; ± 170.65). This wide variability indicates very different agronomic strategies and is particularly relevant for impacts related to eutrophication and acidification and resource consumption in the "farm-gate" LCA perimeter, where the crop component and N use can play a significant role (Cortesi et al., 2022). Diesel consumption stands at 14,813.94 L/yr (2,000–65,000; ± 13,936.79) and 18.63 L/yr/sheep (3.41–35.77). Electricity purchases amounted to 17,794.71 kWh/yr (1,190–60,000; ± 17,323.27) and 18.34 kWh/ewe (1.63–45.09; ± 12.35), while self-produced electricity averages 6,261.25 kWh/year (1,450–13,000; ± 5,741.08) and 12.58 kWh/ewe (2.44–22.51; ± 11.41). It is particularly important to note that a minority of the farms in the sample produce their own electricity, representing potentially useful technological levers for mitigation, the results are shown in Table 7.

In the sample, the total emission intensity averages 3.61 kg CO_2 eq/kg FPCM, varying widely (1.74–5.67), indicating high potential for benchmarking and identification of management levers. The breakdown by source shows a profile typical of ruminant systems: the largest share of the impact is attributable to enteric fermentation, while manure management, feed purchase and energy consumption contribute to a lesser extent but with farm-specific variability, as shown in Figure 2. This hierarchy is consistent with what has been reported in the literature for sheep's milk: Escribano et al.

(2020) highlight enteric fermentation as the most impactful component and that less productive systems tend to have higher intensities (Escribano et al., 2020). Similarly, Vagnoni et al. (2017) show that environmental performance may not improve even by reducing inputs, precisely because of the predominant effect of enteric fermentation compared to other factors. The high variability between studies and contexts is widely documented. Finocchi et al. (2025) report highly variable enteric contributions to GWP between studies (with a wide range) and emphasise that differences in systems and methodologies can significantly change the relative contributions. The most quantitatively robust result is the relationship between emission intensity and productivity per sheep present (kg FPCM/head/year).

Simple linear regression shows a very strong negative association ($R^2 = 0.818$; adj. $R^2 = 0.807$; $p = 2.55 \times 10^{-7}$), indicating that, in the sample, the increase in output per animal is associated with a marked reduction in CO_2 eq per kg of FPCM, Figure 3.

This evidence is plausible and widely supported in the literature: in ruminants, a significant proportion of emissions (particularly enteric CH_4) is linked to the maintenance and physiology of the animal, so increasing production per head tends to dilute these emissions over a higher denominator, improving emission efficiency per kg of product. Studies on dairy sheep systems show that lower CF values per unit of milk are often associated with more productive systems (albeit with higher inputs), while extensive and less productive systems typically have higher intensities (Ravani et al., 2023; Sabia et al., 2020; Cortesi et al., 2022). In management terms, this positions productivity per head as a first-level KPI for environmental benchmarking, not as an end in itself, but as a metric that summarises health, reproductive management, ration quality and lactation management, all of which are levers that affect emission performance (Sodi et al., 2024). Diesel per head (Diesel use, l/year, sheep) shows a signal that is not fully significant ($p = 0.082$; $R^2 = 0.177$), so on its own it is not a robust driver. However, when a multivariate model controlling for productivity is set up, an $R^2 = 0.907$ (Adj $R^2 = 0.895$) emerges. Therefore, with equal output per head, an increase in diesel is associated with higher emission intensity: this is consistent with the additive nature of energy consumption on CF. In the literature, the role of diesel is well documented as a driver of impacts related to energy and specific categories; Ravani et al. 2023, show that in semi-intensive systems, diesel can account for a very high proportion of some categories (over 50% for some indicators) and, more generally, that fuel burning affects several impact dimensions (Ravani et al., 2023). The simple regression between total EI and purchased feed (Total Purchased Feed, kg/year/sheep) is not significant ($p = 0.117$; $R^2 = 0.146$). This should not be interpreted as an absence of effect, but as evidence that the signal is attenuated on the total because feed can activate improvements in production response and/or ruminal fermentation as the quality/energy of the ration increases. Escribano et al. (2020) discuss the trade-off between intensification and grazing and show that more intensive systems have lower intensities despite different input dynamics. Furthermore, Bosco et al. (2021) demonstrate that a precision feeding approach can significantly reduce impacts per kg FPCM thanks to increased production efficiency and more balanced rations. Vagnoni et al. (2017) explicitly link energy supply to differences in productivity and ruminal fermentation, and therefore to enteric emissions per kg of FPCM. Overall, fertilisers per ha (Total Purchased Fertiliser, kg/year/ha) show no significant relationship ($p = 0.358$; $R^2 = 0.053$). However, when the analysis is aligned with the correct emission source, the signal emerges strongly: the “fertilisers” component per kg FPCM increases with kg/ha ($p = 0.0037$; Adj $R^2 = 0.382$). This is consistent with LCA inventory logic, as the effect of fertilisers is often more evident in N-related categories (eutrophication/acidification) and, on GWP, may be “secondary” to enteric. Finocchi et al. (2025) point out that many impact categories related to air/water/soil are strongly linked to N flows and excretion.

The results of this chapter are not limited to quantifying the CF of the primary phase, but provide an operational package that the CAO can use to implement governance practices, transforming environmental data into technical decisions and, subsequently, into structured support for members. In a collaborative context, this step is strategic because it reduces information asymmetries, ensuring transparency and repeatability in the assessment, and transforms sustainability from an external issue to an internal element of the improvement process. In order to ensure the management of the system, the dashboard must remain simple and consistent over time, structured on two complementary levels: Outcome KPIs (positioning and responsibility): a summary indicator that measures the achievement of objectives and the responsibility of the parties involved. Total emission intensity (kg CO_2 eq/kg FPCM): an indicator that summarises the performance of the system in terms of emissions, positioning and responsibility.

Emissions intensity per hotspot (enteric, manure, energy, fertilisers, feed purchased): diagnostic indicators that indicate where to intervene, avoiding generic actions.

Driver KPIs (levers for improvement and capacity building):

Productivity per head (kg FPCM/head/year) is the most informative driver in terms of emission intensity variability. Therefore, in this study, it acts as a guiding KPI for defining the priorities of interventions aimed at improving technical efficiency, with particular reference to the areas of health, reproduction, lactation management, ration quality and forage. Feed purchased per head, with a unit cost recorded for each head per year, is a key performance indicator for managing external feeding intensity and the efficient use of acquired resources, serving as an information tool for setting up precision feeding programmes (waste reduction, feed quality, consistency between purchases and production response). In the context of capacity building, this KPI makes it possible to distinguish between farms that increase output with the same level of purchases and those that increase purchases without a corresponding increase in production. Diesel per head (L/head/year) is a crucial element in the context of a company that has already achieved satisfactory production levels but maintains a high intensity. In such circumstances, the problem can be mitigated through the adoption of measures such as mechanisation, cultivation actions, logistics and operational management. Fertilisers are purchased per hectare (kg/ha/year) and represent the benchmark KPI for agronomic input intensity. This indicator is essential for supporting farms in the process of rationalising fertilisation, promoting management consistent with land area and crops, significant reduction and more efficient use. Electricity purchased per head is measured in kWh per head per year and is an operational indicator of farm energy efficiency (milking, refrigeration, plant management), revealing how energy resource management is a crucial aspect for farms. This tool allows farms with abnormal consumption to be identified and practical interventions to be targeted, such as plant calibration and maintenance, peak management and equipment efficiency. The potential benefits of this approach are both environmental and economic. The stocking rate (sheep/hectare) or UBA/SAU (UBA/hectare) benchmark is a structural KPI of intensification, which describes the livestock pressure on the land and supports the interpretation of the production model (more grazing vs. more integration). The sample may highlight signals that are not always independent of productivity, but it remains a useful context indicator for interpreting differences between farms and for designing interventions consistent with the territorial base (pasture management, fodder self-sufficiency, load organisation). From an operational point of view, CAO can use these indicators according to a simple and replicable rule: annual internal benchmark (e.g., quartiles on total EI and productivity) and classification by profiles. Farms with high EI (emission intensity) and low productivity become the priority for “structural” capacity building (animal and production efficiency); farms with high EI but already high productivity enter a process optimisation pathway. Farms with low EI are an internal reference (“benchmark”) useful for transferring practices and standardising solutions. In this way, the cooperative moves from a static condition to a cycle of improvement, which includes defining a starting point, implementing targeted interventions, and re-evaluating and updating benchmarks. This aspect is fundamental to consolidating the link with members, as it is not limited to mere classification but focuses on providing clear, shared and measurable parameters.

Conclusion

The case study illustrates how the quantification of the CF of the primary phase by a cooperative is not merely a descriptive activity, but rather a fundamental step in corporate governance. This step makes sustainability measurable, comparable among members and, consequently, manageable. The CAO now has a baseline and emission hotspots that allow it to set up an operational dashboard with a limited number of stable KPIs (total and per source EI; productivity per head; diesel per head; main input indicators), which can be used for internal benchmarking, defining technical support priorities and annual progress monitoring. In relational terms, this approach consolidates the cooperative agreement: members are involved on the basis of transparent and verifiable criteria, following a capacity-building path that aims to fill information gaps and promote good practices without summary judgements.

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Tables and Figures

Table 1. Ym values for different categories of sheep

	Ym (%)
Lactating ewes	11.5
Dry ewes	12
Replacement	10.5
Rams	12

Table 2. Diet digestibility values for different categories of sheep

	Digestibility of the diet
Lactating ewes	65
Dry ewes	60
Replacement	70
Rams	60

Table 3. Fraction of volatile solids present depending on the storage system and emission factor for CH4 from waste.

Sheep	Emission Factor	Reference
Fraction of volatile solids present in manure depending on the storage system	0.78	AWMSi; Table 10A.8
Emission factors for CH_4 from manure	5.1	EFi; (g CH_4 kg $VS^{-1)}$; Table. 10.14
VS excretion values	8.2	VSrate (kg VS 1000 kg animal weight^{-} 1 $_{d}$-1$_{);}$ Table 10.13°
Typical mass	40	Table 10A.5

Table 4. Valori di escrezione di ossido nitroso

Sheep	EF	Reference
Nitrous oxide excretion values, %N_2O-N	0.78	Pasture, (IPCC, 2019)
	2	Barn, (Jarvis et al., 2001)
Nitrous oxide excretion values, % NH_4-N	0.00	(Laubach et al., 2013)
	36	Atzori (et al., 2013)

Table 5. Emission factors for animal feed

Product	EF (kg CO_2eq kg product^{-}	Reference
Corn grain and flour	0.54	Database Ecoinvent 3.1
Barley grain and flour	0.41	Database Ecoinvent 3.1
Oat grain and flour	0.86	Database Ecoinvent 3.1
Wheat and other cereal grits and flour	0.8	Database Ecoinvent 3.1
Soybean grain	2.01	Database Ecoinvent 3.1
Soybean meal	2.44	Database Ecoinvent 3.1
Field bean and other legume grits	0.54	Database Ecoinvent 3.1
Commercial feed	0.76	Processing from database Ecoinve 3.1
Protein supplements	1.43	Database Ecoinvent 3.1
Grass hay	0.25	Database Ecoinvent 3.1
Alfalfa hay	0.104	Processing from database Ecoinve 3.1
Mixed hay	0.213	Processing from database Ecoinve 3.1
By-products (straw, beet pulp, brewe grains, soya hulls)	0.46	Processing from database Ecoinve 3.1
Mineral and vitamin supplements	0.36	Processing from database Ecoinve 3.1

Table 6 Global warming potential (GWP) factors

Gas	GWP-100yr
CO_2	1
CH_4 not fossil	27
N_2O	273

Table 7. Descriptive statistics of dairy sheep farm (mean; SD; min; max)

	Mean	**SD**	**min**	**max**
Climate data: average air temperature (C, range for summer, range for winter)	18.25	0.88	16.00	19.50
Altitude, m a.s.l.	140.33	181.48	7.00	670.00
hectares, ha	111.94	93.68	45.00	450.00
Flock size, n	899.83	585.03	231.00	1975.00
animal weight, kg		3.23	45.00	55.00
Mature ewes, n	692.50	487.21	160.00	1670.00
Lactating ewes, n	616.22	424.84	150.00	1450.00
Replacement, n	164.89	118.19	50.00	500.00
Stocking rate, Ewes/ha	7.65	5.39	2.00	23.52
Annual fertility, %	0.90	0.05	0.80	0.97
Milk production, l/year	151746.28	114232.16	43133.00	453344.00
Total annual production kg of milk, kg FPCM /year	155054.29	116932.45	44143.80	482354.39
Milk production from milked sheep, l/d milked sheep	1.26	0.56	0.69	2.95
Milk delivered per milked animal, l/year	249.18	80.23	145.40	367.68
Fat, %	6.41	0.24	5.85	6.74
Protein, %	5.55	0.21	5.20	5.97
Lactose, %	4.50	0.00	4.50	4.50
Fat/protein ratio, %	1.15	0.04	1.10	1.22
Milk energy, Mcal	1.08	0.03	1.01	1.13
Energy from milk for milk produced, Mcal/l	1.36	0.63	0.72	3.28
Milk price, €	1.77	0.14	1.20	1.80
Production per sheep present, kg FPCM/year per sheep	181.37	67.24	83.98	278.46
Production for lactating ewe, kg FPCM/year per milked ewe	254.73	83.74	143.25	377.28
Production per sheep present, kg FPCM/day per sheep	0.86	0.32	0.40	1.33
Production per lactating ewe, kg FPCM/day per milked ewe	1.21	0.40	0.68	1.80
UBA	89.98	58.50	23.10	197.50
UBA/SAU	1.02	0.69	0.24	2.78
Total Purchased feed, ton, year	129.76	113.82	6.00	440.28
Total Purchased feed, kg/anno/sheep	184.89	148.23	5.83	430.56
Total Purchased fertilizer, kg/year	16708.89	21672.71	0.00	95000.00
Total Purchased fertilizer, kg/year/ha	174.34	170.65	0.00	700.00
Diesel use, l/year	14813.94	13936.79	2000.00	65000.00
Diesel use, l/year, sheep	18.63	10.82	3.41	35.77
Purchased electricity, kWh/year	17794.71	17323.27	1190.00	60000.00
Electricity produced, kWh/year (renewable)	6261.25	5741.08	1450.00	13000.00
Purchased electricity, kWh/year/sheep	18.34	12.35	1.63	45.09
Electricity produced, kWh/year/sheep	12.58	11.41	2.44	22.51

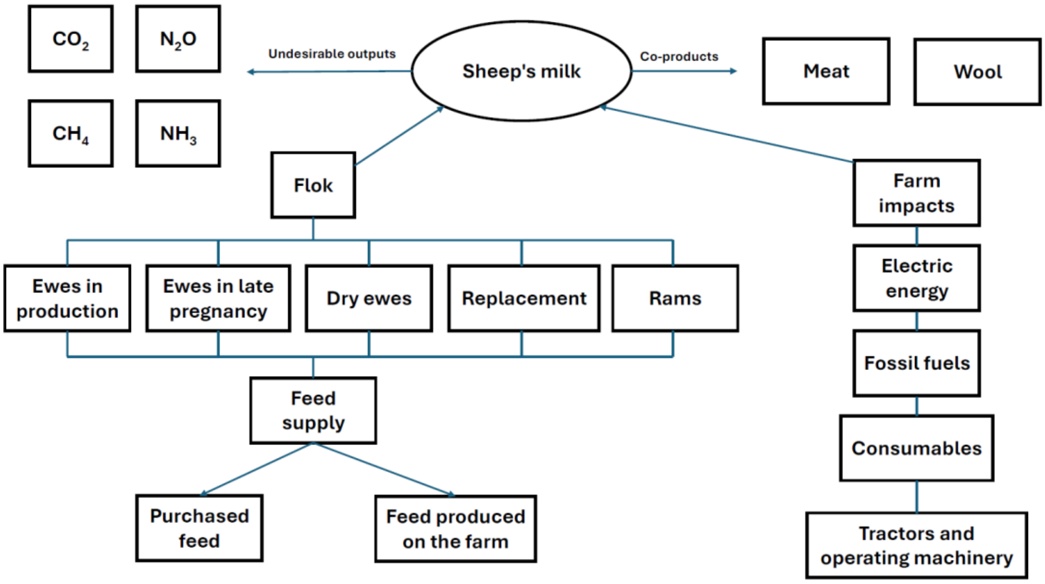

Figure 15. Flow chart of sheep milk production.

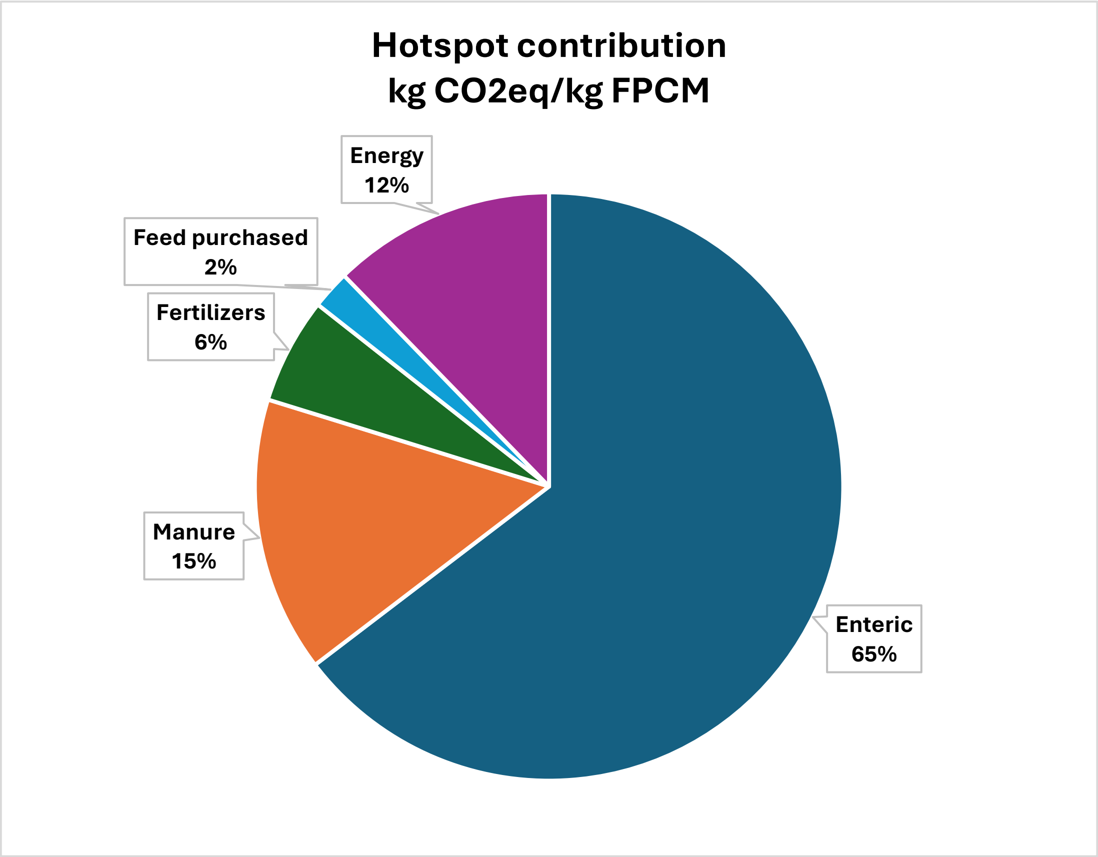

Figure 16. Breakdown of emissions

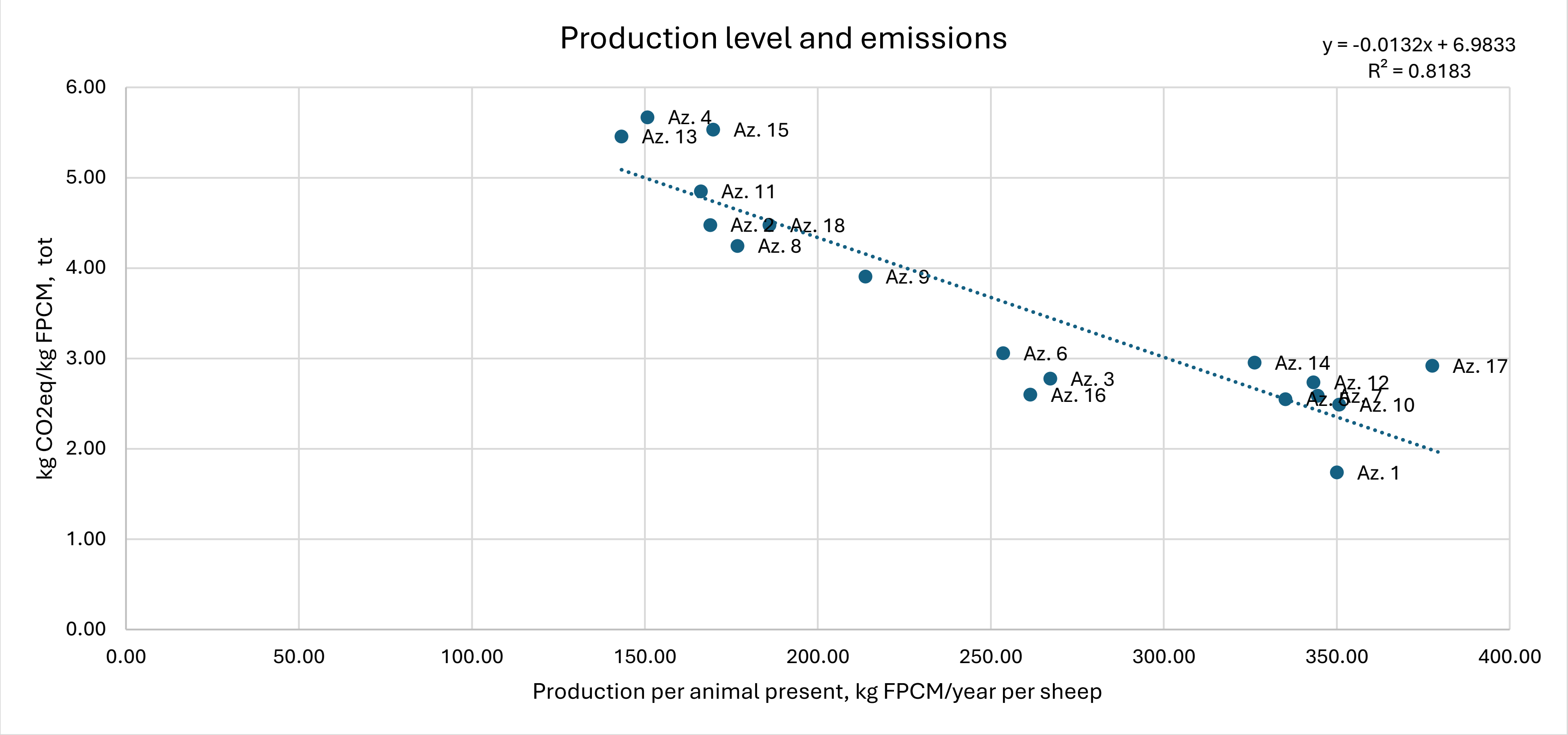

Figure 17. Relationship between milk productivity and carbon footprint intensity

CHAPTER 5

General conclusion

This thesis demonstrates that carbon footprint assessment in sheep dairy farming systems becomes scientifically meaningful and operationally useful only when three conditions are jointly met: methodological consistency, structured and traceable farm data, and the ability to translate results into actionable management priorities. Taken together, the four chapters of the research demonstrate that the value of carbon footprint assessment lies not only in accounting, but in its ability to serve as a decision-making and governance tool from the farm level to the supply chain level. In this sense, the thesis moves from the question of how to measure emissions to the broader question of how to make such measurement comparable, usable and capable of supporting continuous improvement over time. A first conclusion concerns the scientific basis for comparability. The systematic review confirms that the literature on LCA of sheep products is extensive but highly heterogeneous and that a substantial part of the variability observed between studies is not only attributable to real differences between production systems, but also to methodological choices such as system boundaries, functional units, allocation procedures, GWP metrics, and the inclusion or exclusion of soil carbon sequestration. The review also confirms that enteric fermentation is the dominant critical point in dairy, livestock, and wool systems, while feed, manure management, and energy contribute to varying degrees depending on the context and modelling assumptions. Therefore, one of the main scientific implications of this thesis is that environmental benchmarking in the sheep sector requires greater harmonisation of methodological choices and more transparent inventory reporting so that results can be interpreted correctly and used beyond the individual case study. A second conclusion concerns the operational interpretation of emission intensity, demonstrating that the carbon footprint becomes more informative when used not only to compare systems, but also to profile farms and identify concrete mitigation levers. The central message is that emissions intensity in sheep dairy farming systems is determined by a combination of production level and management choices that can be measured at the farm level.

Productivity per ewe emerges as the main driving factor, while feeding strategy, dependence on purchased feed, pasture management, reproductive performance, milk composition, direct energy use and nitrogen-related variables provide additional explanatory power, especially when variability is analysed within the same production system and after adjustment for scale and production. From a scientific point of view, this means that farm heterogeneity should not be considered as background noise, but rather as a source of diagnostic information that allows us to distinguish between widely applicable mitigation levers and measures that need to be adapted to specific production profiles. A third conclusion is that environmental assessment in the sheep sector cannot become routine, verifiable and scalable without adequate data infrastructure. One of the structural bottlenecks in the sector is not only methodological fragmentation, but also the weakness of digital systems for data integration, traceability and reuse. By incorporating a greenhouse gas calculator into an integrated digital platform, the thesis shows that carbon footprint assessment can be transformed from an episodic exercise into a repeatable process supported by formalised rules, explicit assumptions and consistent information flows. The technical implication is that data architecture is not a secondary support element, but part of the methodological robustness of the environmental assessment itself. A further conclusion concerns the scale of governance. Applied to a case study, it shows that carbon footprint quantification at the cooperative level is not merely descriptive, but can serve as an organisational infrastructure for benchmarking, technical support and capacity building. The primary stage of sheep dairy supply chains is confirmed as the key stage on which to focus attention, as it accounts for the dominant share of climate impact and offers the greatest scope for technical intervention. The implication at the cooperative level is that sustainability becomes manageable when it is translated into a small set of stable KPIs, linked to annual monitoring, technical guidance and a transparent process of member involvement. As a whole, the thesis provides a technical-scientific contribution at the intersection of three levels that are often addressed separately: evidence synthesis, farm profiling and digital/cooperative governance. Its main contribution is not simply to add another case study on the carbon footprint of sheep dairy farming systems, but to show how environmental accounting can be organised into a coherent framework that links methodological rigour, data infrastructure and operational use. From a scientific point of view, the work clarifies where non-comparability occurs and how this affects interpretation. From a technical point of view, it identifies measurable factors that help move from generic mitigation discourse to farm-oriented priorities. From an applied point of view, it proposes tools and KPI frameworks that enable the use of carbon footprint assessment for benchmarking, annual monitoring and decision-making support. In this sense, the thesis contributes to repositioning carbon footprinting from a communication indicator to a management indicator.

The practical implications of this work are equally relevant. At the farm level, the results support the use of simple but robust indicators to identify priority areas for action, particularly those related to production efficiency, purchased inputs, and energy use. At the cooperative level, the thesis shows that carbon footprint assessment can support a capacity-building path based on transparent and verifiable criteria rather than impressionistic judgements. At the territorial and institutional level, the APPàre experience suggests that integrated digital platforms can strengthen governance by making environmental information more reusable, comparable and suitable for monitoring progress over time. From a dissemination perspective, the work also has value because it translates the complex logic of LCA into readable indicators and decision-oriented dashboards that can facilitate dialogue between farmers, advisors, cooperatives, policy actors and, potentially, communication schemes based on environmental transparency. At the same time, the thesis has some limitations that should be made explicit. First, although the review clearly identifies soil carbon sequestration as one of the most discriminating methodological factors in the assessment of sheep systems, this component is not integrated into the farm-level empirical applications developed in the thesis. Consequently, the estimates provided for the case studies should be interpreted as carbon footprint values within the adopted accounting boundaries, not as a comprehensive representation of all the climate functions of grazing-based systems. This is particularly relevant for extensive and semi-extensive systems, where carbon sequestration and other ecosystem services may alter the comparative interpretation of environmental performance. A second limitation is that these applications are valid as proof of concept and operational demonstrations, but do not exhaust the diversity of dairy sheep systems across regions, climates and management contexts. Consequently, caution is needed in generalising absolute values, while the transferability of the methodological logic and KPI-based approach is stronger than the transferability of the numerical results themselves. A third limitation concerns the scope of the sustainability assessment. The thesis focuses primarily on climate impact and carbon footprint, while broader environmental dimensions and sustainability attributes remain outside the empirical core of the work. Chapter 1 already highlights the need to move towards more holistic approaches, including animal welfare, ecosystem services, broader environmental categories, uncertainty analysis and cost-effectiveness assessment of mitigation strategies. This means that, although the carbon footprint is a useful starting point, it should not be interpreted as sufficient in itself to represent the overall sustainability of sheep farming systems, particularly in extensive contexts where biodiversity conservation, landscape management and fire prevention are relevant co-functions. A fourth limitation is methodological in nature and concerns the management of uncertainty. The thesis strengthens traceability, comparability and operational interpretation, but future developments should further expand sensitivity analysis and uncertainty quantification, especially when using simplified calculation approaches for large-scale adoption. This step is important to strengthen the credibility of benchmarking and to distinguish robust signals from variability due to assumptions, missing data or completion parameters. On this basis, several future directions emerge. A first priority is the integration of soil carbon sequestration into farm- and cooperative-level applications, particularly for grazing-based and high nature value systems, using harmonised and transparent methods that improve comparability rather than introducing new ambiguities. A second priority is to extend the assessment beyond carbon footprint alone, incorporating additional environmental categories, animal welfare and ecosystem services, in order to better represent the multifunctionality of sheep farming. A third priority is to strengthen uncertainty analysis, including sensitivity and Monte Carlo approaches, together with a more explicit assessment of the economic feasibility and cost-effectiveness of mitigation options. A fourth priority is the expansion of digital infrastructure such as APPàre, both in terms of sample size and interoperability, in order to support larger datasets, longitudinal monitoring and stronger territorial benchmarking. Finally, future work should examine how KPI-based governance models can be adopted by other cooperatives and supply chains and how benchmarking can be linked to advisory services, incentives, eco-labelling and broader dissemination strategies that make sustainability more understandable and actionable for different stakeholders. In conclusion, the thesis demonstrates that the ecological transition of sheep dairy farming systems does not depend solely on better formulas for calculating emissions, but on the ability to link scientific evidence, data organisation and governance practices. Carbon footprint assessment becomes truly useful when it helps to distinguish methodological artefacts from real performance differences, when it identifies measurable levers for improvement, and when it is integrated into digital and organisational structures that enable repetition, comparison and learning over time. Under these conditions, carbon footprinting is no longer a static indicator of impact, but a practical language for driving technical change, comparing farms, and supporting collective governance of the sheep dairy supply chain.