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Research

Transitioning toward sustainable dairy systems in Europe: A systematic literature review

Mousaab Alrhmoun [1], Matthias Gauly [2], Thomas Zanon [1]

[1] Faculty of Agricultural, Environmental and Food Sciences, Free University of Bolzano, 39100 Bolzano, Italy
[2] University of Veterinary Medicine (Vetmeduni), 1210 Vienna, Austria

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Abbreviations

The list of standard abbreviations for JDS is available at adsa.org/jds-abbreviations-24. Nonstandard abbreviations are available in the Notes.

ABSTRACT

The European Union makes a significant contribution to the global dairy industry, producing an estimated 160.8 million tons of milk in 2023, which accounts for more than 20% of the world's total milk production. However, the sector faces increasing pressure to align with sustainability goals amid economic constraints, environmental degradation, climate change, and evolving societal expectations. This systematic literature review examines the transition toward sustainable dairy systems across Europe by synthesizing peer-reviewed studies published over the past decade. It analyzes the range of agroecological practices being implemented, such as rotational grazing, breed selection, and reduced-input systems, alongside the roles played by policy frameworks, socio-economic drivers, and technological innovations. The review identifies key barriers to progress, including fragmented policy support, data limitations, and insufficient incentives for farmers. At the same time, it highlights opportunities for a just and effective transition, emphasizing the importance of multiactor collaboration and the urgent need for standardized evaluation frameworks across diverse agroecosystems. This study provides a conceptual and practical foundation to guide future research, policymaking, and on-the-ground initiatives aimed at fostering resilient and sustainable dairy systems in Europe.

Previous

Next

Key words

dairy; sustainability; transition; milk production; challenges and solutions

INTRODUCTION

In 2015, following the abolition of the European Union's milk quota system, dairy production reached ~164 million tons, marking a period of expansion influenced by increased market freedom (European Commission, 2016). By 2021, however, production had declined to ~155 million tons, reflecting structural adjustments in the sector and growing pressures related to environmental and economic sustainability (European Commission, 2022). Between 2021 and 2024, European Union (**EU**) milk output experienced a modest rebound, rising to 160.0 million tons in 2022 and 160.8 million tons in 2023, with early estimates for 2024 suggesting continued stabilization (Eurostat, 2024). This decade-long trend illustrates a shift from expansion to consolidation, driven by climate policy, changing consumer expectations, and increasing interest in agroecological practices. The focus is now moving from maximizing output to transforming production systems toward greater sustainability and resilience.

Despite a decrease in dairy farms, dairy production has steadily increased in recent years (European Commission, 2022). Intensive dairy farming, a high-input, high-output method that uses enormous herds, restricted housing, concentrated feed, and advanced technologies to increase the supply of milk, now accounts for over 80% of European milk production, mainly in lowland areas (European Commission, 2022). From 2010 to 2020, the average herd size per farm increased from 38 to 58 cows (European Commission, 2022). Although herd sizes in the EU have increased over recent decades as

part of a broader trend toward intensification, they remain relatively small compared with countries such as the United States, Australia, and New Zealand, where large-scale operations are more prevalent. Although productivity has increased due to the move to larger, more automated facilities, questions have been raised about the effect on the environment, animal welfare, and environmental sustainability (Heise and Theuvsen, 2018; Autio et al., 2023). Furthermore, the sector is increasingly criticized for its high dependence on external agricultural inputs, such as soy and cereal imports from foreign countries, excessive water use, and GHG emissions (de Vries et al., 2013). Furthermore, there is an increase in "food neocolonialism," which is the commodification of regional foods for foreign markets (Staffolani et al., 2022; Duglio et al., 2023). Consequently, debate is increasing at the European level on shifting the current dairy production toward a more sustainable one by following an agroecological transition in dairy farming. This change includes agroecological practices, such as precision farming and circular economy, as well as innovative supply chains and business models (de Vries et al., 2013; Arvidsson Segerkvist et al., 2020; Verduna et al., 2020). These shifts require ongoing, systemic innovation rather than isolated, one-time changes (Asayehegn et al., 2017). The EU's Green Deal and Farm to Fork strategy have significantly advanced sustainability by motivating farmers, legislators, and business leaders to take action to promote biodiversity, reduce carbon emissions, and protect the environment (European Commission, 2021). Despite these encouraging advancements, creating a genuinely sustainable dairy industry is still a difficult task. Finding a balance between environmental and economic productivity, incorporating new technologies into current systems, and considering the various local contexts across the EU's diverse farming landscapes are important concerns (Arvidsson Segerkvist et al., 2020; Penker, 2024). These elements make large-scale sustainability implementation more difficult and necessitate customized solutions that take sector-specific issues and geographical variations into consideration.

The purpose of this review is to provide insight into the current and emerging agroecological strategies applied in European dairy farming, across environmental, economic, and social dimensions, as part of the broader shift toward sustainable production. The findings aim to identify critical knowledge gaps and inform future research and policy efforts to support a just and effective agroecological transition in the European dairy sector.

MATERIALS AND METHODS

Following the updated guidelines published by Page et al. (2021), a systematic review of the scientific literature in the Scopus database (https://www.scopus.com ↗) was conducted. To identify relevant literature on sustainability in European dairy systems, a systematic search was conducted using the Scopus database covering the period from 2008 to 2025. The process began with a broad exploration search using the string: (dairy OR milk) AND (cow OR cattle), which yielded 522,679 records. Given the high volume and generic nature of this initial search, a more focused search string was developed to target sustainability-related topics and evaluation frameworks within dairy systems. The refined search string applied was: (dairy OR milk) AND (cow OR cattle) AND (sustainability OR agroecology OR GHG OR welfare OR "ecosystem services" OR LCA OR "life cycle") AND (evaluate OR value OR emission OR approach OR mitigation OR indicator* OR assess* OR impact) AND (environment OR economic OR social)*. This query was further limited to English-language peer-reviewed publications, resulting in 1,197 records. A 4-step screening process was then undertaken (Figure 1). First, studies were filtered based on their geographic focus. Only studies conducted within the EU were retained, which led to the exclusion of 523 records that focused entirely on non-EU contexts. In the second step, abstract screening was conducted using a refined abstract-level query targeting sustainability themes in dairy cattle research. This resulted in the exclusion of 505 records that did not sufficiently align with the focus of this review. As a result, 169 records were carried forward to the next phase. In the third step, titles were screened to remove studies that were clearly outside the scope of dairy cattle transition toward sustainability in Europe. A total of 76 records were excluded at this stage, resulting in 93 articles for full-text review. During the final phase of the screening process, full texts were carefully examined. Twelve studies were excluded because they reviewed articles or did not present original empirical data. An additional 44 studies were excluded because, although affiliated with European institutions, they focused on case studies conducted in non-European countries such as Peru, Brazil, Kenya, or elsewhere in Africa, or focused on nondairy cattle such as sheep, goats, or beef cattle. This rigorous selection process led to a final dataset of 37 peer-reviewed articles (Table 1). These studies form the core material for the subsequent analysis of the environmental, economic, and social dimensions of sustainability in European dairy systems. Though the primary focus is on peer-reviewed literature directly addressing the dairy sector, broader sustainability studies were also considered when they provided transferable insights relevant to agroecological principles or structural transitions in agriculture. To ensure transparency and methodological rigor, articles that were excluded, such as non-European case studies and studies focused on nondairy species or general reviews without sectoral specificity, are summarized in the supplemental materials (see Notes). Given the relative scarcity of explicitly agroecological studies within the dairy sector, sustainability-oriented literature offers a valuable, if indirect, foundation for postulating the dynamics, challenges, and enabling conditions of an agroecological transition. This approach is grounded in the understanding that agroecology is inherently multidimensional and overlaps significantly with sustainability goals related to resilience, equity, and resource efficiency. Our search strategy was carefully designed to focus on sustainability and agroecological themes in the European dairy sector, although we acknowledge that some relevant studies may not have been captured, particularly those addressing broader agricultural transition processes, such as policy shifts, farmer behavior, innovation systems, or rural development, that do not explicitly reference “agroecology” or “sustainability” in their titles, abstracts, or keywords. This review thus reflects a purposive focus on literature that explicitly engages with agroecological or sustainability-related language, which may have led to the exclusion of more implicitly related transition research. Future reviews might complement this work by using a broader set of search terms to capture additional insights on enabling conditions and systemic change in dairy farming.

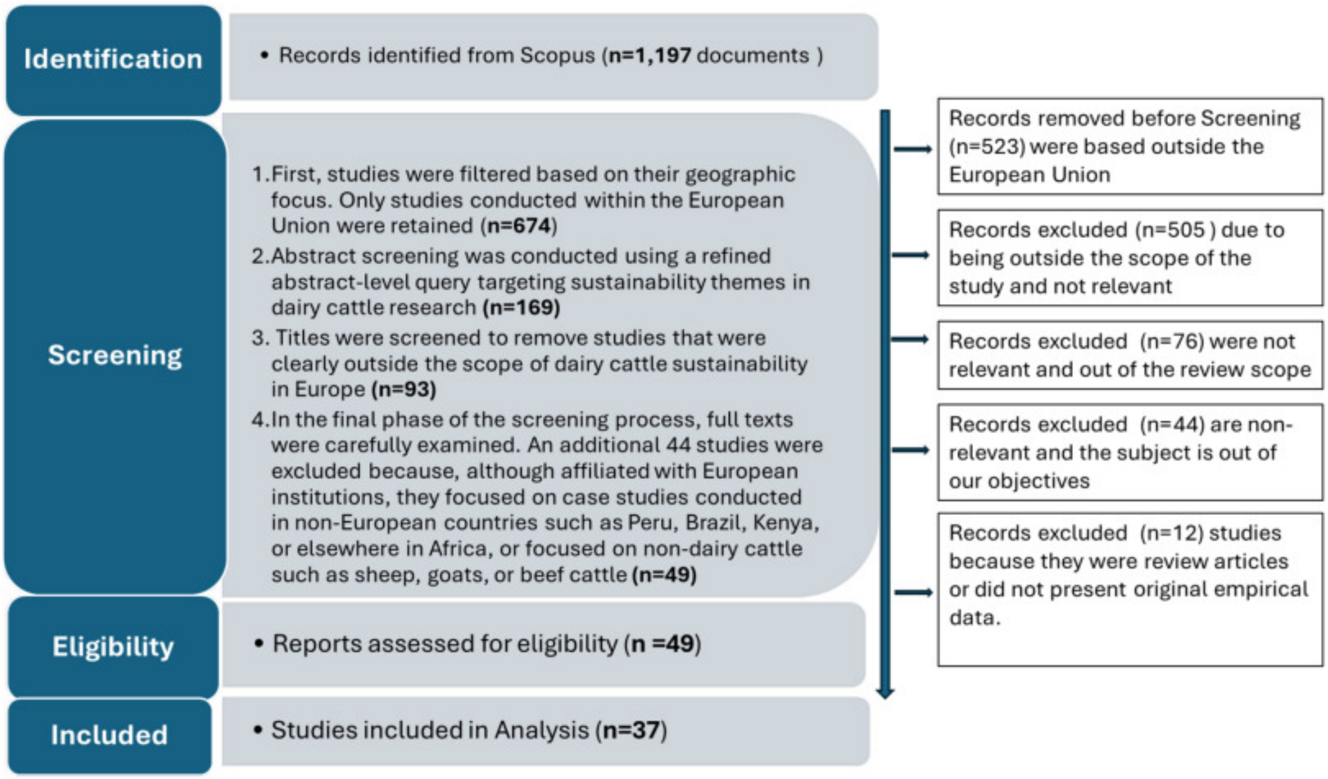

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Figure 1. Flowchart of the systematic literature process.

Table 1. List of available papers based on our screening process[1]

N	Reference	Journal	Title	Country	Theme	Relevance to the agroecological transition
1	Vázquez-González et al., 2021	Sustainability (Switzerland)	Rendered agroecosystem services and dysservices of dairy farming: A bottom-up approach in Galicia (Spain)	Spain	Agroecology, ecosystem services	High
2	Zehetmeier et al., 2020	Agricultural Systems	Is there a joint lever? Identifying and ranking factors that determine GHG emissions and profitability on dairy farms in Bavaria, Germany	Germany	GHG, profitability	High

N	Reference	Journal	Title	Country	Theme	Relevance to the agroecological transition
3	Hansen et al., 2024	Agricultural and Food Science	Comparison of greenhouse gas emissions, nitrogen intensity, gross margin, and land use occupation between conventional and organic dairy farms	Norway	GHG, profitability, organic vs. conventional	High
4	Flaten et al., 2019	Agroecology and Sustainable Food Systems	Links between profitability, nitrogen surplus, greenhouse gas emissions, and energy intensity on organic and conventional dairy farms	Norway	GHG, profitability, organic	High
5	Bórawski et al., 2020	Polish Journal of Environmental Studies	Changes in grassland and their impact on milk production in Poland in the context of environmental protection	Poland	Land use, productivity	Medium
6	Ferronato et al., 2025	Animals	Carbon footprint assessment of dairy milk and Grana Padano PDO cheese and improvement scenarios: A case study in the Po Valley (Italy)	Italy	Carbon footprint, LCA	High
7	Masi et al., 2021	Sustainability (Switzerland)	A typological classification for assessing farm sustainability in the Italian Bovine dairy sector	Italy	Typologies, sustainability assessment	Medium
8	Diakité et al., 2019	Livestock Science	Biotechnical and economic performance of mixed dairy cow–suckler cattle herd systems in mountain areas	France	Mountain systems, system design	High
9	Jan et al., 2019	Livestock Science	Production intensity in dairy farming and its	Switzerland	Intensification, environment	High

N	Reference	Journal	Title	Country	Theme	Relevance to the agroecological transition
			relationship with farm environmental performance			
10	Zhu and Oude Lansink, 2022	PLoS ONE	Dynamic sustainable productivity growth of Dutch dairy farming	Netherlands	Productivity, sustainability	Medium
11	Roques et al., 2023	Animal Feed Science and Technology	Influence of agroecology practices on rumen microbiota associated with methane emission in dairy cattle	France	Agroecology, methane, microbiota	High
12	Botreau et al., 2014	Animal	Toward an agroecological assessment of dairy systems: Proposal for a set of criteria suited to mountain farming	France	Agroecology, Assessment	High
13	Thomassen et al., 2008	International Journal of Life Cycle Assessment	Attributional and consequential LCA of milk production	Netherlands	LCA	Medium
14	Verduna et al., 2020	Frontiers in Veterinary Science	Sustainability of four dairy farming scenarios in an Alpine environment: The case study of Toma di Lanzo cheese	Italy	Alpine, sustainability scenarios	High
15	Díaz de Otálora et al., 2022	Agronomy for Sustainable Development	Identification of representative dairy cattle and fodder crop production typologies at regional scale in Europe	Germany	Typologies	Medium
16	Lehmann et al., 2019	Livestock Science	Extended lactations in dairy production: Economic, productivity and climatic impact on	Denmark	Herd management, emissions	Medium

N	Reference	Journal	Title	Country	Theme	Relevance to the agroecological transition
			herd, farm and sector level			
17	Zhu et al., 2023	European Journal of Operational Research	Economic, environmental, and social inefficiency assessment of Dutch dairy farms	Netherlands	Sustainability metrics	High
18	Reinsch et al., 2021	Frontiers in Sustainable Food Systems	Toward specialized or integrated systems in Northwest Europe	Germany	Specialization, eco-efficiency	Medium
19	Flach et al., 2021	Journal of Cleaner Production	Environmental impact and food production of small-scale mountain dairy farms at different supplementation levels	Italy	Mountain, feeding systems	High
20	Arielle et al., 2022	Agroecology and Sustainable Food Systems	Redesigning systems production toward agro-ecological transition: Is organic conversion a favorable way ...?	France	Agroecological transition	High
21	Mennig and Szigeti, 2025	Journal of Agriculture and Food Research	Synergies and trade-offs between environmental impacts and farm profitability	France	Trade-offs, profitability	High
22	Chetroiu et al., 2022	Sustainability (Switzerland)	Assessment of the relations for determining the profitability of dairy farms	Romania	Profitability, economics	Medium
23	Díaz de Otálora et al., 2021	Sustainability (Switzerland)	Evaluating three-pillar sustainability modeling approaches for dairy cattle production systems	Germany	Sustainability assessment	Medium
24	Romano et al., 2021	Sustainability (Switzerland)	Dairy farms and LCA: The allocation criterion useful to estimate undesirable	Italy	LCA	Medium

N	Reference	Journal	Title	Country	Theme	Relevance to the agroecological transition
			products			
25	Soteriades et al., 2016	PLoS ONE	The relationship of dairy farm eco-efficiency with intensification and self-sufficiency	France	Eco-efficiency, systems	High
26	Børsting et al., 2023	Livestock Science	Replacing silage with concentrate and straw: effects on milk, economics, and climate in Holstein and Jersey cows	Denmark	Feed systems, climate	Medium
27	Denantes et al., 2025	Agricultural Systems	Work in agriculture: A blind spot in reducing pesticide use on dairy farms?	France	Labor, pesticides	Medium
28	Wild et al., 2025	Agricultural Systems	Feed the green for a sustainable and protein-efficient dairy production	Germany	Feed systems, efficiency	Medium
29	Markussen et al., 2015	Frontiers in Energy Research	Net-energy analysis of integrated food and bioenergy systems	Denmark	Energy, system integration	Medium
30	Dorca-Preda et al., 2024	Sustainable Production and Consumption	Climate and environmental effects of nutritional mitigation options to reduce enteric methane	Denmark	Mitigation, LCA	High
31	da Silva Cyrne et al., 2023	Revista de Gestao Social e Ambiental	Organic milk and sustainable development: Evidence from Galicia/ Spain	Spain	Organic, development	Medium
32	van Apeldoorn et al., 2013	Agriculture, Ecosystems and Environment	Coevolution of landscape patterns and agricultural intensification: Dutch dairy	Netherlands	Landscape, intensification	Medium

N	Reference	Journal	Title	Country	Theme	Relevance to the agroecological transition
33	Martin and Willaume, 2016	Agriculture, Ecosystems and Environment	A diachronic study of GHG emissions of French dairy farms according to adaptation pathways	France	GHG, trajectories	High
34	Bettin et al., 2023	Agriculture, Ecosystems and Environment	Relationship between concentrate feeding strategy and grassland phytodiversity on dairy farms	Germany	Feeding, biodiversity	Medium
35	Dentler et al., 2020	Agroecology and Sustainable Food Systems	The impact of low-input grass-based and high-input confinement-based dairy systems ...	Germany	Systems comparison	High
36	Zanon et al., 2025	Journal of Dairy Science	Effect of management system and dietary seasonal variability on environmental efficiency ...	Italy	Seasonality, diet	Medium
37	Magne and Quénon, 2021	Agronomy for Sustainable Development	Dairy crossbreeding challenges the French dairy cattle socio-technical regimen	France	Breeding, socio-technical	Medium

1

LCA = life-cycle assessment.

RESULTS

Agroecological and Sustainability-Related Studies in Dairy Farming Across EU Countries

In the analysis of agroecological and sustainability-related studies in dairy farming across the EU (Table 2), we observe significant regional variations in research focus and intensity. France leads with 9 studies (24.3%), which explore agroecological transitions, mountain farming, breeding systems, pesticide use, and socio-technical changes (Botreau et al., 2014; Martin and Willaume, 2016; Soteriades et al., 2016; Diakité et al., 2019; Magne and Quénon, 2021; Arielle et al., 2022;

Roques et al., 2023; Denantes et al., 2025; Mennig and Szigeti, 2025; Table 2). Germany follows with 7 studies (18.9%), primarily addressing GHG emissions, profitability, biodiversity, and feeding systems (Dentler et al., 2020; Zehetmeier et al., 2020; Díaz de Otálora et al., 2021, 2022; Reinsch et al., 2021; Bettin et al., 2023; Wild et al., 2025). With 6 studies (16.2%), Italy makes a distinctive contribution to the sustainability analysis of individual farming systems by concentrating on carbon footprints, Protected Designation of Origin cheese (**PDO**) systems, and seasonal management, especially in Alpine regions (Verduna et al., 2020; Flach et al., 2021; Masi et al., 2021; Romano et al., 2021; Ferronato et al., 2025; Zanon et al., 2025). The Netherlands contributes 4 studies (10.8%) that address sustainable productivity growth, life-cycle assessments of milk production, and agricultural intensification, emphasizing the intersection of environmental, economic, and social efficiency in Dutch dairy systems (Thomassen et al., 2008; van Apeldoorn et al., 2013; Zhu and Oude Lansink, 2022; Zhu et al., 2023). Denmark, with 4 studies (8.1%), focuses on climate effects, nutritional mitigation for methane emissions, and economic performance in dairy farming, providing insights into the environmental and economic trade-offs of sustainable practices (Markussen et al., 2015; Lehmann et al., 2019; B∅rsting et al., 2023; Dorca-Preda et al., 2024). Spain and Norway each contribute 2 studies (5.4%). Spain investigates the role of organic milk production in sustainable development and agroecosystem services, whereas Norway looks at GHG emissions and the profitability of organic versus conventional dairy farming (Flaten et al., 2019; Vázquez-González et al., 2021; da Silva Cyrne et al., 2023; Hansen et al., 2024). Switzerland and Romania contribute less, each accounting for 2.7% of the studies. Switzerland's study examines the connection between production intensity and environmental performance (Jan et al., 2019), whereas Romania's study examines the profitability of dairy farms (Chetroiu et al., 2022).

Table 2. Country-level summary of dairy sustainability research[1]

Country	**Number (studies)**	**% of total**	**Key focus areas**	**Significance to sustainability**
France	9	24.30%	Agroecological transitions, mountain farming, breeding systems, pesticide use, socio-technical changes	Strong presence of system-level and socio-technical studies; high relevance for policy and agricultural living labs
Germany	7	18.90%	GHG emissions, profitability, biodiversity, and feeding systems	Focus on environmental metrics and systemic farm-level performance
Italy	6	16.20%	Carbon footprint, PDO cheese systems, typology assessments, seasonal management	Emphasis on case-based sustainability (PDO cheese, Alpine systems), offering insights for comparability

Country	Number (studies)	% of total	Key focus areas	Significance to sustainability
The Netherlands	4	10.80%	LCA, eco-efficiency, economic productivity, landscape change	Strong in methodological and efficient evaluations with clear sustainability metrics
Denmark	4	10.80%	Emissions mitigation, extended lactation, energy systems, and feeding strategies	High focus on climate mitigation strategies and herd management

1

LCA = life-cycle assessment.

Dimensions of Sustainability in Agroecological Dairy Transitions

The examination of the 37 distinct studies provides a comprehensive view of how sustainability dimensions, environmental, economic, and social, are addressed in agroecological dairy transitions (Figure 2 and Table 3). A significant portion of the research (12 studies; 32.4%) focused on environmental sustainability, specifically on the effect of dairy farming on land use, GHG emissions, and carbon footprints. Notable studies in this category include Ferronato et al. (2025), which assessed the carbon footprint of dairy milk and Grana Padano cheese in Italy, and Roques et al. (2023), which examined the relationship between agroecological practices and methane emissions in dairy cattle.

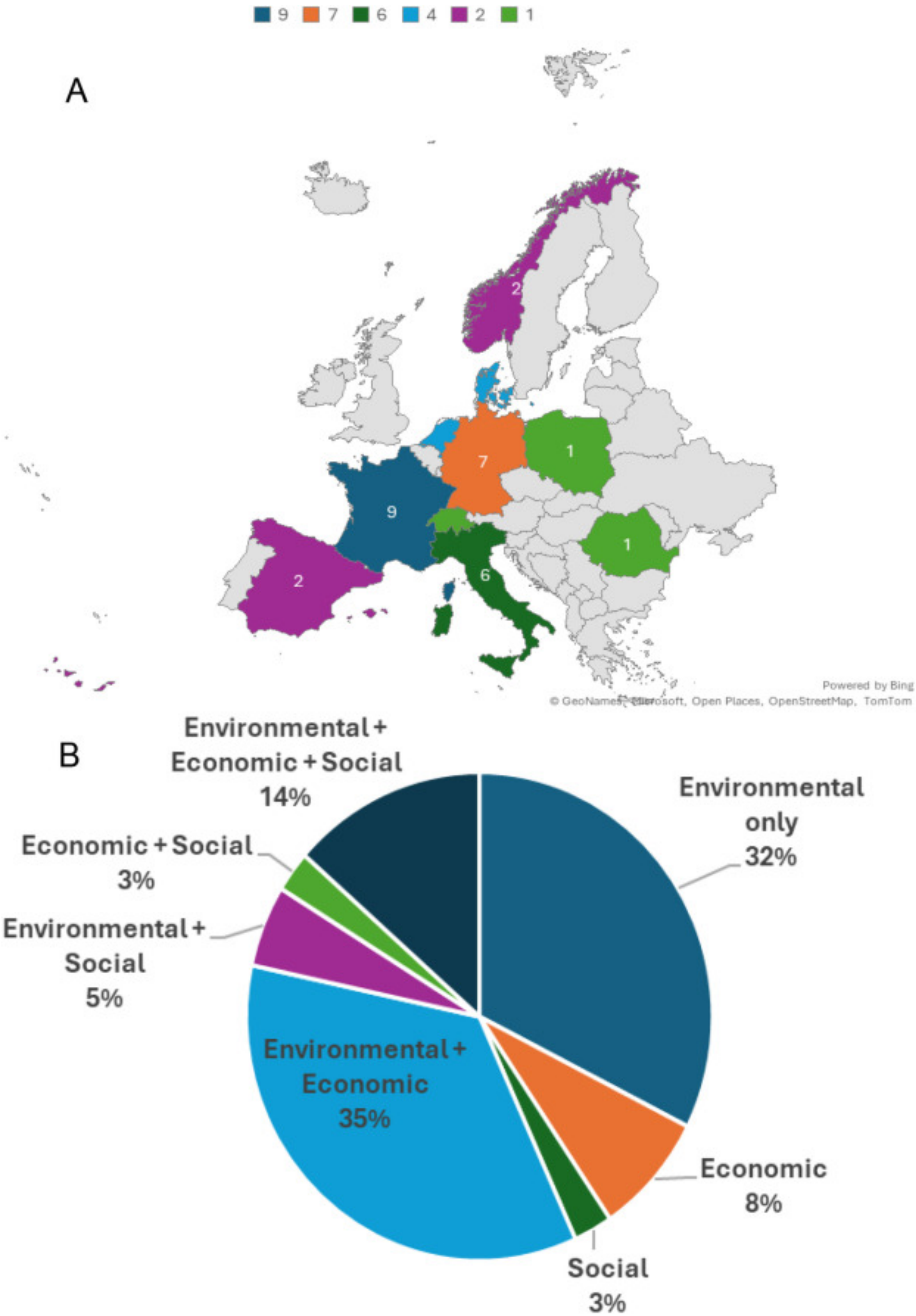

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Figure 2. Represents the geographic distribution of studies in European countries (A), with the percentage breakdown of each aspect (environmental, economic, social) across different countries (B).

Table 3. Distribution of scientific studies on the agroecological transition in dairy farming according to sustainability pillars

Category	Number of studies (N)	Percentage (%)	Reference	Title
Environmental	12	32.4	Thomassen et al. (2008); van Apeldoorn et al. (2013); Markussen et al. (2015); Martin and Willaume (2016); Jan et al. (2019); Dentler et al. (2020); Bettin et al. (2023); Børsting et al. (2023); Roques et al. (2023); Dorca-Preda et al. (2024); Ferronato et al. (2025); Zanon et al. (2025)	Various studies on carbon footprint, GHG emissions, feeding strategies, and impacts on environmental efficiency in dairy farming
Economic	3	8.1	Vázquez-González et al. (2021); Chetroiu et al. (2022); Mennig and Szigeti (2025)	Studies on farm profitability, economic viability, and the impacts of agroecology on economic performance in dairy farming
Social	1	2.7	Magne and Quénon (2021)	Study on social challenges in French dairy farming, focusing on crossbreeding in the socio-technical regimen
Environmental + economic	13	35.1	Soteriades et al. (2016); Flaten et al. (2019); Lehmann et al. (2019); Zehetmeier et al. (2020); Flach et al. (2021); Reinsch et al. (2021); Romano et al. (2021); Díaz de Otálora et al. (2022); Børsting et al. (2023); da Silva Cyrne et al. (2023); Zhu et al. (2023); Hansen et al. (2024); Wild et al. (2025)	Studies on the interplay between environmental sustainability and economic performance, including farm profitability and emissions reduction
Environmental + social	2	5.4	Botreau et al. (2014); Denantes et al. (2025)	Studies examining labor conditions, pesticide use reduction, and agroecological assessments

Category	Number of studies (N)	Percentage (%)	Reference	Title
				in mountain dairy farming
Economic + social	1	2.7	Diakité et al. (2019)	Study on mixed dairy systems in mountain areas, focusing on economic and social performance
Environmental + economic + social	5	13.5	Verduna et al. (2020); Díaz de Otálora et al. (2021); Masi et al. (2021); Arielle et al. (2022); Zhu et al. (2023)	Holistic studies integrating environmental, economic, and social sustainability in dairy farming and agroecological transitions

Other studies addressing environmental factors include B∅rsting et al. (2023), which examined GHG emissions from various feeding practices, van Apeldoorn et al. (2013), which investigated the effect of landscape coevolution on farming practices, and Martin and Willaume (2016), which offered diachronic studies on GHG emissions on French dairy farms. Markussen et al. (2015) and Dorca-Preda et al. (2024) contributed with a focus on net-energy analysis and mitigation options for enteric methane emissions, respectively. Zanon et al. (2025) investigated seasonal variability of dietary influences on environmental efficiency, whereas Thomassen et al. (2008) used life-cycle assessment to examine the environmental effects of milk production. Bettin et al. (2023) and Dentler et al. (2020) provided comparative insights on low-input versus high-input confinement-based dairy systems, grassland phytodiversity, and feeding practices.

In terms of economic considerations, 3 studies (8.1%) explored the relationship between farm profitability and the adoption of sustainable practices. For example, Chetroiu et al. (2022) assessed the profitability of dairy farms transitioning to agroecological systems, highlighting both challenges and opportunities. Similarly, Mennig and Szigeti (2025) discussed the economic trade-offs between environmental sustainability and profitability on dairy farms. Only one study examined social dynamics in the context of agroecological transitions in dairy production. Magne and Quénon (2021) studied the societal concerns raised by dairy crossbreeding in France, focusing on the effects of these practices on the socio-technical regimen of dairy production.

Thirteen studies (35.1%) integrated both environmental and economic dimensions. These studies examined strategies to enhance sustainability by modifying feeding strategies or improving GHG emission reductions. Noteworthy among them, Zehetmeier et al. (2020) explored the interplay between GHG emissions and farm profitability in Bavaria, and Flaten et al. (2019) compared the financial benefits and environmental effects of conventional and organic dairy farms. Two studies

(5.4%) investigated both social and environmental sustainability. Denantes et al. (2025) explored labor conditions in agriculture and emphasized the possible blind spots in reducing the use of pesticides on dairy farms, whereas Botreau et al. (2014) suggested standards for agroecological evaluations in mountain farming systems, stressing the inclusion of both social and ecological factors.

One study (2.7%) examined the intersection of economic and social sustainability. Diakité et al. (2019) assessed the economic and social performance of mixed dairy cow–suckler cattle systems in mountain areas, highlighting the challenges of balancing economic viability with social outcomes.

Finally, 5 studies (13.5%) adopted a holistic approach, addressing all 3 pillars of sustainability: environmental, economic, and social. These studies provided comprehensive insights into the synergies and trade-offs between the 3 dimensions, often focusing on agroecological transitions in specific regions such as the Alps or other mountain areas. Verduna et al. (2020) assessed sustainability scenarios in Alpine dairy farming, whereas Arielle et al. (2022) explored the feasibility of organic conversion in agroecological systems.

Challenges and Suggested Solutions Toward Agroecological Transition in Dairy Farming Systems in Europe

After a thorough review of the existing literature, we have identified several major challenges facing the European dairy sector in its transition. A synthetic overview of these challenges and the corresponding agroecological strategies is presented in Table 4. These strategies, which include knowledge coconstruction, precision feeding, and low-input grazing systems, underline the significant potential of the dairy sector to achieve sustainable transformation. The outlined initiatives provide specific solutions to the many challenges and facilitate the transition to more sustainable dairy practices throughout Europe. However, an in-depth examination of each study shows that contextual factors, methodological approaches, and implementation challenges are critical to understanding the real-world implications and scalability of the provided solutions. The following synthesis investigates these elements in further depth, paying particular attention to trade-offs, synergies, and recommendations applicable to agroecological transition trajectories.

Table 4. Agroecological strategies in dairy farming: Key challenges and solutions from scientific literature[1]

Category	Study	Key challenge	Agroecological solution	Relevant practices
Environment; environmental + economic; environmental +	Ferronato et al. (2025)	GHG emissions, carbon footprint in milk production	Decoupling production intensity from environmental degradation	Integrated production strategies, feed efficiency improvements, methane-reducing feed additives

Category	Study	Key challenge	Agroecological solution	Relevant practices
social	Zehetmeier et al. (2020); Flaten et al. (2019)	High-protein concentrate use, inefficient feed conversion	Enhanced feed efficiency, reduced concentrate use	Precision feeding, low-input pasture systems, more efficient protein conversion
	Flaten et al. (2019)	GHG emissions and nitrogen surpluses in conventional systems	Organic and low-input systems	Organic farming practices, pasture-based feeding systems, reduced nitrogen surplus
	Zhu and Oude Lansink (2022)	Inefficiencies in scale and technical operations in dairy farms	System-wide optimization	Agroecological management, reduced reliance on imported concentrates
	Reinsch et al. (2021)	Environmental footprint, sustainability of conventional dairy systems	Integration of livestock and crop systems	Integrated livestock-crop farming systems (IFG), grassland-based agroecology
	Bettin et al. (2023)	Biodiversity loss and nutrient surpluses due to high-concentrate feeding	Low-concentrate feeding strategies	Low-concentrate feeding, grassland phytodiversity management, biodiversity-friendly systems
	Dorca-Preda et al. (2024)	Enteric methane emissions	Use of methane-reducing feed additives	3-NOP feed additives, mitigation of methane emissions, nutrient management improvements
	Dentler et al. (2020)	High nutrient inefficiency in high-input systems	Low-input, grass-based systems with better nutrient efficiency	Biological nitrogen fixation, grass-based feeding systems, improved nitrogen and phosphorus efficiency
	Soteriades et al. (2016)	Feed and energy inefficiency, reliance on external inputs	Self-sufficiency in feed and energy	Reduced use of imported concentrates, increased feed self-sufficiency
	Wild et al. (2025)	Over-reliance on concentration and biodiversity loss	Incentives for grass-based and biodiversity-friendly	Policy interventions for reduced concentrate use, grass-based systems,

Category	Study	Key challenge	Agroecological solution	Relevant practices
			systems	biodiversity conservation
	Flach et al. (2021); Zanon et al. (2025)	High-input farming systems lead to nutrient imbalances and inefficiency	Low-input systems using local breeds and extensive grazing	Seasonal grazing, use of local breeds (e.g., Tyrolean Grey), low-input farming practices
Economic	Chetroiu et al. (2022)	Structural disparity between small and large farms	Tailored policy interventions and support for small farms	Financial support for small-scale farms, risk management tools, assistance with economies of scale
	Mennig and Szigeti (2025)	Profitability of agroecological strategies, trade-offs in economic gains	"Win-win" practices such as reducing concentrate feed and extending cow life spans	Reduced concentration feeding, extending cow life spans, low-input systems, wetland conservation
	Vázquez-González et al. (2021)	Tensions between agroecosystem services and dysservices	Participatory approach to decision-making, balancing synergies	Grazing management, organic practices, precision feeding, decision-making tools for trade-offs
	General findings	Economic feasibility of low-input systems	Holistic strategy integrating financial, social, and environmental priorities	Comprehensive decision-making tools, balancing multiple sustainability dimensions, social and institutional support
Social	Magne and Quénon (2021)	Underutilization of rotational crossbreeding due to market structures, consumer preferences, and a lack of technical support	Market reforms, expansion of advisory networks, and community-based learning	Premium schemes for sustainably produced milk, expanding agroecological advisory networks, peer knowledge exchange, social innovation

Category	Study	Key challenge	Agroecological solution	Relevant practices
	General findings	Cultural resistance and institutional barriers to adopting alternative practices	Promoting social innovation, shifting attitudes through market incentives, and institutional support	Changing socio-technical norms, incorporating agroecological practices in mainstream advisory systems, community-based learning and peer support
Interconnected challenges and solutions of agroecological transition	Verduna et al. (2020)	GHG emissions, food-feed competition, low generational turnover, limited quality of life for farmers	Low-input systems, efficient pasture management, direct marketing of dairy products	Balances the environmental benefits of low-input systems with economic and social sustainability by addressing farm management and farmer well-being
	Arielle et al. (2022)	Limited organic milk collection networks, milk quotas, conflict between productivity and sustainability	Support for organic transitions, well-organized infrastructure, agricultural extension services	Focuses on socio-economic factors shaping the transition, balancing productivity and sustainability through infrastructure, and addressing market and policy constraints
	Díaz de Otálora et al. (2021)	Complexity of sustainability assessment, balancing resource efficiency with profitability and social well-being	Sustainability modeling, synergies between environmental, economic, and social pillars	Emphasizes the need for sustainability frameworks that consider all dimensions—environmental, economic, and social—ensuring long-term resilience
	Zhu et al. (2023)	Environmental inefficiencies, social inefficiencies, dependence on government support	Reducing cow replacement rates, enhanced advisory services, better policy support	Focuses on the interlinked environmental, economic, and social inefficiencies, recommending policy and advisory improvements to foster sustainability
	Masi et al. (2021)	Resistance to change due to traditional practices, short-term economic	Knowledge-sharing platforms, capacity-building initiatives,	Advocates for creating a supportive policy framework that integrates

Category	Study	Key challenge	Agroecological solution	Relevant practices
		pressures, limited access to knowledge and technologies	financial mechanisms for agroecology	economic incentives, capacity building, and collaboration between stakeholders for agroecological transitions

1

3-NOP = 3-nitrooxypropanol.

Environmental Challenges and Agroecological Solutions

Dairy production is a major contributor to the carbon footprint in cheese production systems, with enteric methane (34%), feed production (36%), and manure management (24%) as key sources (Ferronato et al., 2025). Improving feed efficiency and reducing the use of protein-rich concentrates such as soybean or rapeseed meal has been shown to enhance farm profitability while lowering emissions (Flaten et al., 2019; Zehetmeier et al., 2020). Norwegian organic farms emit 1.3 times less GHG per hectare and have 2.6 times lower nitrogen surpluses compared with conventional farms, without loss of profitability (Flaten et al., 2019). Dutch dairy farms have experienced a 1.1% annual decline in environmental sustainability due to inefficiencies in size and technical operations (Zhu and Oude Lansink, 2022). Integrated dairy-crop systems reduce carbon and nitrogen footprints without sacrificing milk yield (Reinsch et al., 2021), while low-concentrate feeding promotes grassland phytodiversity and biodiversity preservation (Bettin et al., 2023). Methane-reducing additives such as 3-nitrooxypropanol can reduce enteric methane emissions by 13% per kilogram of milk without affecting productivity (Dorca-Preda et al., 2024). Grass-based, low-input systems exhibit 28% higher nitrogen and 98% higher phosphorus efficiencies and over 300% better protein and energy conversion efficiency compared with high-input systems (Dentler et al., 2020). Farms with greater food and energy self-sufficiency show improved eco-efficiency (Soteriades et al., 2016). However, once concentrates exceed 30% of the milk ration, dairy systems become net consumers rather than providers of digestible protein, contributing to biodiversity loss and nutrient surpluses (Wild et al., 2025). In mountain systems, low-input farms using local breeds and seasonal grazing outperform high-input farms in nutrient balance and land-use efficiency, despite slightly higher GHG emissions per unit of milk (Flach et al., 2021; Zanon et al., 2025).

Economic Challenges and Solutions

Recent literature identifies 5 interrelated challenges to economic sustainability that influence the feasibility of agroecological transition in European dairy farming, spanning environmental, structural, and institutional dimensions. Small farms, especially those with fewer than 20 cows, face higher production costs and lower profitability compared with larger farms with over 100 cows, which benefit from economies of scale and higher worker productivity (Chetroiu et al., 2022). Studies on organic, pasture-based farms in Southern Bavaria report “win-win” practices such as reducing concentrate feed and extending cow life spans, which lower environmental effects and increase profitability (Mennig and Szigeti, 2025). However, some environmentally beneficial practices, such as wetland conservation or adopting low-input systems, may not provide immediate economic benefits. Participatory analyses in Galicia identified 19 agroecosystem services and 9 dysservices, illustrating the complexity of balancing positive and negative effects in agroecological practices (Vázquez-González et al., 2021).

Social Challenges and Solutions

Research on agroecological transition in dairy farming often overlooks social challenges, despite their significant influence on the adoption of sustainable practices. Magne and Quénon (2021) highlight the underutilization of rotational crossbreeding in French dairy systems, despite its potential benefits for animal health and sustainability. Key social barriers include market structures favoring purebred milk due to consumer preferences and industry emphasis on high-output breeds, creating strong economic incentives for farmers to maintain conventional purebred herds. Additionally, limited access to technical expertise and agroecological advisory services, predominantly oriented toward conventional farming, restricts adoption. Socio-technical norms prioritizing efficiency and productivity also discourage farmers from embracing alternative practices such as rotational crossbreeding, as these approaches appear less conventional and less market-aligned (Magne and Quénon, 2021).

Interconnected Challenges and Solutions of Agroecological Transition

The reviewed studies provide comprehensive insights into the multifaceted challenges and solutions involved in the agroecological transition in dairy production, spanning environmental, economic, and social dimensions. Verduna et al. (2020) compared high-input versus low-input grazing-based systems in the Alpine region, identifying significant environmental effects such as GHG emissions and feed-food competition mainly in high-input systems. Low-input systems, particularly those utilizing local breeds and efficient pasture management, reduced environmental footprints and feed dependency but faced social issues such as low generational renewal and farmers' quality of life challenges. Arielle et al. (2022) examined organic farming integration in mountainous livestock systems in southern France, highlighting barriers such as limited organic milk networks and milk quotas that restrict market entry. Despite challenges, farmers followed 3 main pathways to organic conversion driven by socio-economic factors and agroecological practices, though some changes conflicted with traditional agroecological principles, especially regarding grazing and biodiversity conservation. Díaz de Otálora et al. (2021) reviewed sustainability models for dairy systems, emphasizing the complex need to balance environmental efficiency, economic profitability, and social well-being, with trade-offs between these pillars requiring decision-support tools. Zhu et al. (2023) analyzed Dutch dairy farms post-2015 milk quota abolition, identifying environmental inefficiencies tied to large farms and cow replacement rates, alongside social inefficiencies involving financial and government support structures. Mitigating these inefficiencies could improve sustainability by reducing replacement rates and enhancing advisory service use. Finally, Masi et al. (2021) addressed resistance to agroecological transition caused by traditional farming habits, economic pressures favoring short-term gains, limited access to knowledge and technologies, and weak institutional support. Proposed solutions included knowledge-sharing platforms, capacity building, financial incentives, and stronger policy frameworks to foster collaboration among farmers, researchers, and policymakers.

DISCUSSION

Why Do France, Germany, and Italy Dominate Sustainability Research in EU Dairy Farming?

The regional focus of sustainability research in dairy farming is reflected in this distribution of studies. The predominance of research outputs from France, Germany, and Italy can be attributed to structural factors such as the size and diversity of their agricultural sectors, strong institutional support for agroecology, and national policies promoting sustainable transitions (Wezel et al., 2009; Darnhofer et al., 2012; Parmentier, 2014). These countries also benefit from well-established advisory systems, research infrastructures, and funding schemes that prioritize agroecological innovation. In Germany, the dairy sector has undergone extensive modernization and consolidation, maintained a strong export orientation, and encouraged investments in sustainability innovation and performance evaluation tools (Henrike et al., 2016). France demonstrates an institutional commitment to sustainable dairy development through national programs such as France Terre de Lait, which supports triple-bottom-line targets and thus stimulates academic research (European Milk Forum, 2021). Italy's emphasis on high-quality regional products, particularly those linked to geographical indications such as PDO cheeses and dairy systems in mountainous and Alpine environments, has attracted attention to sustainability and agroecological challenges. Additionally, these regions are often the focus of EU environmental and rural development funding, reinforcing the research infrastructure. Together, these factors contribute to the high concentration of sustainability-focused dairy research in these 3 countries compared with other EU member states.

Gaps and Synergies in Environmental, Economic, and Social Dimensions of Agroecological Dairy Transitions

The reviewed studies confirm that environmental sustainability remains the dominant focus in the literature on agroecological dairy transitions. This emphasis reflects the growing urgency to reduce the environmental footprint of dairy production, particularly regarding GHG emissions and land use (Knudsen et al., 2014). Agroecological practices offer tangible potential to mitigate these effects through diverse strategies such as dietary adjustments, low-input systems, and improved grassland management (Duru et al., 2015; Mennig and Szigeti, 2025). The integration of life-cycle assessments and carbon footprint methodologies also reinforces the scientific rigor applied to environmental evaluations (Zanni et al., 2022).

Despite this environmental emphasis, the relatively limited attention paid to economic sustainability suggests a potential weakness in the current research landscape. The few studies that addressed economic issues nonetheless underscore their critical importance. For example, Chetroiu et al. (2022) reveal that small dairy farms face higher production costs and lower profitability, making them more vulnerable during agroecological transitions. Similarly, Vázquez-González et al. (2021) highlight the financial trade-offs between agroecosystem services and dysservices. Understanding profitability and the economic implications of transitioning to agroecological systems is essential for adoption and long-term viability. These trade-offs also point to the need for supportive policy measures and targeted incentives that can ease financial constraints and risks for farmers (Mennig and Szigeti, 2025).

Social sustainability, meanwhile, is significantly underrepresented in the reviewed literature. The lack of studies exploring aspects such as farmer participation, labor conditions, gender equity, and community acceptance reveals a notable research gap (Duru et al., 2015; Magne and Quénon, 2021). Although the study by Magne and Quénon (2021) on socio-technical norms and the adoption of rotational crossbreeding in France offers an important entry point, the broader social dynamics of agroecological transitions, such as knowledge exchange, trust, and institutional support, remain largely unexplored. This absence could undermine the holistic understanding and implementation of sustainable practices, especially given that social dimensions are often central to farmers' decision-making processes and the resilience of rural communities (Duru et al., 2015; Magne and Quénon, 2021).

The studies that integrate 2 or more dimensions of sustainability are particularly valuable. For example, Mennig and Szigeti (2025) and Vázquez-González et al. (2021) demonstrate how environmental and economic considerations often intersect, especially when evaluating the viability of pasture-based systems or assessing trade-offs in ecosystem services. More importantly, the few studies adopting a fully integrated, 3-dimensional perspective incorporating environmental, economic, and social dimensions suggest that sustainability in agroecology is not merely about balancing trade-offs but also about identifying synergies that reinforce long-term system resilience (Duru et al., 2015; Zanni et al., 2022). These holistic approaches provide promising models for future research and policymaking, emphasizing the need to consider environmental protection, economic viability, and social well-being as interconnected and mutually reinforcing goals. In conclusion, though environmental concerns are well covered, greater attention to economic and especially social dimensions is crucial for a more comprehensive understanding of agroecological transitions in dairy farming systems. Strengthening the integration of these 3 pillars in research and practice will be essential to designing effective, inclusive, and sustainable pathways toward agroecological transformation.

Interlinked Challenges and Pathways in Agroecological Transitions of Dairy Farming

The findings of this review underscore the complexity of environmental challenges in dairy farming and the potential of agroecological solutions. The significant contribution of enteric methane, feed production, and manure management to carbon footprints suggests that targeted mitigation strategies focusing on improving feed efficiency and manure handling are crucial (Ferronato et al., 2025). Although reducing protein-rich concentrates can simultaneously increase profitability and reduce emissions, trade-offs such as increased emissions from shorter calving intervals and greater management complexity highlight the need for tailored, context-specific approaches (Flaten et al., 2019; Zehetmeier et al., 2020). Organic and low-input systems illustrate that lower input intensity can improve environmental outcomes without economic losses, supporting their wider adoption (Flaten et al., 2019). The decline in sustainability among some conventional farms indicates a need for holistic system optimization (Zhu and Oude Lansink, 2022). Integration of crop and livestock systems aligns with agroecological principles by reducing environmental effects while enhancing biodiversity and management flexibility (Reinsch et al., 2021; Bettin et al., 2023). Nutritional interventions such as methane inhibitors show promise but require life-cycle analyses to avoid unintended nutrient pollution (Dorca-Preda et al., 2024). The challenge of disentangling intensification from self-sufficiency highlights the importance of robust sustainability metrics (Soteriades et al., 2016). Finally, the mountain context presents unique opportunities and constraints, where policies should consider landscape-scale effects and ecosystem services to promote sustainable agroecological transitions (Flach et al., 2021; Wild et al., 2025; Zanon et al., 2025).

The economic challenges in agroecological transition reveal the complexity of balancing profitability with sustainability goals. The structural disadvantage of small farms underlines the need for tailored policy measures and financial support to avoid their marginalization during transition processes (Chetroiu et al., 2022). Although "win-win" strategies demonstrate potential for simultaneous economic and environmental benefits, trade-offs remain inevitable in some practices, highlighting the importance of decision-making tools capable of evaluating synergies and conflicts across sustainability dimensions (Mennig and Szigeti, 2025). The identification of both ecosystem services and dysservices emphasizes that agroecological transitions must carefully consider multifaceted effects to optimize outcomes (Vázquez-González et al., 2021). Ultimately, the agroecological transition requires an integrated strategy that addresses social, financial, and environmental priorities, acknowledging farmers' diverse objectives and institutional contexts to ensure a viable and equitable shift across Europe.

Overcoming social barriers in agroecological transition requires addressing both institutional and cultural factors. Market reforms such as premium pricing for sustainably produced milk and expansion of agroecology-focused advisory services could shift institutional support and farmer attitudes (Magne and Quénon, 2021). Changing socio-technical norms demands concrete social practices that foster change, including peer-to-peer learning networks, participatory knowledge coconstruction, and reforming advisory services to incorporate agroecological expertise. Social innovations such as farmer field schools, participatory workshops, and community-led initiatives build trust, reshape cultural values, and encourage sustainable behaviors. Integrating these social dynamics with technical and economic strategies is essential to unlocking the full potential of agroecological practices in the dairy sector, emphasizing that transition is not solely a technical or economic challenge but deeply embedded in social contexts (Magne and Quénon, 2021).

Beyond recognizing the importance of shifting socio-technical norms, it is crucial to specify the social practices that enable this change. Effective transition strategies include fostering peer-to-peer learning networks among farmers, coconstructing knowledge through participatory approaches involving multiple stakeholders, and reforming advisory services to incorporate agroecological expertise (Ingram, 2018). Social innovations such as farmer field schools, participatory workshops, and community-led initiatives serve to build trust, reshape cultural values, and promote sustainable behavior adoption (Moschitz et al., 2015; Darnhofer, 2020). These concrete social mechanisms provide the behavioral foundation necessary for complementing technical and economic interventions. This study emphasizes the need to incorporate social dynamics into agroecological transition research, as overcoming these challenges is essential for accomplishing the full potential of agroecological practices in the dairy sector (Wezel et al., 2009; Magne and Quénon, 2021).

These studies collectively illustrate that the agroecological transition in dairy farming is an intricate process involving intertwined environmental, economic, and social challenges. Low-input and organic systems show promise in reducing environmental effects and enhancing economic resilience, yet social factors such as generational turnover, quality of life, and access to markets and advisory services remain critical barriers (Verduna et al., 2020; Arielle et al., 2022). The complexity of balancing sustainability's 3 pillars demands integrated modeling and policy approaches that address trade-offs and synergies (Díaz de Otálora et al., 2021). Moreover, inefficiencies related to farm size, replacement rates, and institutional support highlight the need for targeted policy and advisory service improvements (Zhu et al., 2023). Resistance to change and limited institutional alignment with agroecological principles further impede progress, requiring systemic solutions including financial mechanisms, knowledge platforms, and stakeholder collaboration (Masi et al., 2021). The scarcity of holistic studies encompassing environmental, economic, and social dimensions simultaneously reveals a critical research gap. Future efforts must adopt interdisciplinary frameworks recognizing the mutual influence of these dimensions, ensuring agroecological transitions are sustainable, equitable, and context-specific across diverse dairy farming systems.

Recommendations and Practices for the Transition to Sustainable Dairy Farming

According to the findings of this study, a transition toward sustainable dairy farming that is deemed successful requires integrated, system-based approaches that address environmental, economic, and social challenges simultaneously (see Figure 3). This requires not only the adoption of individual sustainable practices but also a reconfiguration of the relationships between farming activities, institutional structures, value chains, advisory services, and broader territorial contexts.

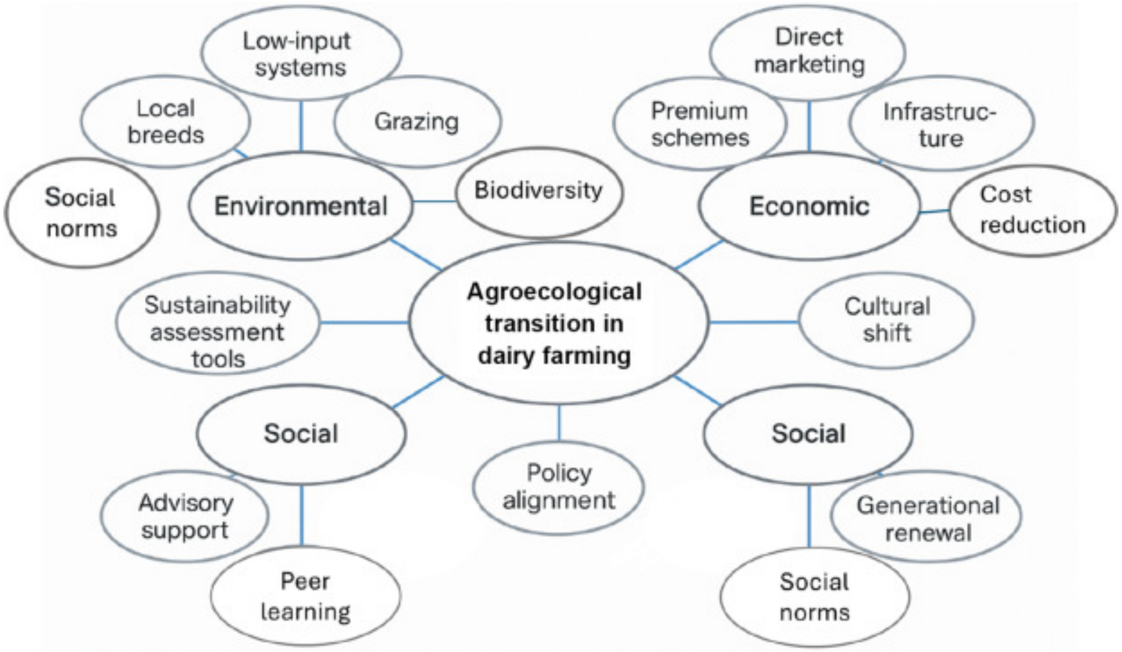

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Figure 3. Conceptual diagram showing the interconnected pillars (environmental, economic, social).

The promotion of low-input, locally adapted farming systems, such as grazing-based models, has the potential to reduce external input dependency, enhance biodiversity, and strengthen resilience to climate variability (Altieri et al., 2015). However, from a systems-based perspective, these technical practices cannot be implemented in isolation. They must be embedded within broader systemic changes that consider the interconnectedness of production, knowledge, infrastructure, and governance (Gliessman, 2014; Wezel et al., 2020).

This includes the development of infrastructural support, such as reliable milk collection networks that ensure timely and hygienic transport of milk from dispersed farms to processing facilities, particularly for organic and sustainably produced milk (Mennig and Szigeti, 2025). These efforts must be complemented by market-based mechanisms, such as premium pricing, participatory certification, and transparent labeling schemes that provide incentives for environmentally and socially responsible practices (Magne and Quénon, 2021). Moreover, achieving policy alignment is imperative to support a coherent and stable environment for agroecological transition. This includes the implementation of targeted subsidies, flexible regulations, and cross-sectoral frameworks that jointly address productivity, ecological health, and social well-being (Díaz de Otálora et al., 2021). Importantly, policy should be designed with attention to feedback loops and interactions across scales, ensuring that national and regional decisions reinforce rather than undermine local sustainability efforts (Verduna et al., 2020).

Integrated sustainability assessment tools also play a key role in this transition. When grounded in systems thinking, such tools enable a holistic evaluation of trade-offs and synergies between ecological performance, farm profitability, and social equity, helping to inform context-sensitive decisions rather than one-size-fits-all prescriptions (Duru et al., 2015; Zhu and Oude Lansink, 2022).

Finally, cultural and social dimensions are inseparable from technical and economic change. Overcoming barriers such as traditional norms that prioritize industrial efficiency requires investment in social innovation, improved quality of life for farming communities, and the revalorization of agroecological knowledge as legitimate, contemporary, and aspirational.

In short, these strategies must not be seen as isolated solutions but as interconnected components of a coherent, systemic transformation. Agroecological transition in dairy farming must be approached as a complex, adaptive process, one that requires coordination across multiple domains, stakeholder groups, and levels of governance. Building on the findings, future research should adopt a transdisciplinary and systemic paradigm that integrates technical, social, economic, and policy dimensions to better understand and guide the complex processes of agroecological transition in dairy farming.

Limitations of the Review

The review was conducted methodically and transparently, sourcing peer-reviewed literature from reputable scientific databases and applying well-defined inclusion criteria. Though we took steps to ensure rigor, we accept numerous limitations. First, even with a structured strategy, we cannot guarantee that all relevant material was obtained. It is possible that some pertinent studies were excluded due to limitations in keyword combinations, database indexing, or language restrictions. Second, although screening and selection were conducted in multiple rounds to minimize bias, a degree of subjectivity in judgment and interpretation may persist. It is also important to recognize that this review may have excluded studies from the broader sustainability or rural development literature that engage with transition processes but do not explicitly adopt agroecological terminology. These could offer additional insights into institutional, policy, and behavioral dynamics influencing change in dairy systems. Finally, although the review gives a comprehensive summary of current research on the agroecological transition in European dairy farming, it may not fully capture all regional differences or gray literature contributions. These limitations highlight the importance of continuous updates and complementary analysis as the subject progresses.

CONCLUSIONS

This comprehensive review of 37 studies underscores the intricacy of the agroecological transition in dairy farming. The analysis reveals that, although environmental and economic dimensions have received considerable scholarly attention, social dimensions have been inadequately explored. A comprehensive review of the extant literature reveals that successful transition requires not only technical- and market-based solutions but also institutional support, advisory reform, and cultural change within farming communities. Integrated, interdisciplinary approaches that connect environmental, economic, and social factors are still lacking but essential. To facilitate a sustainable and inclusive transformation of the sector, it is imperative to prioritize the following: the fostering of cocreation, the strengthening of peer networks, and the alignment of policies. Though this review provides a snapshot of the current literature on sustainability transitions in European dairy systems, future research would benefit from a more integrated and transformative lens. This includes aligning agroecological research with insights from sustainability transitions theory, socio-technical systems, and food systems transformation. There is a need for longitudinal studies that examine not only the effectiveness of specific practices but also the systemic conditions under which transitions are initiated and sustained. Moreover, greater attention should be paid to labor dynamics, policy codesign, and the role of consumer-citizens in shaping agroecological markets. Building such interdisciplinary and participatory research agendas can significantly enhance our capacity to enable deep agroecological transitions across diverse dairy contexts.

NOTES

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Nonstandard abbreviations used: 3-NOP = 3-nitrooxypropanol; EU = European Union; LCA = life-cycle assessment; PDO = Protected Designation of Origin cheese.

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