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Eco-innovation in Mediterranean sheep farming informed by life cycle assessment evidence: stakeholder insights from a Sardinian case study

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Achieving sustainable transitions in extensive livestock systems requires environmental evidence that is not only scientifically robust but also relevant to farmers and other stakeholders operating in specific rural contexts. While Life Cycle Assessment (LCA) provides valuable insights into environmental performance, its contribution to decision-making remains limited when it is not aligned with stakeholder priorities, local knowledge, and contextual constraints. This study explores how stakeholders perceive and prioritise three eco-innovations, precision livestock farming, pasture improvement practices, and environmental labelling, and examines the drivers, trade-offs, and barriers influencing their adoption in Mediterranean sheep farming systems. The analysis builds on environmental evidence from previous LCA studies and combines participatory data from two multi-actor focus groups in Sardinia (Italy) with strategic evaluation and multivariate analysis to explore interactions among technical, economic, institutional, and socio-cultural factors. Pasture improvement practices emerged as the most promising option, showing strong alignment between environmental benefits and farm-level feasibility. Precision livestock farming demonstrated potential to improve system efficiency but was constrained by high investment costs, limited adaptability, and infrastructural shortcomings. Environmental labelling was perceived as the least attractive option because of market uncertainty, concerns about credibility, and weak knowledge exchange. Across all practices, adoption emerged as a context-dependent process shaped by interacting system components, with external constraints outweighing internal limitations. The study shows how stakeholders interpret environmental evidence and how this could support the adoption of context-specific eco-innovations. It reveals persistent mismatches with farm-level decision-making and highlights the need for context-specific innovation pathways, stronger knowledge exchange, and coordinated policy support to enable more effective sustainability transitions in extensive livestock farming.

KEYWORDS
rural sustainability, extensive livestock systems, eco-innovation, precision livestock farming, pasture improvement practices, environmental labelling, stakeholder perceptions

Introduction

Sheep farming is a central component of extensive livestock systems in the Mediterranean Basin, where small ruminants are adapted to marginal and semi-arid environments and support rural economies and traditional dairy products (Durmus et al., 2019). Across Mediterranean countries, sheep numbers exceed 149 million head, with the largest populations concentrated in Turkey, Algeria, Morocco and Spain, accounting for approximately 61% of the total (FAOSTAT, 2021). Mediterranean sheep systems are heterogeneous, ranging from low-input pastoral systems to specialized and intensified production models depending on agro-ecological and socio-economic conditions (Ripoll-Bosch et al., 2012).

Italy hosts around 6.7 million sheep (4.5% of the total; FAOSTAT, 2021) and is characterized by a strong specialization in dairy-oriented systems, particularly in regions such as Sardinia, the major Mediterranean sheep milk production area (Pulina et al., 2018). Sardinia, an Italian island, is characterized by a Mediterranean pastoral production system, with approximately 3.1 million dairy sheep across 10,000 farms, where modern industrial farming practices coexist with long-established pastoral traditions offering a relevant context for analysing livestock - climate interactions (Atzori et al., 2022).

Generally, climate change poses significant challenges, particularly for systems relying on natural pastures. Changes in temperatures and precipitation patterns, along with more frequent drought and extreme events, may reduce forage availability and quality, affecting animal performance and system resilience (Godde et al., 2021). Such a scenario is already perceived particularly in Mediterranean pastoral territories, where extensive livestock breeders might be pushed to adopt adaptive and sustainable resource-use strategies (Martín-Collado et al., 2025). These challenges may reduce feed intake, growth, and reproductive performance, highlighting the need for adaptive strategies, including breed-specific resilience and climate-smart grazing management strategies, to sustain productivity and economic viability (Savian et al., 2021; Bashiru and Oseni, 2025).

In this context, enhancing the adaptive capacity of Mediterranean pasture-based sheep systems requires integrated land-use and management strategies. This involves the adoption of technological innovations, such as precision livestock farming (PLF) approaches adapted to extensive conditions (Mura et al., 2026), pasture improvement practices (PIP) and grazing management practices aimed to sustain Mediterranean rangeland resilience (Oikonomou et al., 2023; Poulopoulou et al., 2024), and the development of sustainability-oriented value chains and environmental labelling (EL) schemes for pastoral products (Primi et al., 2024).

In pasture-based systems, PLF technologies may improve livestock management, welfare monitoring, and decision-making under extensive conditions (e.g., real time tracking of animals and grazing patterns) (Aquilani et al., 2022). Adoption remains limited in small ruminant systems due to economic, technical, and evaluative uncertainties (Tzanidakis et al., 2023).

PIP, such as grazing system design, soil fertility enhancement, and diverse multi-species swards, may enhance forage quality and livestock performance in pasture-based systems, since diverse swards have been associated with improved growth and productivity in grazing studies (Porqueddu et al., 2017; Beaucarne et al., 2025). Therefore, this approach might enhance both farm feed self-sufficiency and environmental performance through ecosystem services provision (Arca et al., 2021).

In the food sector, EL promotes green markets by providing simplified and trustworthy information on product environmental performance while highlighting companies' sustainability efforts (Cossu et al., 2024). Farmers' involvement in EL schemes depends on the benefits of group participation and on uncertainties regarding distribution of advantages along the supply chain (Pinto et al., 2014). Their adoption is also influenced by farm structure and socio-economic characteristics (e.g., age, education, experience, income, labour conditions, and farm type) (Kuan et al., 2021), and by scheme design, including technical support, governance, and clear environmental objectives (Altobelli et al., 2019). Their credibility is also crucial; greenwashing, where claims overstate sustainability, may increase consumer scepticism (Jakubczak and Gotowska, 2020). Therefore, understanding how stakeholders, particularly farmers, perceive and respond to certification is essential to support meaningful eco-labelling.

These practices were investigated within the context of three European research projects: SheepToShip LIFE, LIFE MAGIS, and SUREPASTOR. The SheepToShip LIFE project evaluated improved pasture management techniques and PLF strategies in Sardinian sheep farms, including pasture improvement through oversowing of mixed species and low-input soil management practices, as well as enhancements in reproductive and productive efficiency of sheep flocks (SheepToShip, 2020; Atzori et al., 2022; Vagnoni et al., 2024). Environmental labelling schemes were analysed within the LIFE MAGIS project, which developed Product Category Rules for hard sheep milk cheese based on the Product Environmental Footprint methodology (Cossu et al., 2024; LIFE MAGIS, 2024). Building on these studies, the present research integrated environmental evidence derived from Life Cycle Assessment (LCA) with stakeholder perspectives collected through participatory methods. Stakeholder engagement was conducted within the framework of the SUREPASTOR project, which aims to strengthen the resilience of Mediterranean agro-pastoral systems by promoting eco-innovative management practices in marginal areas (SUREPASTOR, 2024).

Adoption of innovative and sustainable practices is shaped by multiple interacting factors (e.g., education, technical support, incentives, and networking), requiring a flexible approach rather than consideration of single drivers separately (Rizzo et al., 2024). Evaluating these practices requires more than technical or environmental assessment, since adoption depends on stakeholders' perceptions and the capacity of analytical tools to capture system-level outcomes. Local production system characteristics provide essential context for understanding these dynamics and links between livestock systems and climate change strategies. Evidence from EU countries indicates carefully designed agri-environmental measures may reduce impacts without compromising farm profitability, highlighting the need for integrated, context-sensitive policies (Ait Sidhoum et al., 2023). In livestock systems, where environmental impacts result from interconnected processes, LCA provides robust environmental evidence to inform decision-making. In fact, this approach is

based on the understanding that products and services follow a value chain where resources are consumed, wastes are generated, and impacts are distributed across different actors and regions (UNEP and SETAC, 2012). LCA is a standardized method for quantifying environmental impacts along the supply chain, evaluating alternative management and mitigation options while accounting for potential trade-offs (Hellweg et al., 2023; Lanzoni et al., 2023). However, the practical LCA value depends on how stakeholders interpret results within their production contexts. Without such contextualization, LCA outcomes may not effectively support decision-making at farm and territorial levels, as they need to be interpreted in light of environmental, economic, technical, and socio-cultural conditions (Fan et al., 2022). Integrating LCA evidence is essential because extensive livestock systems involve complex environmental trade-offs that stakeholders' perceptions alone cannot fully capture. LCA provides the objective baseline data to identify environmental hotspots along the sheep supply chain, such as greenhouse gas emissions and resource depletion (Lanzoni et al., 2023; Vagnoni et al., 2024). However, environmental performance alone does not ensure that sustainable practices are adopted, particularly when they conflict with farmers' socio-economic realities. Using prior LCA results as an informational basis therefore grounds participatory discussions in empirical evidence and helps ensure that the eco-innovations evaluated are both ecologically sound and feasible in practice.

From a systems perspective, the evaluation of eco-innovative practices requires moving beyond isolated assessments to consider the trade-offs embedded within extensive sheep systems, where interactions between farming practices and landscapes shape both environmental and socio-economic outcomes. These dynamics are situated within rural systems, where livestock farming is understood as a multifunctional activity extending beyond production, particularly in relation to landscape management and the socially constructed priorities of rural development (Barnaud and Couix, 2020). In this perspective, environmental evidence derived from LCA studies might be complemented by broader socio-economic and nutritional assessments of pastoral systems, including Social- and Nutritional-LCA approaches (Franca et al., 2025).

Participatory approaches may help address this limitation by combining life cycle tools with stakeholder engagement and decision support methods, enhancing the relevance, validity, and stakeholder acceptance of sustainability assessments such as LCA (De Luca et al., 2017). In extensive sheep farming, these approaches may provide a structured means of integrating farmers' knowledge into sustainability assessments, thereby improving understanding of how LCA-informed practices are perceived and used in practice.

Against this background, this study contributes to the literature by using participatory approaches focused on LCA-based evidence to assess stakeholders' perceptions of eco-innovative practices, providing a system-oriented and context-specific analysis of their role in improving the sustainability and resilience of Sardinian sheep farming. By investigating stakeholders' perceptions of PLF, PIP, and EL in sheep farming, the study focuses on perceived benefits and constraints associated with these practices, as well as on the contextual conditions that shape their adoption, including environmental, production-related, and socio-cultural factors.

Materials and methods

Study framework and innovative practices

This study applied a participatory stakeholder approach to evaluate the strategic potential of innovative practices derived from LCA analysis in sheep farming systems. The framework integrates environmental performance information with stakeholders' knowledge and perceptions to support the identification of sustainable management strategies (Figure 1).

Three innovative practices (PLF, PIP, and EL) previously described and evaluated in LCA-based research activities as mentioned before, were considered. These practices were analysed in relation to two main stages of the sheep dairy supply chain, namely milk and cheese production. The environmental sustainability indicators analysed in the focus group were based on the main impact categories assessed in these previous LCA studies (e.g., greenhouse gas emissions, land use, and resource efficiency). This ensured that the stakeholder discussions were strictly grounded in empirical environmental evidence (Supplementary Sections S1, S2).

Focus group protocol

The focus group (FG) methodology was used to explore stakeholders' perceptions of the adoption and applicability of innovative practices in extensive sheep farming systems (Figure 2).

A focus group is a structured discussion facilitated by one or more moderators with a small group of participants to explore a topic in depth (Acocella, 2005). It is designed to collect qualitative data through open-ended questions focused on specific topics (Masadeh, 2012). This approach enables the integration of scientific knowledge and local experience and allows an in-depth exploration of stakeholders' perceptions, opinions, and experiences (Nyumba et al., 2018).

In other terms, the objective of a focus group is not to achieve consensus among participants, but to capture a wide range of viewpoints (Krueger and Casey, 2015). For this reason, the moderator plays a key role in managing group dynamics and fostering an open and comfortable environment that encourage discussions among participants, including those who are not familiar with each another (Rabiee, 2004). Appropriate logistical conditions, such as a circular seating arrangement in a quiet distraction-free location, supports interaction and engagement (Masadeh, 2012).

During the design phase, session objectives are defined and a discussion guide is developed. Questions are open-ended and organized progressively, starting from general topics and moving towards more complex issues (Powell and Single, 1996) (Figure 3).

The guide ensures that relevant information is collected while allowing flexibility for participants to introduce additional perspectives. Participant recruitment is a critical step since discussion quality depends on group interaction and diversity of perspectives. Focus group size varies widely in the literature, with reported ranges from approximately 4 to over 12 participants (Masadeh, 2012). Group composition should be balanced to avoid excessive homogeneity, which may limit the diversity of opinions, or excessive heterogeneity, in terms of gender, social

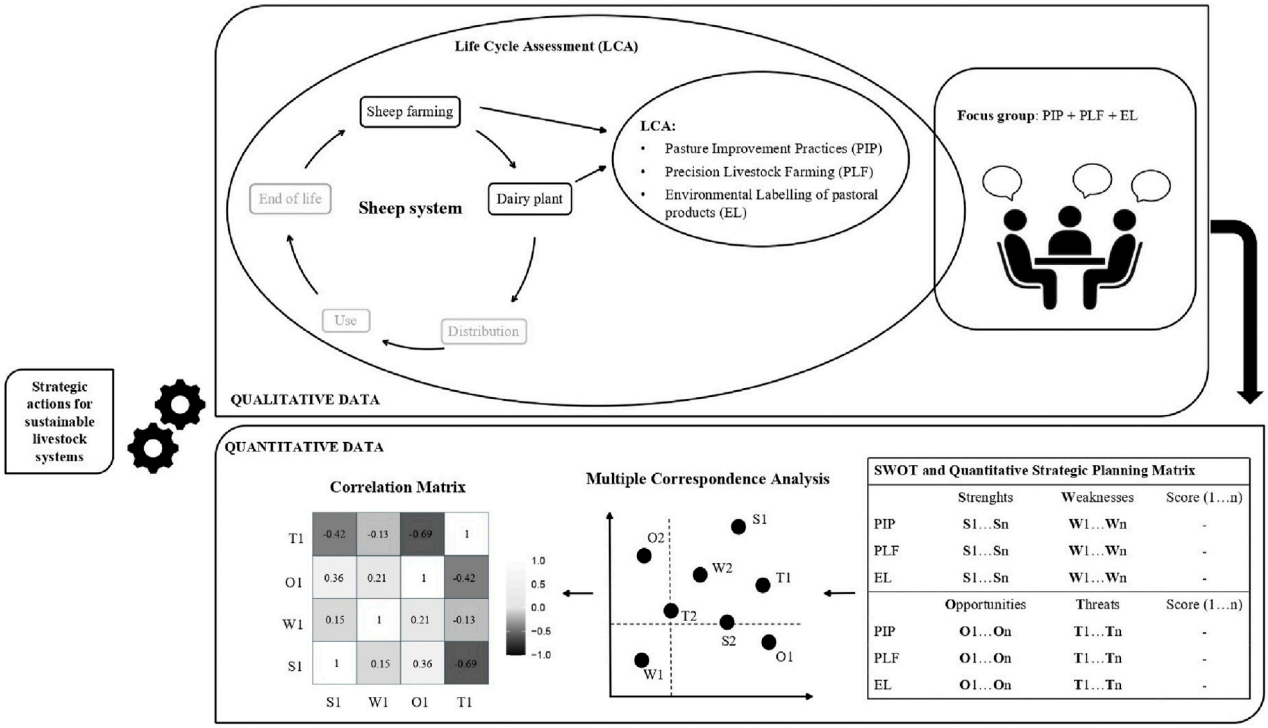


FIGURE 1
Integrated analytical framework combining life cycle assessment, stakeholder perspectives, and the strategic prioritisation of sustainability innovations.

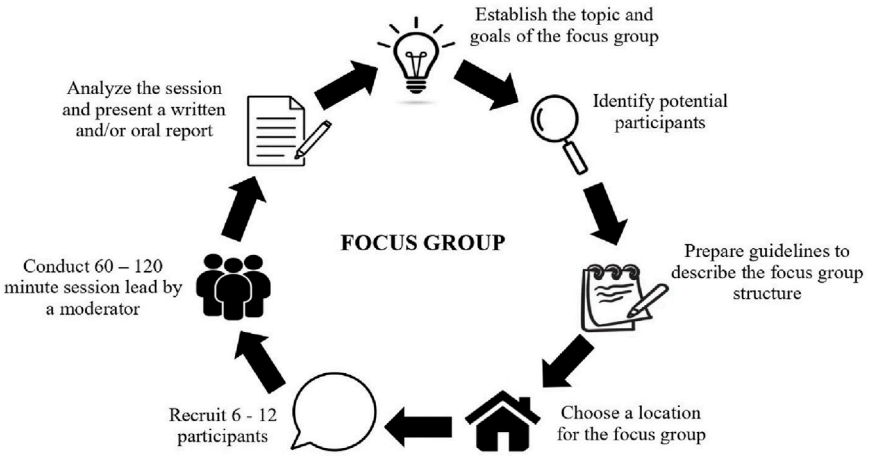


FIGURE 2
Steps to conduct a focus group (adapted from 'Steps to conduct a focus group retrieved from (Focus Groups, 2017)' by Tümen-Akyıldız and Ahmed, 2021), licensed under CC BY 4.0.

class, or professional experiences, which may influence how individuals contribute to the discussion (Gibbs, 1997), leading to dominance of a few participants. Sessions typically last 60–120 min (Nyumba et al., 2018), since duration depends on the topic complexity and the group size (Powell and Single, 1996).

At the beginning of the session, the moderator presents the objectives, explains the structure of the discussion, outlines the basic rules, and clarifies how the information collected will be used, including confidentiality and anonymity considerations (Sim and Waterfield, 2019). Sessions may be audio- or video-recorded and transcribed, or documented through detailed notes taken by the moderator and co-facilitators (Busetto et al., 2020). The use of open-ended questions and interactive discussion facilitate the emergence of perceptions that may not be captured through questionnaire-based surveys (Tümen-Akyıldız and Ahmed, 2021).

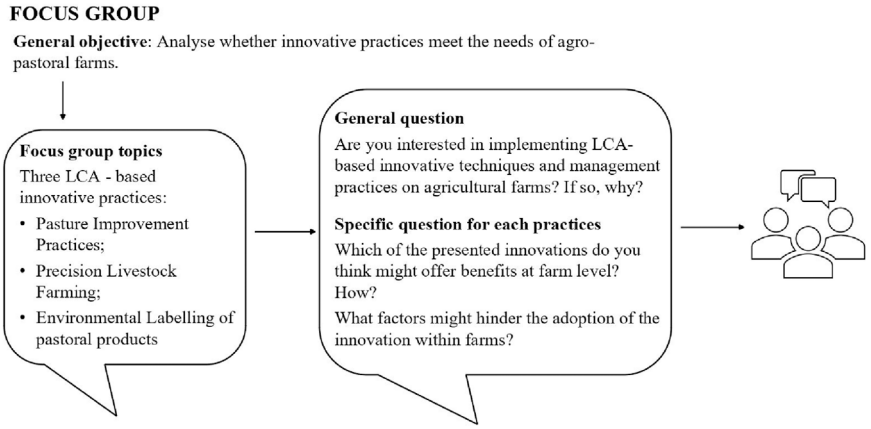


FIGURE 3
Focus group structure.

Stakeholder engagement: focus group

Stakeholder perceptions regarding the potential applicability of the proposed innovative practices were collected through FG discussions conducted in July 2024 in Ollolai, an upland municipality in central Sardinia (Italy). Nineteen stakeholders were purposively selected by the authors based on their knowledge of and experience within the local sheep supply chain, ensuring the inclusion of participants with relevant expertise and perspectives. Participants included farmers, researchers, regional institutional representatives, freelancers, and members of trade and consumer associations, with both male and female stakeholders and an age range of approximately 30–60 years. Participants were recruited through the collaborative and institutional networks of the SUREPASTOR, SheepToShip LIFE, and LIFE MAGIS research projects, following a purposive sampling strategy and a multi-actor approach. Potential participants were selected from the stakeholder databases developed during these projects, to ensure familiarity with sustainability issues in the sector. They were first contacted by e-mail and then by phone, with the aim of achieving a balanced representation of different professional backgrounds, including primary producers, researchers, and representatives of the trade sector.

The sample was designed to ensure heterogeneity across key stakeholder categories in line with the exploratory purpose of the activity. This allowed the involvement of multiple and potentially contrasting perspectives relevant to innovation adoption in pastoral systems. Participants were divided into two groups (FG1: n = 9; FG2: n = 10), following established methodological recommendations for focus group design, while ensuring balance in professional background and gender distribution.

Each session lasted approximately 1 hour and was moderated by a facilitator who introduced the objectives of the meeting, explained the discussion structure, and ensured balanced participation among stakeholders. Before the discussion, participants received a comprehensive overview of the three innovative practices and their environmental performance assessed in previous LCA studies (Atzori et al., 2022; Vagnoni et al., 2024), in order to provide a common informational basis for the subsequent opinion exchange. During the discussion, stakeholders were invited to share their perspectives on the potential applicability of the proposed practices, highlighting perceived benefits, limitations, and contextual factors influencing their adoption. The qualitative information collected during the sessions was analysed using a SWOT framework.

SWOT and QSPM analytical procedure

Information collected during the focus group discussions was analysed using an integrated qualitative and quantitative approach.

Qualitative data were structured through a SWOT framework to systematically organise stakeholders' perceptions of the innovative practices investigated. SWOT analysis is a strategic planning tool used to identify internal and external factors influencing a system by categorising them into strengths, weaknesses, opportunities, and threats (Gürel and Tat, 2017). Accordingly, stakeholders' responses were coded into the four SWOT categories and organised into a SWOT matrix for each innovative practice. Strengths and weaknesses were considered as internal factors related to intrinsic characteristics of the practices, whereas opportunities and threats represented external factors associated with farm management conditions and the broader territorial context affecting their adoption and effectiveness in extensive sheep farming systems. To enable quantitative comparison and prioritisation of the innovative practices, SWOT matrices were further analysed using a Quantitative Strategic Planning Matrix (QSPM). The QSPM is a decision-support tool that allows the comparison of alternative strategies by quantifying their relative attractiveness based on key strategic factors (Nourbakhsh et al., 2023). In the present study, the QSPM approach was adapted to the structure of the focus group data following the procedure described by Ommani (2011).

The analysis consisted of several steps. First, internal (strengths and weaknesses) and external (opportunities and threats) factors were identified from stakeholders' qualitative responses. These factors were subsequently transformed into binary variables indicating their presence ("yes") or absence ("no") within each innovative practice, allowing their quantitative assessment. Second, each SWOT factor was assigned a weight (W) ranging

from 0.00 to 1.00, calculated as: W = nS/tS, where nS represents the number of stakeholders expressing the same opinion and tS represents the total number of participants. This value expresses the proportion of stakeholders sharing a given opinion relative to the total number of participants, thereby reflecting the frequency of agreement regarding each factor. Third, each factor was assigned a rating according to a four-point scale based on its strategic relevance. Ratings of 4 and 3 indicated major and minor strengths or opportunities, respectively, whereas ratings of 2 and 1 indicated minor and major weaknesses or threats, respectively. Fourth, the final score for each factor was calculated as the product of its weight and rating. These weighted scores represented the aggregated stakeholder evaluation of the relevance and applicability of each innovative practice. Finally, weighted scores were summed within each SWOT category to obtain an overall strategic profile for each practice. These profiles were used to compare the relative strategic attractiveness and support the prioritisation of innovative practices.

Multiple correspondence analysis and correlation analysis

To further explore the structure of stakeholders' perceptions, a Multiple Correspondence Analysis (MCA) was conducted on the categorical dataset derived from the SWOT responses collected during the focus group discussions. Although primarily developed for the analysis of qualitative data, MCA may also include quantitative variables after their transformation into categorical classes (Greenacre, 2010). The method assigns factor scores to both observations and categories, representing their position within a low-dimensional space (Abdi and Valentin, 2007; Blasius et al., 2009). In this study, SWOT responses were transformed into binary variables indicating the presence ("yes") or absence ("no") of specific items identified by stakeholders, enabling quantitative analysis. The MCA was therefore applied to examine patterns of association among SWOT elements across the three innovative practices. Categories are represented as points in the factorial space, and distances between points reflect similarities in response patterns (Greenacre, 2010). The extracted dimensions summarised the main structures of association within the dataset, while category contribution values quantified the relative importance of each SWOT item in defining the factorial axes (Blasius et al., 2009). MCA results were interpreted through the graphical representation of the factorial space, in which variables were displayed using aggregated labels (e.g., S1, S2) to improve readability while preserving the information derived from the original binary coding. The spatial configuration of variables was used to identify associations and divergent patterns among SWOT elements, whereas contribution values supported the identification of the most influential elements shaping each dimension. All statistical analyses were performed using R (version 4.4.3; R Core Team, 2023) within the RStudio environment (RStudio 2026.01.1 + 403).

To complement the MCA results, correlation analyses were performed separately for each innovative practice to explore co-occurrence patterns among SWOT elements. Pearson's correlation coefficients were calculated using the binary (0/1) variables obtained from SWOT coding, following a commonly applied approach for assessing associations among categorical variables (Schober et al., 2018). While MCA provides a global multivariate representation of the relationships among SWOT elements, correlation analysis offers a complementary perspective by quantifying specific pairwise associations within stakeholders' perception structures.

Together, SWOT analysis, QSPM, MCA, and correlation analysis provided an integrated and transparent framework for analysing stakeholder perceptions and supporting the evaluation and prioritisation of eco-innovative practices in extensive sheep farming systems.

Results

SWOT analysis and QSPM model

The weighted SWOT results quantified the stakeholders' perceptions and operational feedback regarding the three innovative practices previously evaluated through LCA. They show how participants prioritise and accept each practice after being informed of its environmental performance, and highlight the trade-offs they perceive under real-world farming conditions. Regarding internal factors, significant variation emerged among the practices. PIP showed the most favourable internal assessment, with nearly three times as many strengths as weaknesses (14 vs. 5). PLF exhibited a more balanced distribution (9 strengths vs. 6 weaknesses), whereas EL showed an equal number of strengths and weaknesses (3 each) (Figure 4A).

These findings suggest greater stakeholders' confidence in PIP, while PLF and EL elicited more cautious responses. With respect to the external factors, threats were the most frequently reported across all three practices (Figure 4B). In both PIP and PLF, threats were more than three times as often as opportunities (14 vs. 4 and 13 vs. 2, respectively). EL showed a particularly negative perception, with threats outnumbering opportunities by a ratio of 8 to 1.

Overall, this highlights the perceived relevance of external constraints, which might influence the adoption of PLF and EL, especially among farmers. The SWOT analysis revealed an imbalance between internal and external factors: strengths were mentioned more frequently than weaknesses, whereas threats outweighed opportunities across all practices. This contrast suggests that, although participants recognized positive attributes within the practices, they also perceived substantial external barriers to their implementation. Notably, the gap between threats and opportunities was more pronounced than that between strengths and weaknesses, indicating that stakeholders attributed greater importance to external challenges than to internal limitations.

The QSPM, built on these SWOT components, compared the strategic attractiveness of each practice (Table 1).

PIP achieved the highest total score by a clear margin, followed by PLF and EL, consistent with the qualitative findings. Internal strengths exceeded weaknesses in all cases, with PLF strengths more than double the weaknesses, PIP strengths nearly seven times higher, and EL strengths more than three times higher. In contrast, external threats consistently exceeded opportunities across all practices, with the largest imbalance observed for EL.

PLF threats were roughly three times higher than opportunities, PIP threats were less than twice as high, and EL threats exceeded

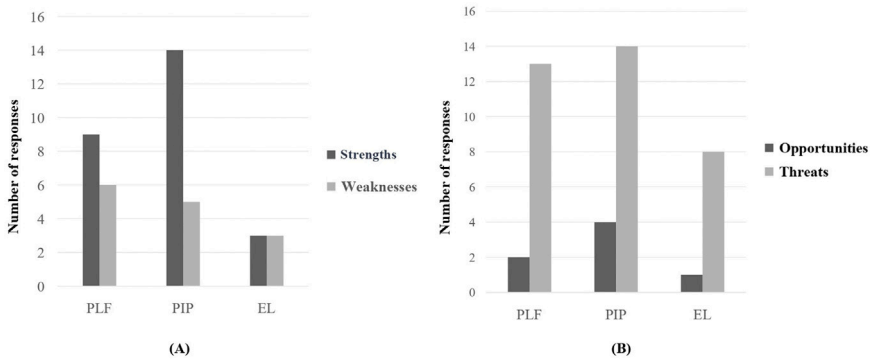


FIGURE 4
Internal **(A)** and external **(B)** factors associated with the three management practices (PLF, Precision Livestock Farming; PIP, Pasture Improvement Practices; EL, Environmental Labelling).

TABLE 1 QSPM scores for the three practices based on SWOT analysis.

Internal factors	Strengths	Weaknesses
Precision livestock farming	4.84	1.90
Pasture improvement practices	5.21	0.78
Environmental labelling	2.32	0.74
Total weighted score	**12.37**	**3.42**
External factors	**Opportunities**	**Threats**
Precision livestock farming	0.59	1.90
Pasture improvement practices	0.98	1.59
Environmental labelling	0.20	1.27
Total weighted score	**1.77**	**4.76**

Bold numbers indicate the total weighted strategic scores.

opportunities by more than sixfold. The QSPM results highlight distinct profiles across the three practices: PIP combines strong internal advantages with moderate external pressures, EL shows a narrower internal margin and the greatest relative exposure to threats, and PLF occupies an intermediate position between these extremes (Supplementary Section S3).

Multiple correspondence analysis

To investigate stakeholders' perceptions regarding the three innovative practices, a MCA was conducted. The meanings of the labels used in the MCA plots are provided in Table 2.

In the MCA plot, variables located farther from the origin contribute more to the definition of the dimensions, while those closer to the origin represent more widely shared and less discriminating perceptions. The MCA of stakeholders' perception of PLF revealed a structured distribution of SWOT variables across four quadrants, with the two dimensions explaining just over 30% of the total variance (Figure 5). Dimension 1 primarily captured technical and economic aspects of implementation, whereas Dimension 2 distinguished systemic and policy-related issues from more operational factors.

In the first quadrant, several strengths related to technological efficiency, such as remote animal control (S1, 8.0% on Dimension 2) virtual fencing (S2, 10.1% on Dimension 2), and reduced working time (S6, 6.2% on Dimension 2), were grouped together with the availability of public incentives (O2, 6.9% on Dimension 1), indicating a complementarity between operational benefits and institutional supports. However, these were closely associated with technical constraints, particularly the limited adaptability of devices to sheep systems and practical issues such as collar size, with the latter showing a notable contribution (T9, 6.9% on Dimension 2), highlighting a tension between innovation potential and field applicability.

The second quadrant was mainly characterized by regulatory and infrastructural barriers, including the lack of clear regulation (T4, 5.3% on Dimension 2) and unreliable signal reception, which appeared relatively isolated, suggesting their role as distinct constraints.

In the third quadrant, weaknesses and threats related to high technological costs, data management challenges, limited data exchange, and institutional distrust were grouped, indicating the presence of systemic barriers to adoption.

Finally, the fourth quadrant combined strengths linked to resource efficiency and monitoring with socio-cultural constraints. The strengths included input reduction (S3, 6.2% on Dimension 1 and 8.1% on Dimension 2), crop production monitoring (S4, 5.6% on Dimension 1), and spatial grassland management (S5, 4.1% on Dimension 1). The constraints referred to low technological orientation and limited engagement in innovation processes (T1, 5.0% on Dimension 1; T2, 6.6% on Dimension 2). The need for public incentives also emerged as a key factor shaping Dimension 1 (T8, 9.5%), suggesting that although technological solutions may improve farm management, their adoption remains strongly influenced by farmer-related and institutional conditions.

The MCA of PIP explained 31.4% of the total variance and showed a substantial concentration of variables near the origin, indicating the presence of widely shared perceptions among stakeholders regarding the adoption of these practices (Figure 6).

The first quadrant was characterized by a dense grouping of strengths, including lower labour cost (S8), smaller flock size (S9), shorter working time (S10), minimized soil tillage (S3, 7.2% on

TABLE 2 SWOT-based classification of stakeholder responses for the three innovative practices.

Strength	
Precision livestock farming	
Remote animal control (GPS devices)	S1
Support in flocks confinement (virtual fencing)	S2
Input reduction	S3
Crop production monitoring	S4
Spatial management of grassland	S5
Reduction of working time	S6
Decrease in labour cost	S7
Low cost of herbometer and drone	S8
Environmental sustainability/preservation of biodiversity	S9
Pasture improvement practices	
Increase in the nutritional value of plant biomass	S1
Increase in the quantity of plant biomass	S2
Reduction of soil tillage	S3
Reduction of costs in the medium and long term	S4
Integrated grassland management (collaboration between farmers and institutions)	S5
Land protection	S6
Environmental protection (fire prevention)	S7
Decrease in labour cost	S8
Flock reduction	S9
Reduction of working time	S10
Improvement of animal productivity	S11
Availability of scientific research of seed	S12
Increase in cost effectiveness	S13
Environmental sustainability/preservation of biodiversity	S14
Environmental labelling of pastoral products	
Higher selling price of products	S1
Improvement of product quality	S2
Social acknowledgment of farmer's role in providing sustainability	S3
Weakness	
Precision livestock farming	
Animal data collection tool more useful to researchers than to farmers	W1
Poor reliability of the technique's effectiveness	W2
Poor reliability of signal reception (e.g., presence of trees)	W3
High cost of techniques	W4
Inability to handle the flocks movement (virtual fencing)	W5
Poor adaptability of the techniques (collars, weight control, virtual fencing) to sheep (flock's size)	W6

(*Continued*)

TABLE 2 Continued

Strength	
Pasture improvement practices	
Lack of analysis in many pasture areas (contextualization)	**W**1
Limited research on the adaptability of seeds to different contexts	**W**2
Shortage of soil analysis	**W**3
High cost of practices	**W**4
Poor seed availability	**W**5
Environmental labelling of pastoral products	
High cost of the environmental labelling	**W**1
Low economic convenience for individual farmer compared to the processor	**W**2
No differentiation of the various production practices of the raw material	**W**3
Opportunity	
Precision livestock farming	
Adaptability of innovative techniques to specific farms	**O**1
Availability of public incentives	**O**2
Pasture improvement practices	
Availability of public incentives	**O**1
The willingness to invest own resources in research on seeds	**O**2
Adaptability of innovative techniques to specific farms	**O**3
Improvement of the farmer's quality of life	**O**4
Environmental labelling of pastoral products	
Availability of public incentives	**O**1
Threat	
Precision livestock farming	
Poor technology-oriented farmers (cultural/age factor)	**T**1
Poor involvement of farms in the adaptative process	**T**2
Lack of in-depth studies at different scales	**T**3
Lack of regulations for the use of collars	**T**4
Challenges in managing large volumes of data	**T**5
Poor dissemination of information and knowledge transfer	**T**6
Poor sharing of data along the supply chain	**T**7
Need for public incentives	**T**8
Lack of studies to reduce the size of sheep collars	**T**9
Abandonment trend of agricultural and livestock farming	**T**10
Farmer's distrust in institutions and researchers	**T**11
Negative environmental impacts of battery (collars) and antennas	**T**12
Poor technical extension	**T**13

(*Continued*)

TABLE 2 Continued

Strength	
Pasture improvement practices	
Inadequate support for grassland under the common agricultural policy	**T**1
Poor ability in labour recruitment	**T**2
Low willingness to change work methods and practices of pasture management	**T**3
Poor sharing of data along the supply chain	**T**4
Need for public incentives	**T**5
Climate conditions	**T**6
Poor dissemination of information and knowledge transfer	**T**7
Poor training of farmers	**T**8
Poor technology-oriented farmers (cultural/age factor)	**T**9
No premium price for the higher costs	**T**10
Abandonment trend of agricultural and livestock farming	**T**11
Farmer's distrust in institutions and researchers	**T**12
Risk of disappearance of local mixtures	**T**13
Poor technical extension	**T**14
Environmental labelling of pastoral products	
Poor technology-oriented farmers (cultural/age factor)	**T**1
Poor training of farmers	**T**2
Presence of too many types of labels (confusion)	**T**3
Market variability on the price of the eco-labelled product	**T**4
Poor dissemination of information and knowledge transfer	**T**5
Poor technical extension	**T**6
Abandonment trend of agricultural and livestock farming	**T**7
Risk of greenwashing	**T**8

Bold alphanumeric labels (e.g., S1, W3, O1, T1) represent the specific SWOT classification codes for the stakeholder responses.

Dimension 1), and environmental protection (S7, 6.6% on Dimension 1), together with the opportunity related to improvements in farmers' quality of life (O4, 10.9% on Dimension 1). Notably, S8, S9, and S10 overlap with O4, reflecting their consistent co-occurrence in stakeholder responses and a strong perceived link between economic and labour-related benefits and improvements in farmers' quality of life.

Within the same area, poor seed availability (W5, 7.7% on Dimension 1) emerged as the only weakness, indicating that agronomic constraints coexist with generally positive perceptions.

The second quadrant combined opportunities and weaknesses related to research and resource availability, including public incentives, investment willingness, limitations in seed adaptability, and soil analysis, which jointly contributed strongly to Dimension 2 (13.8%). It also highlighted more isolated threats, such as agricultural abandonment (T11, 10.0% on Dimension 2) and the lack of adequate economic compensation for higher implementation costs.

In the third quadrant, socio-cultural and knowledge-related barriers, including low willingness to change practices, limited dissemination, and low technological orientation, were closely associated, indicating a coherent group of adoption constraints. A second group within the same quadrant linked broader systemic issues, such as insufficient policy support, labour constraints, and climate-related challenges, suggesting that institutional and environmental factors further reinforce adoption barriers.

The fourth quadrant included variables with low contributions, reflecting less discriminating perceptions, particularly regarding animal productivity improvement and risks associated with local variety, as well as elements related to technical support and integrated grassland management through collaboration between farmers and institutions.

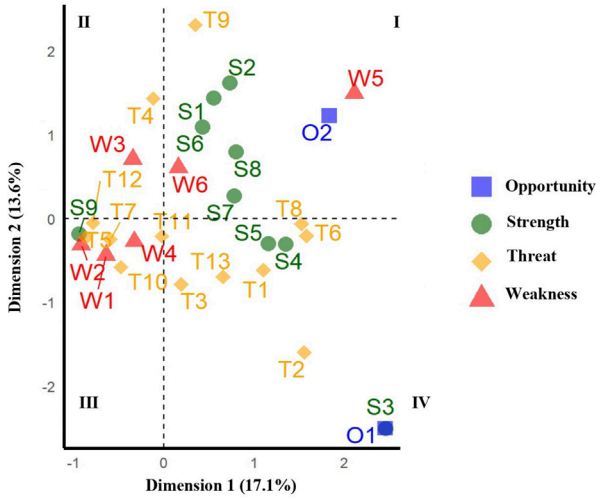


FIGURE 5
Multiple correspondence analysis of SWOT results for precision livestock farming.

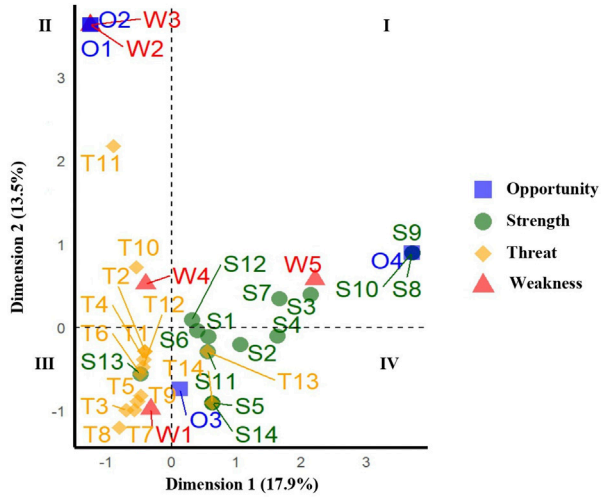


FIGURE 6
Multiple correspondence analysis of SWOT results for pasture improvement practices.

The MCA of EL explained 36.5% of the total variance and showed a clear differentiation between market-related and operational dimensions (Figure 7). Dimension 1 primarily captured market dynamics, while Dimension 2 reflected operational, economic and systemic aspects.

In the first quadrant, higher product selling prices (S1, 13.4% on Dimension 1) and social recognition of farmers (S3, 13.0% on Dimension 1) were closely associated with concerns such as label proliferation (T3, 9.4% on Dimension 1), greenwashing (T8, 9.0% on Dimension 1), and insufficient technical support.

The second quadrant was dominated by constraints related to training and knowledge transfer, particularly inadequate

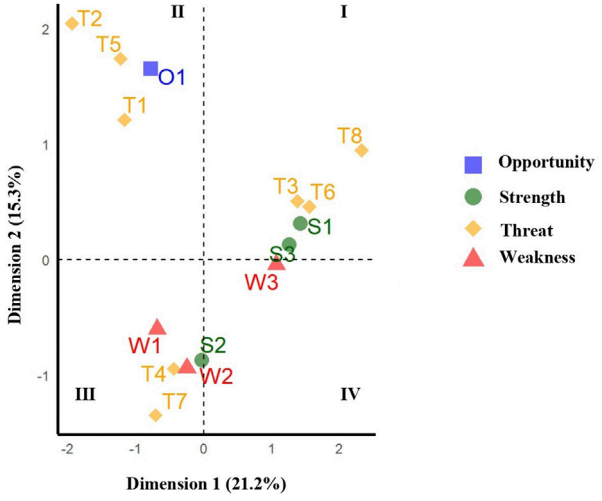


FIGURE 7
Multiple correspondence analysis of SWOT results for environmental labelling.

dissemination of information (T5, 20.8% on Dimension 2), limited technological orientation (T1, 10.1% on Dimension 2), and poor training (T2, 9.6% on Dimension 2), together with the availability of public incentives (O1, 6.3% on Dimension 2). This configuration highlights the importance of knowledge-related and institutional factors in supporting adoption.

In the third quadrant, economic feasibility and broader structural challenges emerged, including high implementation costs (W1, 5.5% and 5.8% on Dimensions 1 and 2) and low economic convenience (W2, 10.0% on Dimension 2), alongside market variability, agricultural abandonment, and improvement of product quality suggesting that financial and systemic constraints remain central.

The fourth quadrant contained only one variable related to the lack of differentiation among production practices, which appeared relatively isolated, indicating a more marginal role in shaping stakeholders' perceptions (Supplementary Table S2).

Correlation analysis of stakeholder perceptions

To complement the MCA results and further quantify the relationships among stakeholder-perceived strengths, weaknesses, opportunities, and threats, correlation matrices were computed for each innovative practice (Supplementary Tables S3–S5). The correlation analysis of PLF perceptions revealed relationships characterised by both complementarities and trade-offs. Technological solutions for flock management, such as remote animal control (S1) and virtual fencing (S2), were positively associated ($r = 0.6$), confirming their perceived complementarity. Similarly, monitoring and land management functions showed strong relationships with environmental sustainability (S4 - S8, $r = 0.8$), while input reduction (S3) was consistently associated with monitoring and spatial management (S4 - S5, $r = 0.5$) and farm-specific adaptability (O1, $r = 1.0$), indicating synergy between efficiency gains and context-specific solutions.

Economic and technical constraints emerged as key limiting factors: high implementation costs (W4) were negatively associated with several technological strengths and public incentives (S1, S2, S5, S7, O2, T8, r = −0.4 to −0.6), and limited adaptability to small flocks (W6) showed similar patterns (S5, r = −0.3; O1, r = −0.2). Notably, limited technical knowledge (T1), weak farmer engagement (T2), and insufficient extension services (T6) were interrelated, with T1 - T6 showing the strongest correlation (r = 0.7) and other pairings weaker (T1 - T2, T2 - T6: r = 0.2). These socio-cultural constraints were positively associated with operational and enabling factors (S3, S5, O1, O2; r = 0.5 - 0.7), acting as interconnected drivers of adoption.

The correlation analysis for PIP highlighted dense positive relationships among strengths, particularly environmental sustainability, labour reduction, and improvements in farmers' quality of life. Several variables were perfectly or strongly correlated, including improvements in farmers' quality of life and labour-related benefits (S8, S9, S10, O4, r = 1.0).

Agronomic improvements, such as reduced soil tillage and environmental protection, were also strongly associated (S3 - S7, r = 0.8), while increases in plant biomass were linked to long-term cost reductions (S2 - S4, r = 0.7). Constraints related to seed availability, limited research on adaptability, and insufficient soil analysis showed an articulated pattern: limited research and shortage of soil analysis were strongly correlated (W2 - W3, r = 1.0), whereas poor seed availability had weak negative relationships with these factors (W2 - W5, W3 - W5, r = −0.1) and was positively associated with several benefits (S7, S8, S9, S10, r = 0.7 - 0.8).

Socio-cultural and institutional barriers, including low willingness to change, limited knowledge transfer, and insufficient training, formed a coherent group (T3 - T7, r = 0.8; T3 - T8, r = 0.7), while broader systemic issues such as policy limitations and labour constraints were also strongly interrelated (T1 - T2, r = 1.0), with links to data-sharing constraints (T4 with T1 - T2, r = 0.7). Negative relationships suggested potential trade-offs: high implementation costs were negatively correlated with expected cost reductions (W4 - S4, r = −0.3) and with other constraints, including poor data sharing and adverse climate conditions (W4 - T4; W4 - T6, r = −0.3).

The correlation analysis for EL showed relationships linking economic, social, and institutional dimensions. Higher selling prices (S1) and social recognition (S3) were positively associated (r = 0.6), with moderate correlations between these benefits and potential threats, namely insufficient technical support (T6, r = 0.46) and risk of greenwashing (T8, r = 0.39). In contrast, high eco-labelling costs (W1) were negatively associated with selling price and social recognition (S1, r = −0.4; S3, r = −0.2), suggesting a potential economic trade-off.

The availability of public incentives (O1) was positively associated with market-related challenges (T5, r = 0.5), while socio-cultural constraints (T1 - T2) were moderately interrelated (r = 0.5), and relationships among other market and informational threats (T3, T4, T5) remained weak (r = −0.2 to −0.1).

Discussion

To ensure a systematic discussion, Sections *Precision Livestock Farming, Pasture Improvement Practices, Environmental Certification* follow a common structure. Each subsection combines the qualitative findings and stakeholder statements from the focus groups with the quantitative SWOT-QSPM profiles and Multiple Correspondence Analysis (MCA) dimensions, and then discusses these results in the light of the literature on agricultural and pastoral systems.

Precision livestock farming

Stakeholders' responses indicate that PLF technologies are seen as potentially improving efficiency in Sardinian sheep systems, particularly through applications such as remote animal control, virtual fencing, and spatial grassland management. However, their practical integration at the farm level remains uncertain, reflecting concerns reported in the literature, where adoption in pasture-based systems is often limited by device characteristics, system adaptability, and implementation costs (Paolino et al., 2025). The original conceptualization of PLF as individual animal monitoring in controlled environments (Berckmans, 2017) helps explain why stakeholders perceive greater challenges when applying these technologies in extensive versus intensively managed systems. In this study, stakeholders acknowledged potential benefits but expressed scepticism regarding practical applicability.

MCA and correlation analyses highlighted associations between several weaknesses and threats, including limited adaptability to sheep flocks, the need for collar miniaturisation, and environmental concerns related to battery disposal. As a freelancer (agronomist) and expert in PLF for sheep farming noted:

> "*In my view, the system is not particularly functional. It is essential to assess both functionality and the balance between advantages and disadvantages. Accurate weighing of animals, especially sheep, requires that they pass over the weighing system one at a time. This process necessitates a controlled and directed passage, which may be difficult to achieve in practice. Training animals to follow such a path, and ensuring its effectiveness across an entire flock, would be particularly challenging*".

Similarly, concerns were raised about applying PLF technologies in large sheep flocks due to management complexity and cost.

As a farmer remarked:

> "*Precision livestock farming is challenging to implement in large flocks due to high costs and practical constraints. Technologies such as GPS, while promising, often face limitations in large farms, where managing numerous animals is complex, and data transmission is hindered by low network coverage*".

These perceptions aligned with MCA and correlation matrix findings, highlighted persistent infrastructural (e.g., network coverage, device compatibility) and organisational (e.g., flock management complexity, labour demands) barriers to adopting PLF tools such as virtual fencing, animal weighing systems, and GPS-enabled collars. Conversely, remote animal control and virtual fencing were identified as related strengths based on their proximity in the MCA plot and moderate correlation. Complementing these observations, recent literature highlighted the potential of PLF technologies to support real-time monitoring and provide decision-support tools in grazing livestock systems, particularly through automating routine management tasks, while still

requiring active farmer involvement in decision-making processes (Tzanidakis et al., 2023). Similarly, pasture and crop monitoring tools, including spatial grassland management, were perceived as valuable for supporting resource-use efficiency and grazing planning. This aligns with Marchegiani et al. (2025), who highlighted the potential of PLF technologies to enhance animal monitoring, pasture management, and overall resource efficiency in sheep systems, while also emphasizing significant knowledge gaps and the need for pilot studies and careful technology integration.

Although primarily used in intensive systems, PLF technologies might also be effectively used in extensive pasture systems, where the scale, variability, and remoteness of grazing areas make animal supervision challenging. In these contexts, their broader adoption may promote animal welfare, support rangeland conservation, facilitate decision-making, reduce labour, and improve farm productivity (Aquilani et al., 2022).

Despite these opportunities, economic viability emerged as a critical condition for adoption. An institutional representative noted:

> "*Researchers in this field must ensure that these devices become economically viable and align with the profit-oriented logic of farms*".

This concern reflects relevant barriers to the adoption of new technologies in pasture-based dairy sheep systems, including financial constraints, conservative attitudes among farmers, and farm-scale limitations, although emerging economic and environmental trends may promote wider adoption over time (Odintsov Vaintrub et al., 2021). Despite these adoption challenges, extensive grazing continues to provide important ecosystem and social services, contributing to the survival and wellbeing of rural regions beyond simple production outputs, as emphasised in Mediterranean dairy sheep farming contexts (Madau et al., 2022).

Applicability of PLF technologies varies with farm characteristics: larger and more structured farms are more likely to benefit, whereas small farms located in marginal areas may face greater constraints. Stakeholders emphasised that farm size, management capacity, and personnel experience influence adoption potential, illustrating the interconnection of technical, organisational, and socio-cultural barriers. This variability also reflects broader structural conditions, such as access to infrastructure, capital availability, and labour organisation, which shape the feasibility and expected returns of PLF investments. In this context, integrating complementary, lower-cost solutions (e.g., weather stations, drones, and herbometers) was highlighted as a way to improve grazing management and biomass monitoring. These tools may operate synergistically, enhancing monitoring accuracy and decision-making efficiency, while enabling adaptive grazing and resource optimisation. Their modular nature might allow farmers to adopt innovations gradually, introducing individual devices without fully replacing traditional practices, thereby reducing entry barriers.

Pilot studies and participatory trials emerged as crucial factors for building trust and evaluating performance under real-world conditions. As a researcher noted:

> "*It is also true that many innovations remain insufficiently tested on a large scale, so their benefits are not yet well understood. While they may perform very well in some cases, their effectiveness may be lower in others. It is also important to identify the optimal conditions under which these innovations may deliver the greatest benefits, knowledge that, in my opinion, is still generally lacking*".

Such initiatives not only support technical validation but also help identify context-specific performance conditions and reduce uncertainty associated with environmental and management variability. Socio-cultural and knowledge-related barriers may further constrain PLF adoption. Strengthening agricultural knowledge systems and facilitating structured knowledge transfer may help farmers understand and adopt precision agriculture technologies by reducing perceived complexity, as emphasised by Masi et al. (2022). In this context, coordination among rural actors, including researchers, local advisors, technology providers, and farmers, is key to align technological solutions with the actual needs and expectations of extensive farming systems. Strengthening these collaborative and participatory extension networks is therefore essential for successful PLF implementation.

Without these enabling conditions, PLF may remain a specialised innovation with limited impact for farmers in structurally disadvantaged and extensive farming areas, potentially reinforcing inequalities in access to innovation.

Pasture improvement practices

Stakeholders' perceptions revealed that effective pasture management in Sardinian sheep farming relies on a dynamic interaction between technical knowledge, operational efficiency, and institutional support. Knowledge gaps were identified as key constraints, particularly regarding adapted seed availability to different contexts and the limited availability of soil analyses.

These limitations were linked both to public incentives and farmers' willingness to invest privately, highlighting the pivotal role of technical information alongside financial and policy instruments in enhancing pasture biomass and animal productivity. The persistent absence of site-specific soil mapping, especially in marginal areas, continues to hinder tailored pasture improvement strategies. As a farmer explained:

> "*Some pastures in Barbagia*[1] *remain unmapped and unanalysed, preventing the identification of the best improvement practices to boost animal production and farm performance*".

This underscores the need for precise, locally relevant soil data, as systematic analyses capture spatial variability in fertility that directly affects pasture productivity (Moral et al., 2022). Furthermore, the adaptability and genetic variation of forage species determine establishment, growth, and resilience under different environmental conditions, reinforcing the importance of species-specific information for effective management (López et al., 2025).

1 Barbagia is a mountainous inland area of central Sardinia (Italy), historically associated with pastoralism and extensive sheep farming.

Integrating soil diagnostics with adapted forage species is therefore critical for the effective management of extensive Mediterranean sheep pastures. Operational efficiency also emerged as a key factor for both productivity and farmer wellbeing. Reductions in labour requirements, smaller flock sizes, and shorter working hours were perceived to enhance quality of life without compromising production. As a farmer noted:

> *"By reducing the sheep number, I have more time available, I work more efficiently, and I do not require additional labour. I manage the farm on my own and I have reduced the flock from 500 to 200 animals while maintaining the same level of production. In my experience, improving pasture management is the most important aspect, especially in sheep farming. Animal performance depends less on supplementary feed and more on the quality and timing of grazing. Pasture management does not mean only sowing but also management of land use and animal movement. Although technological devices such as drones may assist in monitoring the flock, I believe that the physical presence of the farmer remains essential. I rotate the flock once or twice a day, and during the spring season even three times ensuring that the sheep graze appropriately in each designated area. I have been applying this rotational grazing approach for the past three years and have observed clear benefits. Initially, I was sceptical, concerned that this system might negatively affect milk production. However, over time, it became evident that the approach leads to tangible advantages in terms of both animal welfare and farmer wellbeing".*

These observations show how adaptive pasture management practices (e.g., rotational grazing and flock size adjustment) enable farmers to respond effectively to environmental variability while maintaining productivity. Aligning management strategies with site-specific conditions transforms technical interventions into tangible, context-sensitive benefits, improving animal welfare, pasture quality, and long-term efficiency (Kaiser, 2024). Resilience-oriented approaches, emphasizing flexibility, continuous learning, and ecological stability, support pastoral systems in adapting to stressors while preserving sustainability.

Concepts of resilience in pastoral systems have been discussed by Lin (2011) and Teague and Kreuter (2020), highlighting the capacity of such systems to maintain productivity under variable environmental conditions. Our findings support this argument, showing that pastoral resilience cannot be assessed on the basis of environmental data alone, but depends on balancing sustainable management practices with the effective farmers' capacity, economic constraints, and quality of life of the farmers. Stakeholders also highlighted socio-institutional barriers, emphasizing that effective pasture improvement requires not only technical expertise but also active knowledge transfer, farmer engagement, and institutional coordination. Knowledge gaps were linked to rural abandonment trends, indicating that the lack of scientific evidence, particularly regarding soil management, remains a structural barrier to innovation. Vanino et al. (2023) reported that stakeholders across Europe perceive significant gaps in the production, dissemination, and adoption of soil-management knowledge, emphasizing the need for tailored knowledge-sharing networks and region-specific strategies.

Seed availability emerged as another constraint, with high costs, weak supply chains, and regulatory barriers limiting access to quality forage seeds and the adoption of improved practices (Burkart and Mwendia, 2024). Addressing these constraints requires integrated actions connecting research institutions, seed suppliers, and policy frameworks.

Positive correlations between integrated grassland management and environmental sustainability suggest that collaborative management and ecological goals might reinforce one another. Co-production of knowledge and structured stakeholder collaboration may increase the adoption of pro-environmental innovative management practices (Concu et al., 2020; DeLong et al., 2024; Milliet et al., 2024). However, transformative sustainability transitions depend not only on stakeholder involvement but also on well-designed participatory living labs that ensure meaningful engagement rather than superficial participation (Aare and Hansen, 2024). Conflicting interests and overlapping responsibilities often create tensions in rangeland governance, complicating cooperative approaches and raising concerns regarding the long-term sustainability of pastoral systems (Mairomi and Kimengsi, 2021).

Finally, the focus groups findings emphasized that the extent to which pasture improvement practices deliver expected environmental and economic benefits depends on structural and contextual factors that are unevenly distributed across farms. For instance, practices such as reduced tillage are associated with environmental protection and labour savings; however, adoption is constrained by farmers' capacity, resource availability, and perceptions of risk. The moderate negative correlation between high implementation costs and delayed economic returns further highlights a temporal misalignment that may discourage early adoption, suggesting potential systemic weaknesses in current incentive frameworks. A freelancer (agronomist) observed:

> *"It is necessary to contextualize. Farms with highly productive land are unlikely to introduce permanent pastures; on the other hand, for farms with less suitable land for cultivation, such as slopes or rocky soils, this is one of the best solutions."*

This underscores that, although PIP interventions are often promoted as broadly applicable, their effectiveness is contingent upon biophysical and structural constraints. Without acknowledging this complexity, policy and extension efforts risk overgeneralising solutions suitable only for a limited number of farms. Grazing management is influenced by a variety of topographical, environmental, and anthropogenic factors, highlighting the need to understand these dynamics to effectively manage land resources (Errea et al., 2025).

Environmental labelling

Stakeholders considered EL in sheep systems as a socio-technical innovation, whose adoption and impact depend on market conditions, institutional support, and the ability of farmers to implement it effectively.

Both qualitative and quantitative findings indicate that perceptions of EL are shaped primarily by economic, institutional, and social factors rather than by its technical characteristics alone. Compared to PLF and PIP, EL emerged as the innovation more associated with concerns about economic feasibility and market reliability. Higher selling prices were identified as a potential benefit, but this was consistently contrasted with concerns regarding high certification costs and limited economic convenience.

This discrepancy between perceived market recognition and actual economic returns was clearly reflected in the farmers' perspectives:

> *"From the consumer's perspective, the willingness to pay more for an eco-labelled product is a recognition of the farm's contribution and efforts toward environmental and economic sustainability". However, they also noted that "In the end, the cost of certification is higher than the economic benefit of the certified product. . . and it would be better if there were any incentives available."*

Institutional actors emphasized the broader social role of EL, describing it as both a communication tool and an emerging market requirement:

> *"Eco-labelling is not just a marketing tool, but also a way to demonstrate to society what is being achieved. . ."*

and

> *"Nowadays, environmental certification is a prerequisite for entering the market."*

These perspectives align with the quantitative results, where threats and weaknesses outweighed opportunities and strengths, suggesting that the distribution of added value along the supply chain remains a critical challenge.

Concerns about label proliferation, lack of differentiation, and insufficient technical support indicate that stakeholders associate the value of EL with the transparency and credibility of certification systems. This reflects broader dynamics identified in the literature, where eco-labelling may enhance perceived product value without necessarily generating net economic benefits for primary producers (Yenipazarli, 2015). In pastoral sheep systems, similar patterns have been observed, where the added value associated with sustainability claims often fails to offset structural constraints and additional compliance costs (Bernués et al., 2011). These limitations are further compounded by reputational risks such as greenwashing, which may undermine consumer trust and increase scepticism toward environmental claims (Persakis et al., 2025).

The analysis also highlighted the importance of organizational factors in facilitating adoption. Participation in collective structures, such as cooperatives, may support farmers by sharing costs, improving coordination, and providing access to technical and administrative resources. As noted by a farmer:

> *"When part of a cooperative, however, farmers may directly benefit, as profits are shared among members. Having certification would thus enhance the market value of this type of product."*

This is consistent with Kuan et al. (2021), who found that farmers engaged in collective organizations are more likely to adopt certification schemes. Nevertheless, economic viability remains a central condition. As highlighted by stakeholders, certification costs must be balanced by adequate market returns, and overly complex regulatory requirements may discourage participation. A trade association representative noted:

> *"Environmental certification is very useful, but the costs must not exceed the increase in the selling price of the certified product."*

Similarly, concerns were raised about cost distribution along the supply chain, particularly when financial burdens are partially transferred to farmers, potentially undermining the sustainability of certification schemes. These perspectives underline broader structural constraints, including limited technological orientation, insufficient training, and weak dissemination of information, which further constrain the adoption of eco-labelling schemes.

Adoption often requires additional efforts and investments, such as administrative costs, skills upgrading, and input purchases (Praneetvatakul et al., 2022), suggesting that EL adds complexity to already fragile advisory and knowledge-transfer systems. Concerns regarding the complexity and cost of certification systems, which may act as market barriers for small producers, have been highlighted in recent analyses of environmental labelling in agri-food systems (Primi et al., 2024). Moreover, systematic reviews indicate that sustainability certification may generate negative economic effects for smallholders and firms operating in resource-constrained contexts, due to proportionally higher certification costs and limited access to financial and institutional resources (Rossi et al., 2024). Evidence from a choice experiment indicates that farmers' willingness to bear the cost for environmental certification is influenced by scheme design and institutional support. In particular, higher willingness is observed when certification delivers clear environmental outcomes and is supported by credible certification bodies and technical assistance (Altobelli et al., 2019). This highlights the importance of governance structures in shaping both the perceived legitimacy and the practical feasibility of certification schemes. In particular, the focus group results indicate that governance weaknesses, such as limited institutional support and a lack of transparency, contribute to stakeholder distrust and hinder the adoption of environmental labels. While environmental certification is recognized as a valuable tool for enhancing product differentiation and demonstrating sustainability, its adoption in extensive sheep systems remains constrained by economic, structural, and organizational factors. Strengthening cooperative structures, improving advisory services, and designing more accessible and context-sensitive certification schemes are essential to support wider adoption and ensure that the benefits of EL are more equitably distributed across the supply chain.

Stakeholder perspectives on eco-innovation adoption informed by LCA

The participatory approach adopted in this study, focused on environmental evidence from previous LCA applications, enabled a comprehensive analysis of how stakeholders perceive and integrate environmental information into decision-making processes within Sardinian sheep farming. In the methodological design of this study, these prior LCA findings were presented to the participants as a standardised baseline before the focus group sessions. However, several methodological limitations and operational gaps emerged from the analysis. The technical complexity of LCA indicators, together with the partial misalignment between LCA system boundaries and stakeholders' immediate priorities may constrain the perceived usability of results (Jouini et al., 2019). This misalignment is a key finding of the study, as it shows that stakeholders tend to filter environmentally assessed innovations through the pragmatic lens of immediate farm-level feasibility, including costs, labour, and infrastructure. This highlights a critical gap between the production of scientific environmental evidence and its effective integration into farm-level decision-making. Results indicate that stakeholders do not interpret eco-innovations uniformly across their environmental, economic, and social dimensions. Rather, their evaluations are shaped by context-specific constraints, operational priorities, and perceived risks, leading to selective interpretation, or even disregard, of environmental evidence when it is not aligned with immediate concerns. Despite this, the combined use of SWOT, MCA, and correlation analysis allowed the identification of cross-cutting drivers and barriers, showing that adoption dynamics emerge from the interaction of institutional, technological, informational, and socio-cultural factors.

Across all practices, stakeholders more frequently identified internal strengths than weaknesses, while external threats were perceived as more relevant than opportunities, reflecting the structural vulnerability of Sardinian sheep farms, particularly in marginal areas. Institutional and policy-related barriers, such as lack of coordination, insufficient funding mechanisms, and limited policy coherence, consistently emerged as key constraints to adoption (Restrepo Campuzano et al., 2023). Although coherent policy frameworks, targeted subsidies, and extension services are recognised as key enablers (Ike, 2024), these factors alone are not sufficient. Context-specific participatory strategies may help align technological solutions with local conditions (Bertolozzi-Caredio et al., 2021), but adoption is also strongly shaped by socio-cultural and demographic dynamics, including intergenerational turnover, declining interest in livestock farming, and the erosion of knowledge transmission. In this regard, an institutional representative highlighted that:

> *"Factors influencing the adoption of innovative practices on farms are not only economic but also social, psychological, and cultural… when farming households encourage the next-generation to pursue occupations outside livestock management, the intergenerational transmission of pastoral knowledge is effectively interrupted."*

Differences in perceived usefulness among stakeholder groups further shape adoption pathways. Generally, farmers tend to prioritize productivity and labour efficiency, institutional actors emphasise policy alignment and data reliability, and researchers focus on knowledge generation and demonstration through pilot applications. This reflects broader evidence that stakeholder priorities differ in small ruminant systems, including economic vulnerabilities, training needs, and the role of research in addressing farm-level problems (Belanche et al., 2021).

Adoption therefore depends on multiple interconnected factors, such as local conditions, knowledge, infrastructure, and networks, and may not be explained by individual decision-making alone (Campobasso et al., 2025). In this context, multi-actor partnerships are essential to facilitate interaction, mutual learning, and co-development of context-specific solutions (Guerrero-Ocampo et al., 2022).

In pastoral systems, management practices are closely linked to environmental and territorial functions. As an institutional representative noted:

> *"Wood pastures may play a crucial role in fire prevention, but their benefits go beyond that, contributing to land and rural road maintenance and supporting fire detection and firefighting operations."*

These functions increase the complexity of evaluating eco-innovations, particularly when benefits extend beyond the farm level, reinforcing knowledge- and data-related barriers as additional cross-cutting constraints. Limited familiarity with technologies, insufficient training, and lack of data-sharing platforms hinder understanding and implementation, whereas distrust toward institutions and reluctance to share data further constrain adoption. Participatory studies show that local knowledge, training, and experiential learning may reduce perceived complexity and support adoption processes (Ojango et al., 2023).

Structural constraints such as labour shortages, demographic decline, and adherence to traditional practices may further limit adoption (Theodoridis et al., 2021), particularly when combined with restricted access to technical information and weak institutional support (Restrepo-Campuzano et al., 2023). Governance conditions, including trust, coordination, and stakeholder interaction, therefore play a key role as system-level determinants of adoption (Addorisio et al., 2025). Within this framework, the use of LCA-based evidence within participatory approaches is a crucial mechanism for facilitating these processes: while LCA provides robust evidence on environmental and economic trade-offs, participatory processes enhance relevance and interpretability by embedding assessment within stakeholders' practical realities (Jouini et al., 2019).

Context-specific evaluation frameworks remain essential, as spatial variability strongly influences environmental and economic outcomes in territorial LCA applications (Lulovicova and Bouissou, 2023). Improving communication, strengthening multi-actor collaboration, and increasing stakeholder involvement in the interpretation and application of LCA results may enhance awareness and support more effective and coordinated innovation pathways. These efforts might be facilitated by strengthening

extension services and participatory knowledge-sharing mechanisms, which help translate complex evidence into actionable knowledge and better align institutional objectives with farmers' priorities (Becerra-Encinales et al., 2024).

However, important limitations remain. The technical complexity and data intensity of LCA may limit accessibility, particularly in systems with limited digital infrastructure and managerial capacity. Data governance issues, such as unclear ownership, control, and sharing rules, may undermine trust and slow adoption of data-intensive innovations (Wiseman et al., 2019). In addition, misalignment between the scale at which benefits identified in LCA studies are realised and the scale at which farmers bear costs and risks further constrains adoption.

Although evidence suggests that incentive schemes are more effective when tailored to local conditions and trade-offs (Piñeiro et al., 2020), our results are consistent with Ma and Rahut (2024) who highlighted that economic incentives alone are insufficient without complementary institutional, advisory, and social support mechanisms. Overall, innovation adoption in Sardinian sheep systems emerged as a systemic and context-dependent process shaped by interdependent institutional, socio-cultural, and technical factors. These findings highlight the need for integrated policy frameworks combining LCA-based evidence, participatory design, targeted incentives, and context-specific strategies to support sustainable innovation pathways. However, the findings of this study are context-specific and closely linked to the socio-economic and biophysical conditions of Sardinia. Given the relatively small sample size and limited geographical scope, they should not be generalised to other Mediterranean pastoral areas and livestock systems. The main contribution of the study is therefore methodological: the proposed framework demonstrates how qualitative stakeholder insights and quantitative evaluation tools can be combined to extend environmental assessment beyond its conventional boundaries. Future research should apply and validate this participatory framework to other Mediterranean pastoral areas, to test how different local socio-economic dynamics affect the prioritization and adoption of sustainability innovations in small ruminant systems.

Importantly, the results reveal varying degrees of alignment between LCA-based evidence and stakeholder perceptions across the three practices analysed. While pasture improvement practices show a relatively strong alignment between perceived and assessed environmental benefits, precision livestock farming and environmental labelling exhibit more fragmented interpretations. This suggests that the effectiveness of eco-innovations depends not only on their environmental performance, but also on how such performance is communicated, understood, and operationalised by stakeholders.

In this context, LCA-derived environmental information represents a valuable but underutilised resource. Its integration into decision-making processes would require not only methodological robustness, but also effective communication, simplification, and adaptation to local conditions. Strengthening local advisory networks, improving extension services, and fostering participatory knowledge co-creation mechanisms may help bridge the gap between environmental assessment and practical decision-making. Finally, these findings highlight that the effectiveness of eco-innovations in pastoral systems depends not only on their technical and environmental performance, but also on their alignment with local contexts, knowledge systems, and stakeholder priorities. This underscores the need for more integrated and context-sensitive approaches to support sustainable rural innovation pathways.

Conclusion

This study explored stakeholders' perceptions of some eco-innovations (i.e., PLF, PIP, and EL) in Sardinian sheep systems, identifying drivers, barriers, and contextual conditions for their adoption. By using participatory approaches within LCA-based evidence, environmental performance was linked to stakeholders' knowledge, priorities, and constraints, highlighting trade-offs and complementarities within the local sheep system. Stakeholders recognised the potential of these practices to enhance the resilience of sheep farming systems under climate change.

However, adoption emerged as a systemic process influenced by technical, economic, institutional, and socio-cultural factors. Embedding environmental information derived from LCA within a participatory framework allowed environmental indicators to be interpreted in relation to farm-level realities such as labour availability, management complexity, and risk perception, increasing the relevance of LCA-based evidence for decision-making. Key drivers included public incentives, targeted research and effective communication and coordinated knowledge transfer strategies.

Adoption dynamics differed among practices: PLF was constrained by technical and infrastructural limitations and high investment costs, particularly in large flocks or marginal areas; PIP was limited by knowledge gaps on soil, seed, grazing management, and restricted access to training and advisory services; EL was recognised for improving market visibility and social recognition, but adoption depended on economic feasibility, certification costs, and uncertainty regarding price premiums and value distribution along the supply chain. Socio-cultural factors, particularly weak intergenerational turnover and declining transmission of pastoral knowledge, further constrained long-term innovation pathways.

The mixed-methods framework (SWOT, QSPM, MCA, and correlation analysis), informed by LCA-based environmental evidence, effectively integrated qualitative and quantitative information and supported interventions aligned with environmental and stakeholder priorities. Although the empirical results reflect specific regional dynamics, this study provides a transferable and replicable methodological framework to support sustainable innovation pathways in other extensive livestock systems. However, methodological limitations emerged: the complexity of LCA indicators and terminology constrained knowledge transfer to non-expert actors and hindered practical application. Mismatches between LCA system boundaries and stakeholders' concerns further highlighted the need for continuous co-creation and better alignment of the analytical framework with stakeholders' priorities.

These findings highlight that participatory approaches play a crucial role for translating LCA studies into actionable strategies. Future research should broaden stakeholder representation, refine participatory tools, and ensure continuous engagement throughout the LCA process to co-develop context-specific interventions.

Integrated policy measures, including incentives, advisory services, and training might further support the adoption and scaling of eco-innovations in Mediterranean sheep farming systems.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Ethics statement

Ethical approval was not required for this study in accordance with national and institutional regulations, as the research did not involve the processing of personal data within the meaning of Article 4 of Regulation (EU) 2016/679 (GDPR). Participation was voluntary and limited to adult stakeholders. In line with the CNR Ethical Toolkit on informed consent in scientific research, participants were informed prior to the sessions of the study objectives, the focus group procedures, the participant selection criteria and their right to withdraw at any time without consequence, and gave verbal informed consent. Results are reported in anonymised and aggregated form.

Author contributions

SS: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review and editing. PA: Investigation, Writing – review and editing. SK: Investigation, Writing – review and editing. GMA: Investigation, Writing – review and editing. AP: Investigation, Writing – review and editing. AF: Investigation, Supervision, Writing – review and editing. EV: Conceptualization, Investigation, Funding acquisition, Project administration, Supervision, Writing – review and editing. AF and EV share last authorship and jointly supervised this work.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontierspartnerships.org/articles/10.3389/past.2026.17425/full#supplementary-material

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