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Socio-technical Dynamics of Silvopastoral Systems for Sustainable Cattle Farming

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ABSTRACT

Silvopastoral systems (SPS) have emerged as an innovative strategy for promoting sustainable livestock production through the integration of trees, shrubs, pastures, and livestock within the same production unit. Despite the environmental, productive, and social benefits reported across different regions of the world, their adoption continues to face challenges associated with technical, economic, institutional, and sociocultural factors. The objective of this study was to analyze the socio-technical dynamics influencing the implementation and adoption of silvopastoral systems worldwide through a systematic review of scientific literature published between 2014 and 2026. A comprehensive literature search was conducted using Google Scholar, SciELO, Redalyc, Dialnet, Latindex, and EBSCOhost databases. A total of 250 scientific articles were initially identified, of which 120 met the inclusion criteria and were selected for final analysis. The collected information was organized into six thematic dimensions: livestock productivity, animal welfare, soil quality, biodiversity conservation, climate change mitigation, and socio-technical adoption factors. The findings indicate that SPS improve forage quality and availability, enhance animal welfare by reducing heat stress, contribute to carbon sequestration, improve soil physical and biological properties, and promote biodiversity conservation in livestock systems. The review also identified financial constraints, limited technical assistance, weak institutional support, and the persistence of conventional production models as the main barriers to adoption. It is concluded that the large-scale expansion of SPS requires integrated strategies aimed at strengthening socio-technical networks, knowledge transfer mechanisms, and public policies that support the sustainability of livestock production systems.

INTRODUCTION

Livestock production is one of the most important agricultural activities worldwide, contributing significantly to food security, income generation, and rural livelihoods. However, conventional livestock production systems have been widely associated with several environmental problems, including deforestation, soil degradation, biodiversity loss, and increased greenhouse gas (GHG) emissions, raising growing concerns about the sustainability of current livestock systems (Broom, 2017; Jose and Dollinger, 2019). In this context, the search for productive alternatives capable of balancing livestock productivity with natural resource conservation has become a priority for researchers, international organizations, and policymakers.

In response to these challenges, silvopastoral systems (SPS) have emerged as an innovative strategy for promoting sustainable livestock production. These systems integrate trees, shrubs, forage species, and livestock within the same management unit, fostering ecological interactions that simultaneously improve productivity and environmental performance in agricultural systems (Jose and Dollinger, 2019; Yadav et al., 2019). The incorporation of woody components contributes to increased carbon sequestration, improved soil fertility, enhanced nutrient cycling, reduced soil erosion, and the creation of favorable microclimatic conditions that benefit animal welfare (Aryal et al., 2022; Díaz Lezcano et al., 2020; Torres et al., 2023).

Scientific evidence has extensively documented the ecological and productive benefits of silvopastoral systems across different regions of the world. Several studies have reported improvements in forage quality and availability, increases in livestock productivity, reductions in heat stress, and greater resilience to climate-related disturbances (Huertas et al., 2021; López-Vigoa et al., 2017; Sales-Baptista and Ferraz-de-Oliveira, 2021). Likewise, SPS have demonstrated a remarkable capacity to increase carbon storage in both aboveground biomass and soils, contributing to climate change mitigation and the enhancement of ecosystem services within livestock landscapes (Aryal et al., 2022; Contreras-Santos et al., 2020; Chará et al., 2020).

In addition to their environmental benefits, silvopastoral systems contribute to improved animal welfare through shade provision and microclimate regulation. Reduced heat stress promotes natural grazing and rumination behavior, improves physiological indicators, and can lead to higher weight gains and productivity levels (Améndola et al., 2016; Huertas et al., 2021; Murga-Orrillo et al., 2025). Similarly, the structural diversification provided by these systems supports biodiversity conservation and the restoration of ecological processes that are essential for the sustainability of agroecosystems (Ramírez-Barajas et al., 2019; Chará et al., 2020).

Despite the growing body of evidence supporting their productive and environmental advantages, the adoption of silvopastoral systems remains limited in many livestock-producing regions. Numerous studies have shown that the implementation of these systems depends not only on technical factors but also on a complex interaction of economic, institutional, social, and cultural variables. Factors such as access to financing, availability of technical assistance, public policies, farmers' perceptions, and knowledge-sharing networks significantly influence adoption decisions and the long-term permanence of these innovations (Oliva et al., 2018; Sandoval et al., 2021; Vargas-de la Mora et al., 2021; Zepeda Cancino et al., 2016).

From this perspective, the socio-technical approach provides an appropriate analytical framework for understanding the relationships among social actors, institutions, innovation processes, and technologies involved in the transformation of agricultural production systems. The adoption of silvopastoral systems can be understood as the outcome of dynamic interactions among farmers, researchers, extension agents, governmental organizations, and financial institutions, whose actions determine the opportunities for implementation and scaling of these practices (Apan-Salcedo et al., 2021; Sandoval et al., 2021; Romero-Mena et al., 2024).

Although there is an extensive body of scientific literature addressing the ecological and productive benefits of silvopastoral systems, evidence regarding the socio-technical dynamics that shape their adoption and expansion at the global level remains fragmented. Most previous reviews have focused primarily on productive performance, environmental benefits, or climate change mitigation, while institutional, economic, and sociocultural factors associated with SPS implementation have received comparatively less attention. This knowledge gap limits a comprehensive understanding of the processes that facilitate or constrain the transition toward more sustainable livestock production systems.

Therefore, the objective of this study was to analyze the socio-technical dynamics associated with the adoption and implementation of silvopastoral systems through a systematic review of scientific literature published between 2014 and 2026. Specifically, the review examined the contributions of SPS to livestock productivity, animal welfare, soil quality, biodiversity conservation, and climate change mitigation, while identifying the main enabling factors and socio-technical barriers influencing their adoption and long-term sustainability.

MATERIALS AND METHODS

Research design

This study employed a systematic literature review approach to analyze the socio-technical dynamics associated with the adoption and implementation of silvopastoral systems (SPS) worldwide. Systematic reviews enable the synthesis of scientific evidence generated from multiple studies and facilitate the identification of trends, knowledge gaps, and emerging research directions within a specific field (Broom, 2017; Jose and Dollinger, 2019). The methodological framework adopted in this study was based on a qualitative and interpretative approach, integrating findings from environmental, productive, socioeconomic, and institutional studies related to silvopastoral systems.

Literature search strategy

The literature search was conducted between January and March 2026 using six major academic databases: Google Scholar, SciELO, Redalyc, Dialnet, Latindex, and EBSCOhost. These databases were selected due to their broad coverage of agricultural, environmental, livestock, and rural development research.

The search strategy combined the following keywords and Boolean operators:

"silvopastoral systems"

"sustainable livestock production"

"silvopastoral adoption"

"livestock agroforestry"

"sustainable cattle farming"

"agroforestry livestock systems"

The terms were combined using the operators AND, OR, and NOT to maximize the retrieval of relevant scientific publications while minimizing duplication and irrelevant records.

Eligibility criteria and study selection

Only peer-reviewed scientific articles published between 2014 and 2026 were considered. The inclusion criteria were:

Studies focused on silvopastoral systems.

Research evaluating environmental, productive, socioeconomic, institutional, or animal welfare dimensions of SPS.

Studies reporting empirical findings, case studies, field experiments, surveys, or adoption assessments.

Articles published in English, Spanish, or Portuguese.

The exclusion criteria included:

Conference abstracts without full-text availability.

Editorials, opinion papers, and technical notes lacking scientific evaluation.

Duplicate records retrieved from multiple databases.

Studies not directly related to silvopastoral systems.

The selection process consisted of three stages: (i) title screening, (ii) abstract screening, and (iii) full-text assessment. A total of 250 records were initially identified through database searches. After removing duplicate and non-relevant publications, 120 articles met the eligibility criteria and were included in the final review and synthesis.

Data extraction

Information from the selected studies was systematically extracted and organized into a review matrix using Microsoft Excel. The following variables were recorded for each article:

Author(s)

Year of publication

Country or region of study

Research methodology

SPS characteristics

Environmental outcomes

Productive outcomes

Animal welfare indicators

Socioeconomic and institutional factors

Main conclusions

This procedure facilitated the comparison of findings across different geographical and production contexts (Huertas et al., 2021; López-Vigoa et al., 2017).

Data analysis

The selected literature was classified into six analytical categories derived from the objectives of the study:

Livestock productivity.

Animal welfare.

Soil quality and fertility.

Biodiversity conservation.

Climate change mitigation and carbon sequestration.

Socio-technical factors influencing adoption.

A thematic content analysis was conducted to identify recurring patterns, relationships, and emerging trends across the reviewed studies. Particular attention was given to the interaction among technological innovations, institutional arrangements, knowledge networks, and farmer decision-making processes, following a socio-technical perspective of agricultural innovation (Oliva et al., 2018; Sandoval et al., 2021; Vargas-de la Mora et al., 2021; Zepeda Cancino et al., 2016).

Quality assessment

To ensure the reliability of the evidence included in the review, all selected studies were evaluated according to their methodological rigor, clarity of objectives, relevance to the research topic, and consistency of reported findings. Studies presenting robust methodological designs and explicit evaluation criteria were prioritized during the synthesis process (Aryal et al., 2022; Torres et al., 2023).

Table 1: Distribution of reviewed studies by thematic category

Research theme	Number of studies	Percentage (%)
Livestock productivity	32	26.7
Animal welfare	18	15.0
Soil quality and fertility	20	16.7
Biodiversity conservation	16	13.3
Climate change mitigation	17	14.2
Socio-technical adoption factors	17	14.2
Total	120	100

PRISMA flow of study selection

The systematic review process followed a structured selection procedure. Initially, 250 records were identified through database searches. After duplicate removal and eligibility assessment, 120 articles fulfilled the inclusion criteria and were incorporated into the final análisis.

RESULTS AND DISCUSSION

Distribution and evolution of scientific research on silvopastoral systems

The systematic review included 120 peer-reviewed articles published between 2014 and 2026. The analysis revealed a sustained increase in scientific interest in silvopastoral systems during the study period. Early investigations primarily focused on ecological restoration, soil conservation, and biodiversity enhancement, whereas more recent studies increasingly addressed climate change mitigation, animal welfare, technological adoption, and socio-technical transition processes (Murgueitio et al., 2015; Jose and Dollinger, 2019; Chará et al., 2020).

The evolution of scientific research demonstrates a progressive shift from ecological approaches toward interdisciplinary analyses integrating productive, environmental, economic, institutional, and social dimensions. This trend reflects the growing recognition of SPS as multifunctional production systems capable of simultaneously addressing sustainability challenges in livestock production (Aryal et al., 2022; Chará et al., 2020; Torres et al., 2023).

Contributions of silvopastoral systems to livestock productivity

One of the most consistently reported findings among the reviewed studies was the positive impact of SPS on livestock productivity. The integration of trees and shrubs within grazing systems improves forage availability and quality by providing protein-rich fodder resources and enhancing nutrient cycling processes (Palma García and Anguiano Cárdenas, 2015; López-Vigoa et al., 2017).

Several studies documented increases in animal weight gain, milk production, reproductive performance, and feed conversion efficiency. The diversification of forage resources also reduces seasonal feed shortages and enhances system resilience under adverse climatic conditions (Martínez-Hernández et al., 2019; Lerma-Lasso et al., 2023; Nota et al., 2024).

Likewise, intensive silvopastoral systems have demonstrated the capacity to increase forage biomass production while improving nutritional quality through the incorporation of leguminous trees and shrubs (Murgueitio et al., 2015; Nuncio Ochoa et al., 2024). These findings suggest that SPS contribute not only to environmental sustainability but also to the economic viability of livestock operations.

Animal welfare improvements in silvopastoral systems

Animal welfare emerged as a key benefit associated with SPS implementation. The presence of trees creates shaded environments that reduce solar radiation and thermal stress, particularly in tropical and subtropical regions where high temperatures negatively affect animal performance (Huertas et al., 2021; Jose and Dollinger, 2019).

Research has demonstrated that cattle raised in silvopastoral environments exhibit lower physiological stress indicators, improved grazing behavior, and greater comfort compared with animals maintained in conventional open pastures (Améndola et al., 2016; Broom, 2017).

Recent studies have further shown that silvopastoral systems reduce heat stress across different altitudinal gradients and improve behavioral and physiological responses associated with animal welfare (Murga-Orrillo et al., 2025). Consequently, improved welfare conditions frequently translate into better productive performance and reproductive efficiency.

Environmental benefits: soil quality and biodiversity conservation

The reviewed literature consistently identified soil restoration as one of the most important ecosystem services provided by SPS. Tree roots improve soil structure, reduce compaction, enhance water infiltration,

Table 2: Main socio-technical barriers identified in the reviewed literature

Barrier	Main references
Limited financing	Oliva et al. (2018); Borda (2023)
High establishment costs	Vargas-de la Mora et al. (2021)
Lack of technical assistance	Sandoval et al. (2021)
Weak institutional support	Romero-Mena et al. (2024)
Cultural resistance	Zepeda Cancino et al. (2016)
Limited producer training	Apan-Salcedo et al. (2022)

and increase organic matter accumulation, resulting in improved soil fertility and long-term agricultural sustainability (Díaz Lezcano et al., 2020; Apan-Salcedo et al., 2021).

Several studies reported significant increases in soil organic matter and improvements in soil physical and biological properties when compared to conventional pasture systems (Contreras-Santos et al., 2020; Saucedo-Uriarte et al., 2022).

Similarly, biodiversity conservation was frequently reported as a major environmental benefit. The structural complexity created by trees and shrubs provides habitat for birds, insects, pollinators, and soil organisms, promoting ecological connectivity and enhancing ecosystem resilience (Ramírez-Barajas et al., 2019; Chará et al., 2020).

Research conducted in tropical and subtropical environments has shown that SPS increase species richness and restore ecosystem functions that are often lost in conventional grazing systems (Trejo-Arista et al., 2023; De la Peña-Domene et al., 2022).

Climate change mitigation potential

Climate change mitigation represented another major research theme identified in the literature. SPS contribute to reducing greenhouse gas emissions through carbon sequestration in aboveground biomass, root systems, and soil organic matter (Aryal et al., 2022; Contreras-Santos et al., 2023; Torres et al., 2023).

Several studies also reported reductions in enteric methane emissions due to improved forage quality and increased digestibility of diversified diets, particularly those incorporating leguminous species (Jiménez-Santiago et al., 2019; Sandoval Pelcastre et al., 2020).

Carbon stock assessments conducted in Mexico and other Latin American countries demonstrated that SPS store significantly greater quantities of carbon than conventional grazing systems, reinforcing their relevance within climate-smart livestock production strategies (Aryal et al., 2022; Torres Rivera et al., 2023).

Socio-technical factors influencing adoption

Despite the numerous environmental and productive benefits documented across the reviewed studies, adoption rates remain relatively low in many regions. Analysis of the literature revealed that the principal constraints are not technological but socio-technical in nature.

The most frequently reported barriers included high establishment costs, limited access to credit, insufficient technical assistance, weak institutional support, and cultural resistance to changes in traditional livestock management practices (Oliva et al., 2018; Zepeda Cancino et al., 2016).

Studies conducted in Mexico, Peru, Colombia, and Argentina consistently identified financial and institutional limitations as major obstacles to adoption (Apan-Salcedo et al., 2022; Borda, 2023; Vargas-de la Mora et al., 2021).

Likewise, deficiencies in extension services and the absence of long-term public policies frequently limit the diffusion of SPS among small- and medium-scale producers (Sandoval et al., 2021; Romero-Mena et al., 2024; Marroquín-Pugas et al., 2022).

These findings indicate that successful implementation depends on the development of socio-technical networks involving producers, researchers, extension agents, financial institutions, and government agencies.

Implications for sustainable livestock development

The findings of this review indicate that silvopastoral systems constitute one of the most promising pathways toward sustainable livestock production. Their capacity to simultaneously improve productivity, animal welfare, biodiversity conservation, soil restoration, and climate change mitigation supports their role as multifunctional agricultural systems (Chará et al., 2020; Jose and Dollinger, 2019).

However, the persistence of socio-technical barriers demonstrates that technological superiority alone is insufficient to ensure widespread adoption. Future efforts should focus on strengthening extension programs, facilitating access to financing, promoting farmer-to-farmer learning networks, and developing policy instruments that support long-term sustainability transitions (Sandoval et al., 2021; Vargas-de la Mora et al., 2021; Romero-Mena et al., 2025).

CONCLUSION

This systematic review analyzed 120 scientific studies published between 2014 and 2026 to examine the socio-technical dynamics associated with the adoption and implementation of silvopastoral systems (SPS). The evidence reviewed demonstrates that SPS represent an effective strategy for advancing sustainable livestock production by simultaneously generating productive, environmental, and social benefits.

The findings indicate that SPS improve forage quality and availability, enhance animal welfare through the reduction of heat stress, increase soil fertility, promote biodiversity conservation, and contribute significantly to climate change mitigation through carbon sequestration and reductions in greenhouse gas emissions. These multiple benefits confirm the potential of SPS as multifunctional production systems capable of improving both agricultural productivity and environmental sustainability.

The review also revealed that the principal limitations to SPS expansion are not technological in nature but rather socio-technical and institutional. Limited access to financing, insufficient technical assistance, weak policy support, inadequate extension services, and cultural resistance to changes in traditional livestock management practices were identified as the most recurrent barriers influencing adoption. Consequently, the successful implementation of SPS depends on the interaction among producers, researchers, extension agents, financial institutions, and public organizations operating within broader socio-technical networks.

Furthermore, the evolution of scientific research during the study period reflects a transition from studies focused primarily on ecological restoration and productive performance toward more comprehensive approaches that integrate environmental, economic, social, and institutional dimensions. This shift highlights the growing recognition that sustainable livestock transitions require interdisciplinary perspectives capable of addressing both technological and governance challenges.

Therefore, future efforts to promote SPS should prioritize the strengthening of extension programs, knowledge-sharing networks, financial incentives, and public policies that facilitate adoption at scale. Expanding access to technical support and investment mechanisms will be essential for overcoming socio-technical barriers and accelerating the transition toward more resilient and sustainable livestock systems.

Finally, further research is needed to evaluate the long-term socioeconomic impacts of SPS adoption, assess their scalability under different environmental and institutional contexts, and develop policy frameworks that support their widespread implementation as a key component of sustainable livestock development worldwide.

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