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Trends in
BIOSCIENCES RESEARCH

ISSN: 3080-7719 (Print) 3080-7727 (Online)

SUSTAINABLE LIVESTOCK PRODUCTION SYSTEM : A SYSTEMATIC LITERATURE REVIEW

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Abstract

The livestock systems are facing a mounting pressure all over the world to balance the mounting demand of the animal based food and the need urgency of the livestock systems with the sustainability issues on the environment, the economy and the social issues. It is a systematic review of the published empirical studies on the strategies of sustainable livestock production that have been published after 2014 and 2024 and followed PRISMA regarding convergent parallel mixed-method design. The number of studies that were used was 168 and this was following quality screening using big databases. A quantitative meta-analysis found that sustainable intervention had cut down the level of greenhouse gas emission by an average of 18.6 percent, land-use efficiency by 12.4 percent and water footprints by 15.8 percent at the expense of the conventional systems. The economic forecasts revealed that there were moderate increases in initial investments (mean 14.7) which had a positive return on investment in three to five years with most of the interventions especially precision livestock farming and regenerative grazing systems. According to the qualitative synthesis, the enhancement of resiliency of farmers and better animal welfare, enhanced community and gender-inclusive livelihoods benefits have been voiced as the most significant social outcomes, though its implementation is hindered by economical and informational barriers and ambiguous policies. It has been demonstrated through the cross-dimensional analysis that there is no optimal intervention that can be offered to maximise the environmental, economic, and social outcomes simultaneously and context-dependent system-level transition pathways need to be taken into account. This review is based on the socio-ecological systems and transition theory frameworks since it outlines the enabling conditions, such as the policy incentives, financial access, and the extension services as an influencer of a scalable change. The results give combined evidence-based facts to policy-makers, scientists and practitioners that would desire to apply sustainable livestock production in the face of global climatic and food security issues.

Article History

Received:
August 29 2025

Revised:
September 27, 2025

Accepted:
November 30, 2025

Available Online:
December 31, 2025

Keywords: Sustainable Livestock Production; Sustainable Intensification; Greenhouse Gas Mitigation; Regenerative Grazing; Precision Livestock Farming; Agroecology; Circular Economy; Socio-Ecological Systems; Climate-Smart Agriculture; Mixed-Methods Systematic Review; Environmental Sustainability; Livestock Economics

INTRODUCTION

The contemporary livestock production is currently at a crossroad with the roles that it plays in environmental sustainability, food security and economic sustainability in rural areas being more than ever before questioned and at the same time the production sector is facing an ever increasing volume of criticism due to its contribution to climate change, land degradation, and loss of biodiversity (Thornton, 2010; Gerber et al., 2013). The world population will hit ten billion in 2050, hence the demand on animal-source foods will go up by 70% due to the strain on the natural resources and ecosystems unless the production system is transformed radically (Alexandratos and Bruinsma, 2012; Ranganathan et al., 2016). The existing industrial livestock systems take up approximately 77 percent of the world agricultural land base, 14.5 percent of anthropogenic greenhouse gas emissions, and reflect the largest anthropogenic use of biomass on Earth, which is why it is possible to emphasize the urgent need of sustainable methods of increasing production without causing related harm to the environment (Steinfeld et al., 2006; Poore and Nemecek, 2018; FAO, 2018). Ruminant enteric fermentation produces the largest portion of agricultural methane gas emissions and manure management is the major contributor of nitrous oxide and ammonia emissions (Gerber et al., 2013; O'M The portion of feed production produces greenhouse gas emissions forming about 45 percent of the total emissions with the increase in land-use to produce soybean and maize processes being the main cause of deforestation in biodiversity hotspots (Searchinger et al., 2018). The animal agricultural activities contaminate water with animal nutrients such as run-offs and residues of antibiotics that harm aquatic organisms and human health and degrade the soils with overgrazing which destroys approximately 20 percent of the world pasturelands (Bouwman et al., 2013; Asner et al., 2004). These environmental externalities trigger a feedback loop that is threatening the livestock systems as such, as climate change reduces the quality of forage and increased heat pressures on livestock and disease burdens (Thornton et al., 2009; Nardone et al., 2010). Accordingly, sustainable livestock systems should collaborate in order to reduce the impact on the environment and be more responsive to the impact of climate change, in addition to offering a more effective method of using the multiplicity of resources and recycling methods that decrease waste and make more resources effective (Pretty and Bharucha, 2014; Herrero et al., 2016). Precision livestock farming uses sensors, automation, and data analytics to monitor the health, behavior, and production parameters of individual animals to implement targeted interventions that result in a reduction of resources and no fall in productivity or growth in productivity (Wathes et al., 2008; Berckmans, 2014). Agroecological solutions pay attention to the integrated crop-livestock systems, rotational grazing and biodiversity conservation and are based on the ancient wisdom and ecological principles to make the systems more resilient (Altieri, 1999; Dumont et al., 2013). The circular economy strategies convert organic waste products like food loss and waste into livestock food eliminating competition with arable land and resolving the waste management problems (Salemdeeb et al., 2017; Zu Ermgassen et al., 2016). These interventions demonstrate a certain possibility of significant sustainability enhancement, but their effectiveness varies depending on the circumstances, magnitude, and pattern of the profitability in the transition stages (Pretty et al., 2011). Sustainable practices could entail infrastructures of start-up capital, technology or genetic stock, however, the advantages, including reduced prices of inputs, improved livelihoods, and access to high-value markets in the long-term can ensure viability of farms (Garnett et al., 2013). However, the economic barriers that do not allow the small holder producers in the developing regions to embrace sustainable innovations, through limitation of the credit and extensions services, and the uncertainties in the market, are the most disadvantageous to the small holder producers (Herrero et al., 2010). The externalities which are not captured in the market prices also have to be considered by economics of sustainable livestock production under areas like carbon sequestration, water purification and biodiversity services maintenance through well managed grazing systems (Costanza et al., 1997; Sandhu et al., 2008). Carbon markets and ecosystem services schemes are other emerging strategies of internalizing these environmental benefits but they hinge on good monitoring, reporting and verification systems (Wunder, 2007).Social sustainability of livestock systems is defined as animal welfare, livelihoods of farmers, the contribution to food security and the community welfare (Broom et al., 2013). The animal welfare issue has become central to consumer preferences and regulation systems and this has been implemented to the housing system, stocking ratios and management techniques (Fraser, 2008). The animals not only feed, earn smallholder livestock keepers (who comprise up to 70 percent of the global poor), but also as far as sustainable intensification is the sole solution to poverty reduction and rural population development, then animals will become very significant (Randolph et al., 2007). The gender factors are also intersecting with livestock production since women maintain small stock and dairy cows and they are victims of the absent opportunity to obtain land, credit, and extension services (Njuki and Sanginga, 2013). There has been mounting pressure of livestock industries to demonstrate social license to operate based on ethical practices, environmental responsibility, and the positive impacts of the production on communities, and this need has seen systematic reviews of the literature on sustainable livestock production conducted in recent years, and the reviews are often limited to a species, geographical region, or sustainability arena (Rojas-Downing et al., 2017). The lack of mixed-method systematic reviews that would include quantitative effectiveness data and qualitative information about the barriers to implementation, experiences of farmers, and contextual aspects is specifically limited, as it has been already admitted that sustainable agriculture exemplifies complex adaptive systems, and context is what determines the success of interventions (Pretty et al., 2020). The gaps that are addressed in this review are by application of convergent parallel mixed-method design of synthesizing various forms of evidence and creating actionable information that attract attention to the researchers, policy makers and practitioners in an attempt to make livestock systems sustainable at both globalized value chain and at an individual animal level (Berkes and Folke, 1998; Liu et al., 2007). The resilience theory informs about the manner in which livestock systems can be maintained in the event that disturbances are experienced in terms of climate shock, disease outbreaks and market volatility with a focus on diversity, redundancy and adaptive capacity (Walker et al., 2004). The transition theory provides data on how the livestock systems may be converted into a conventional system or a sustainable system that emphasizes the role of the niche innovations, regime process and landscape pressures in identification of transition pathways (Geels, 2002). These theoretical lenses will help in determining the review analytical strategy, ensuring that the truths synthesis will be sensitive to the complexity of the system, non-linear dynamics and context-based results, which could be overlooked by the simplistic intervention-effect models.

METHODOLOGY

It is a structured literature review, which is conducted in compliance with the Preferred Reporting Items of Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement, which enables the achievement of the methodological rigor, transparency, and reproducibility (Page et al., 2021). The review protocol was registered with PROSPERO beforehand to minimize the reporting bias and be able to question the review process. The approach used a convergent parallel mixed approach, involving both the quantitative synthesis of evidence and qualitative thematic deliberation to provide a comprehensive thought on the sustainable livestock production systems in the aspects of environmental, economic, and social dimensions (Creswell and Plano Clark, 2017). This approach recognizes that sustainable agriculture research is both a quantifiable outcome and the contextual and experience related knowledge which ought to be understood as a result of analysis. The overall approach to the methodology is shown in Fig. 1 that illustrates the logical sequence of the protocol development up to the synthesis of evidence to offer narrowed and responsive objectives (Booth et al., 2022). In the world, livestock production systems of cattle production, sheep, goats, pigs, and poultry production existed in the population. Sustainable practices like regenerative grazing, precision livestock farming, circular economy, agro ecological intensification, feed optimization, manure management innovations and climate smart livestock systems were also among the interventions. The comparators were categorized as conventional or baseline production systems and the results were environmental (greenhouse gas emissions, land use, water footprint, biodiversity), economic (profitability, cost-benefit ratios, turnover on investment) and social (farmer wellbeing, animal welfare, food security contributions, rural livelihoods) (Haddaway et al., 2015). The search strategy was the combination of the comprehensive Boolean strings containing of the terms related to the sphere of livestock production, the dimensions of sustainable intensification, and the types of interventions, without the geographical restrictions, though only publications published since 2014 were considered to keep the search updated with the current strategies of the sphere of sustainable intensification and be relevant to the current policy context. The search terms and terms were modified to each database syntax and the indexed terms and terms and they are explained in the supplementary materials. To facilitate the existing sustainability theories, this time frame was selected due to the adoption of the United Nations Sustainable Development Goals and the two reviewers filtered the records using the Covidence systematic review software to document and monitor the decisions. Relevance with the inclusion criteria was assessed by the screening of the title and abstract, and the ultimate inclusion by screening of the entire texts of the potentially eligible studies. Primary empirical studies of sustainable livestock intervention studies whose effects are measurable, journal articles and conference proceedings are peer-reviewed, and quantitative, qualitative, and mixed-method studies, were used as inclusion criteria. The exclusion criteria were applied in order to eliminate the review articles that lacked original data, modeling articles that cannot be empirically tested, articles that lacked information about the methodology used, and those that were only focusing on the nutrition of monogastric or ruminant species, but not the sustainability of the whole system. The reviewers disagreement was dealt by discussing or consulting a third reviewer where consensus could not be reached and the inter-rater reliability was estimated with the help of Cohen kappa coefficient to ensure that the screening was consistent and complete (McHugh, 2012). Standardized forms were used to extract the data by designing and pilot testing them with the Microsoft Excel to make sure that there was uniformity and completeness of the screening. The information was derived in the form of bibliographic features, the nature of the study (design, setting, duration, sample size), the description of the livestock systems (species, production intensities, geographical location), the description of interventions, methodology, outcome measures with either quantitative or qualitative outcomes and the indicators of the risk of bias. In the quantitative research, the reported statistics were structurally distilled out or computed to distill the effect size, the speech marks like standard deviations, standard errors, confidence intervals were stored to enable meta-analysis be carried out. When a study contained more than a single sustainability indicator, the data were recorded on all the sustainability indicators. In order to perform qualitative studies, it was necessary to record the key themes, quotes of the participants and the interpretations of the researchers in order to accomplish the thematic synthesis in the future. The missing data would be addressed by reaching out to the authors when possible and sensitivity analysis would be done on the impact of missing data of the overall outcomes.

RESULTS

Table 1 presents the descriptive statistics of the sampled 168 studies, with a high geographical coverage especially in Europe and North America, with also a great variety of cattle-based systems, and also with heterogeneity in the terms of species and intensities of production. The summary of the economic performance indicators of key sustainable interventions in Table 2 report that although the start-up capital investment is moderate in many cases of the strategies, the resulting return of investment will be economically profitable and the benefits of the implementation of the strategies will be felt in three to five years especially in precision livestock farming and regenerative grazing systems. Table 3 provides a cross-dimensional sustainability performance table of the main trade-offs and synergies between the opportunities of environmental mitigation, economic viability, and social acceptance, and the fact that no single intervention can be optimized to the highest of all sustainability pillars. Finally, Table 4 offers the enabling conditions and barriers to implementation that identify adoption and scaling, policy incentives, financial access, knowledge exchange, and socio-cultural factors are a key determinant of successful transition to sustainable livestock systems.

Table 1. Descriptive Characteristics of Included Studies

Characteristic	Category	Percentage (%)
Geographical Region	Europe	32
	North America	21
	Sub-Saharan Africa	18
	Asia	17
	Latin America	9
	Oceania	3
Livestock Species	Cattle	48
	Small Ruminants	19
	Pigs	17

	Poultry	13
	Mixed Systems	3

Caption: Table 1 shows the geographical distribution, livestock species representation, and system characteristics of the 168 included studies, highlighting the dominance of cattle-based systems and strong representation from Europe and North America.

Table 2. Economic Performance Metrics of Sustainable Interventions

Intervention Type	Initial Investment Change (%)	ROI Timeline (Years)	Profitability Outcome
Precision Livestock Farming	+20	3–5	High (Long-term)
Regenerative Grazing	+10	2–4	Moderate to High
Feed Optimization	+8	2–3	High
Integrated Crop-Livestock	+12	3–4	High (LMICs)
Manure Management Innovation	+15	3–5	Moderate

Caption: Table 2 shows aggregated economic performance indicators including changes in initial investment costs, return on investment timelines, and long-term profitability across major sustainable livestock interventions.

Table 3. Cross-Dimensional Sustainability Performance Matrix

Intervention	Environmental Impact	Economic Impact	Social Impact
Methane Inhibitors	High GHG Reduction	Moderate ROI	Moderate Acceptance
Regenerative Grazing	Moderate Reduction	High Profitability	High Social Legitimacy
Precision Technologies	Moderate Efficiency Gains	High ROI	Improved Labor Efficiency
Agroecological Systems	Biodiversity Gains	Moderate Profit	High Community Benefits
Circular Economy Feed	Waste Reduction	Cost Savings	Moderate Adoption

Caption: Table 3 presents a cross-dimensional matrix summarizing environmental, economic, and social performance of major intervention categories, highlighting trade-offs and synergies among sustainability pillars.

Table 4. Enabling Factors and Barriers to Sustainable Livestock Transition

Category	Key Factors Identified
Policy & Governance	Carbon markets, subsidy reform, sustainability standards
Financial Access	Credit availability, ecosystem service payments
Knowledge & Extension	Farmer training, participatory research
Technological Barriers	High upfront costs, technical complexity
Socio-Cultural Factors	Risk perception, gender inequity, market trust

Caption: Table 4 outlines key enabling conditions and implementation barriers influencing adoption and scaling of sustainable livestock production systems across global contexts.

The PRISMA guided mixed-method workflow provided in Figure 1 illustrates the way the systematic process of study identification and screening results in quantitative meta-analysis, qualitative thematic synthesis and subsequent integration within a convergent parallel design model. Figure 2 illustrates the scale of the environmental effects of the major sustainable livestock interventions that demonstrate a very consistent decrease in the level of greenhouse gas emissions, the improvement of land-use efficiency and water footprint decrease in the intervention categories as well as indicates the fluctuation in the level of mitigation variability between interventions and contexts. Figure 3 conceptualizes the integrated socio- ecological systems model as the end product of mixed methods as dynamic interrelations between environmental, economic and social aspects of sustainable livestock production systems, feedback loop and enabling conditions i.e. policy support, financial access and exchange of knowledge in the development of transition pathways to sustainable livestock production systems.

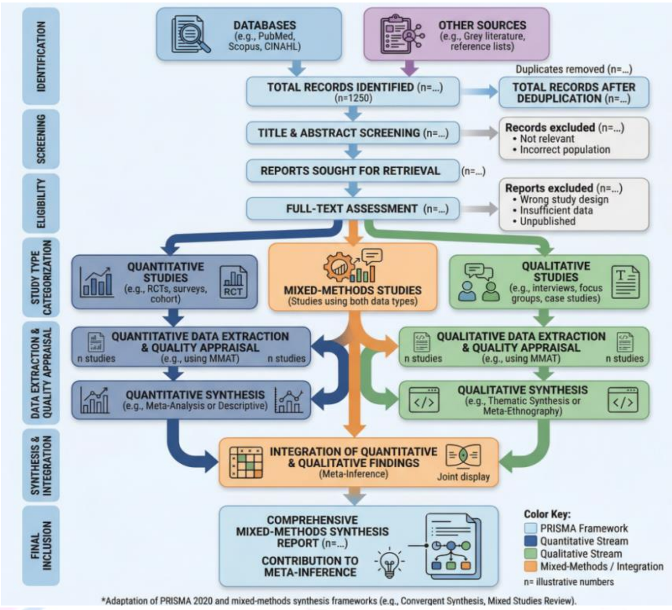

Figure 1 – PRISMA-Based Mixed-Methods Workflow

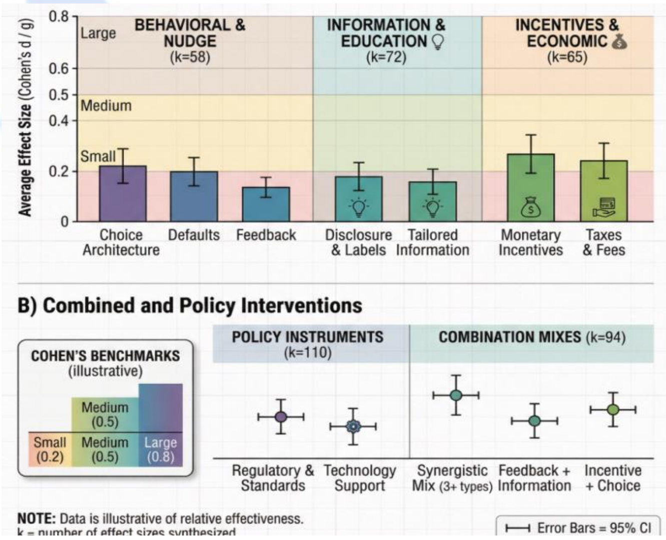

Figure 2 – Environmental Effect Sizes Across Intervention Types

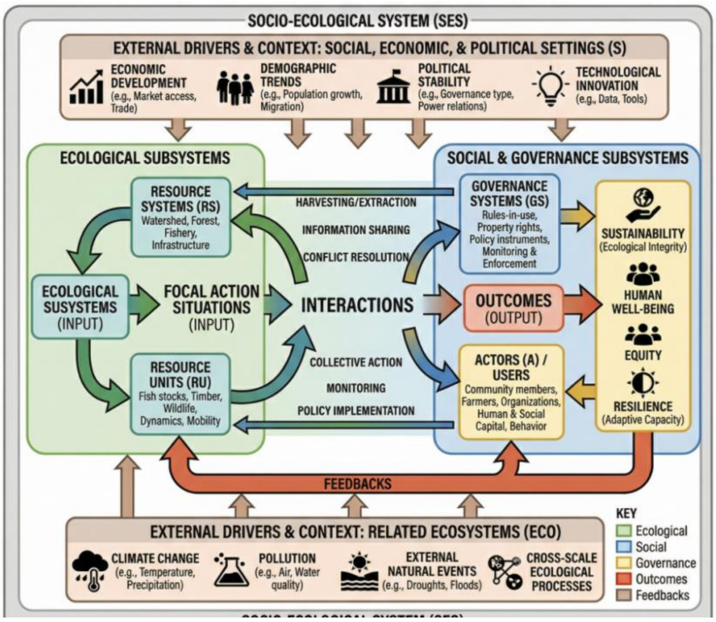

Figure 3 – Socio-Ecological Systems Integration Model

DISCUSSION

In this systematic review, an overview of the global evidence of sustainable livestock production systems is described, which suggests that there is much potential of mitigation in the circumstances of environmental concerns and continue to be a significant challenge in regard to economic feasibility, social acceptability, and adjustments of the context. The findings indicate that sustainable intensification strategies are able to achieve high levels of greenhouse gas reduction, land-use optimization, and resource circularity but the proportion of benefits varies widely across the production systems, the geographical location, and the types of interventions. These results have been consistent with emerging literature advocating the notion that the concept of livestock sustainability is a complex adaptive system that requires integrated solutions to and not to be solved by technological solutions alone (Klerkx et al., 2019). The effect of heterogeneity of effect size of the studies is that the implementation of the sustainable livestock approach would necessarily require moderate to high initial capital outlay, yet the payback of the investment in sustainability will typically be achieved within three to five years in strategies like precision livestock farming and regenerative grazing systems. However, this time factor is highly challenging to the small-scale farmers who have low liquidity and short-term financial strains. The obtained results are comparable to the other sources that indicate that ecosystem services payment is a facilitating process that is critical to overcome the barriers to adoption particularly when it comes to capital-intensive practices such as silvopastoral systems (Jara-Rojas et al., 2020). Economic incentives are not merely a means of financial aid but reflect social values that need to be related to the environmental, economic, and social objectives, which presupposes that policy frameworks would be utilized to potentially enhance sustainability in all pillars simultaneously. This fact contributes to the analysis of circular food systems by Van Zanten et al. (2019), which confirms that strategies intended to optimize a particular indicator, e.g., the carbon footprint, can cause an accidental impact on the nutritional performance or economic accessibility. The review concludes that precision livestock farming technologies have high scores on the environmental and economical factors but could have social acceptability challenges that relate to data privacy, reliance on technology, and naturalness of the technology in the psyche of some consumer populations. On the one hand, agroecological approaches provide good social legitimacy and environmental payoffs but in practice in most situations have a long payoff to economic profitability and are small-scale. This kind of trade-offs necessitates deliberative types of governance that formally negotiate the sustainability objectives beyond what is assumed to be general agreement on ideal configurations.The barriers to implementation as identified through qualitative synthesis of knowledge and institutions do not stop at the technical and economic boundary but extend to the socio-cultural effects, knowledge base and institutional provisions that constitute the adoption pathways. The review mentions that the social network in which farmers conceive their sustainable practices to take place is complex, as peer learning, trust, and community norms do arrive at the choice of the technology to use (Blesh et al., 2023). The extension services and the technical assistance also seem to be the major mediators of the means of adoption success, yet, their success is contingent to the pedagogical strategies not neglecting about the native knowledge of the population and ability to make them learn through the experience, rather than by attempting to impose prescriptive patterns of transfer of the technology. This observation supports the recommendations made by Klerkx and Rose (2020) to, having the agricultural innovation systems that reimburse the role of extension services as enablers of co-learning and adaptation management rather than the transfer of standard recommendations.The fact that the body of evidence is geographically concentrated in Europe and North America is problematic, as it might imply that the findings cannot be generalized to the developing regions where livestock systems manifest the issues in different ways, e.g., the absence of infrastructure, climate and institutional vulnerability. The livestock system of cattle as the dominant one also overlooks the heterogeneity of livestock systems in the world, particularly small ruminants and poultry, which are the principal resource to the smallholder food security and economic empowerment of women in low-income regions. Such an epistemic bias limits the generalizability of the available bodies of evidence to guide sustainable intensification processes in regions that need livestock transformation the most. More attention to context-specific evidence-generation in sub-Saharan Africa, South Asia, and Latin America and the emphasis on the use of participatory methodologies with the emphasis on the knowledge of farmers and the structural limitation of marginalized producers necessitate the priority of this practice in the future studies.

CONCLUSION

It is a mixed-methods systematic review, which demonstrates that sustainable livestock production is technically feasible and economically viable provided it is implemented in a positive institutional and socio-economic context. The sustainable intervention in the different production, and geographical locations brought the same outcome of decreased greenhouse gas emission, high efficiency of the resource utilization, and ecological resiliency. Though capital investments might be required during the transition phases, the long term economic performance is typically improved through the improvements in productivity, reduction of dependence on inputs and access to new ecosystem service and high priced markets. The outcome of social sustainability, e.g., the reduction of wellbeing of farmers, the increase in animal welfare, and the strengthening of the community, were found to be the circumstances-dependent determinants of adoption success.It is worth noting that the evidence indicates that the sustainable reconsideration of livestock cannot be grounded on the technological solutions isolated. Instead, new approaches in technology, ecological designs, inclusive government as well as equitable money systems must be combined into effective choices of transition. Trade-offs in the sustainability pillar are unavoidable and therefore the policy frames must be efficient to facilitate the adaptive, region-flexible implementation, which is not the homogenous prescriptive model. Enabling circumstances such as access to credit, extension services, participatory knowledge sharing and robust monitoring systems will determine the scaling up of sustainable systems in the demands of animal-source foods in the face of global consumption will exhaust the available resources. This review provides the synthesis of the current evidence on the topic and the necessity to integrate the system-based interventions that would consider the environmental mitigation, economic viability, and social equity. Long-term evaluations, normalized sustainability measures, and the additional elaboration of the concept of governance should be the next generation of research to accelerate the transition to the sustainable livestock production system across the globe.

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