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Review

Sustainable Small Ruminant Production in Low- and Middle-Income African Countries: Harnessing the Potential of Agroecology

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Abstract: The role of small ruminant production in achieving sustainable and resilient food systems in low- and middle-income countries (LMICs) is yet to be fully explored or incorporated into current agroecological practices and policies. This review examines the principles and practices of agroecology, focusing on circular food systems and the sociopolitical aspects of their implementation for small ruminant production in LMICs. It discusses Gliessman's five levels of agroecological transition and eight principles for integrating small ruminant production into agroecology: input reduction, animal health, soil health, biodiversity, recycling, synergy, economic diversification, and co-creation of knowledge. The review highlights that, while there are differing interpretations in the scientific literature, there is a growing consensus that agroecological practices applied to small ruminant production have the potential to improve integration and self-sufficiency in farming systems, improve animal health, reduce reliance on external inputs, and promote circularity and biodiversity. This reinforces the view that agroecological approaches to small ruminant production can foster a sustainable and interconnected system that strengthens the relationships between animals, plants, and the environment and enhances circularity. To achieve successful implementation and widespread adoption of these approaches, it is crucial to facilitate greater collaboration and cocreation of knowledge among small ruminant farmers and stakeholders in the small ruminant livestock industry.

Keywords: agroecology; sustainable; circular agrofood system; Gliessman's five levels of transition; small ruminants; low- and middle-income countries

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1. Introduction

Livestock, especially small ruminants, contribute to human society by providing food, fiber, and other commodities [1,2]. The livestock industry supports approximately one billion smallholder farmers in low- and middle-income countries (LMICs) [3]. This sector makes up 40% of the agricultural gross domestic product, and its contribution to household incomes in LMICs varies from 2% to over 33% [3]. Small ruminants play a critical role in agricultural livelihoods in LMICs, with an estimated 80% of the global small ruminant population located in these regions [4,5]. The average herd size varies across regions and production systems, but in many LMICs, small ruminants are typically raised in small flocks, with a herd size of 5–30 animals per farmer [6–8].

Small ruminants adapt to a range of environments [9,10], making them valuable for farmers seeking to optimize production and profits. They are mainly kept under extensive production systems, including free-ranging, semi-intensive, and pastoral systems, where they feed on natural pastures, crop residues, and shrubs [6,7,11–13]. Women are typically responsible for managing small ruminants in LMICs, which in turn provides them with direct benefits [14,15].

Despite these benefits, small ruminant production systems face several challenges. Limited feed availability during the dry season and poor productivity in meat, milk, and fitness (reproduction and survivability) can hinder profitability [5,16]. Diseases such as contagious caprine pleuropneumonia (CCPP), 'peste des petits ruminants' (PPR), brucellosis, and foot and mouth affect small ruminant production, resulting in high mortality rates and reduced productivity [17–19]. In addition, climate change threatens small ruminant production, with changing weather patterns and increased frequency of extreme events leading to decreased productivity and increased disease risks [20].

Current small ruminant production systems have been scrutinized for their negative environmental and social (effects of the environmental impacts on people and communities) impacts, including pollution, deforestation, and animal welfare concerns [21] but have been ignored in most agroecological thinking [22,23]. In recent years, agroecology has gained increasing attention as a potentially effective strategy to transform livestock production [22,24,25]. Today, the term "agroecology" refers to a scientific discipline, an agricultural practice, and a political or social movement, all of which strive to promote sustainable and resilient agricultural systems [26,27].

The disconnection between small ruminant animals and agroecosystems poses a significant threat to the sustainability of animal-farming systems. This is particularly true in arid and semi-arid regions, where climate change is leading to high temperatures, erratic rainfall patterns, and prolonged dry periods, thus contributing to feed scarcity and negatively impacting livestock productivity. Small ruminants also have the potential to thrive in agroecosystems by utilizing byproducts from the food industry and biomass from crops and grasslands to provide ecosystem services such as food and manure, leading to the promotion of a sustainable and circular food system that helps maintain the balance and resilience of agroecosystems [28,29].

This review explores the principles, science, practices, and sociopolitical dimensions of agroecology and the concept of circularity as applied to small ruminant production systems in LMICs. Specifically, it links eight high-level panel of expert (HLPE)-identified agroecological principles [30], namely input reduction, animal health, soil health, biodiversity, recycling, synergy, economic diversification, and cocreation of knowledge, to Gliessman's five levels of transition pathways [31] toward sustainable food systems. It discusses key points for sustainable small ruminant production systems using transition pathways. Furthermore, the review extensively draws upon journal articles, books, and other published materials sourced from prominent databases, including Google Scholar, PubMed Central, and Scopus, to provide a comprehensive analysis. Finally, it examines the literature to identify the technical and organizational innovations required to implement agroecological principles in small ruminant production systems in LMICs.

2. The Pathway to an Agroecosystem in Small Ruminant Production

Small ruminant production originated in natural ecosystems (Figure 1), where farmers relied on the natural environment and the animal's instincts to manage the herd [32,33]. Over time, these practices developed into traditional small ruminant systems involving more farmer-directed management, such as selective breeding and targeted grazing [34,35]. Subsequently, conventional small ruminant systems were developed, which were intensive and heavily reliant on external inputs, such as feed and medications [22,36].

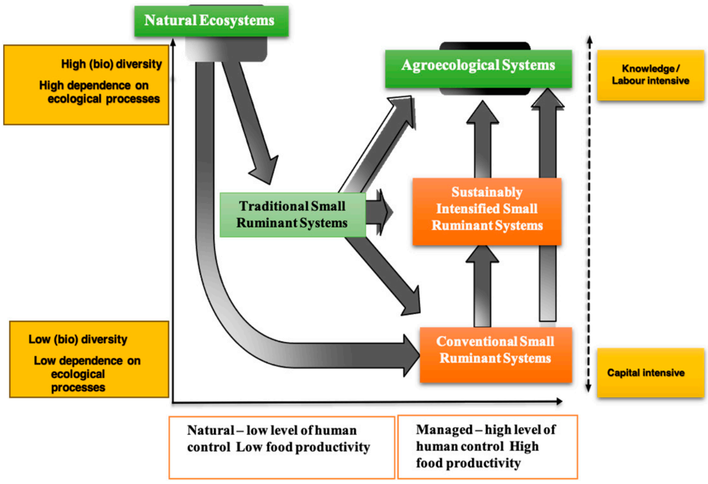

Figure 1. Small ruminants' journey to agroecological systems: charting a path from past to present. The arrows indicate the various pathways to agroecosystems: yellow boxes show the characteristics of each pathway; orange boxes signify production systems with heavy reliance on external inputs; and green boxes symbolize "greener" production systems. Adapted from HLPE [30], Griffon [37], HLPE [38].

The unsustainability of the conventional system prompted the shift toward more sustainable intensification methods [25,39], which involved practices that improved productivity while reducing environmental impact. Ultimately, the goal is to transition to agroecological systems [40], which integrate biodiversity, ecosystem health, and social equity with productivity [24,41]. FAO [42] outlined ten components of agroecology: diversity, joint knowledge development, synergies, efficiency, recycling, resilience, human and social values, cultural and food traditions, responsible governance, and a circular and solidarity economy. The HLPE [30] report consolidated multiple concepts of agroecology from the literature into a list of thirteen principles (Figure 2), eight of which are used in this review, as highlighted in Figure 2, to assess the various pathways that can be taken to transition small ruminant livestock production in LMICs. These principles are interlinked with Gliessman's five levels of transition pathways, as well as the three facets of agroecology (i.e., science, practices, and sociopolitical dimensions) and the notion of circularity.

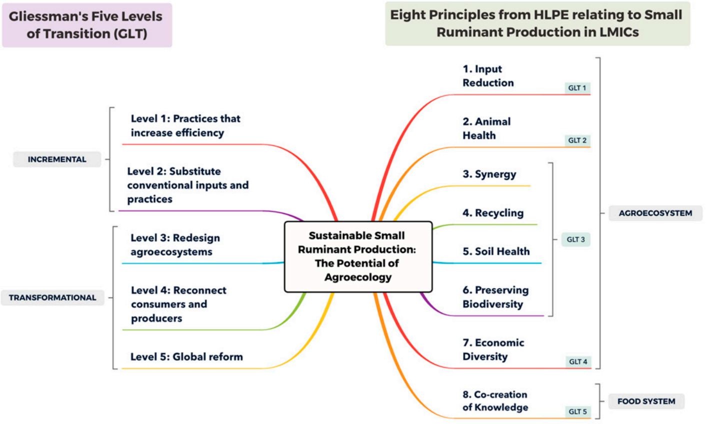

Figure 2. Gliessman's five levels of transition (GLT) toward sustainable food systems and the related eight principles of agroecology pertaining to small ruminant production in low- and middle-income countries (LMICs). Adapted from HLPE [30], Gliessman [43].

3. Concept of Circularity in Small Ruminant Livestock Production Systems

A linear economy operates by converting raw materials into products that are used and eventually discarded as waste. In the food system, this linear approach typically involves extracting resources from the environment, processing them into food products, distributing them, and ultimately generating waste during production and consumption. In contrast, a circular economy aims to prolong the useful life of resources, products, and services by creating closed-loop cycles where waste is minimized and materials are continually reused and recycled [43,44]. Three key tenets form the foundation of a circular economy: reducing waste and pollution, reusing goods and resources, and regenerating the natural world [45]. This idea aims to improve the economic and social elements of food production, especially agricultural output, while minimizing adverse environmental effects.

In small ruminant production, circularity can be achieved through mixed farming or integrated crop–livestock systems [46]. Integrating crop production and animal husbandry can create synergies and reduce waste. In a circular economy, small ruminants can consume the residues from crop production systems, byproducts, or forage and other biomass from marginal lands to produce animal protein for human consumption. Animal manure generated can be used to fertilize the cropland/pasture to close the nutrient loop and reduce the need for synthetic fertilizers (Figure 3). Integrated crop–livestock systems also have added benefits, such as grazing animals controlling weeds and reducing the need for tillage [47]. To maximize circularity, it is essential to reduce reliance on external inputs, such as feed and drugs, and instead use locally available resources like grass, legumes, tree foliage, and agroindustrial byproducts.

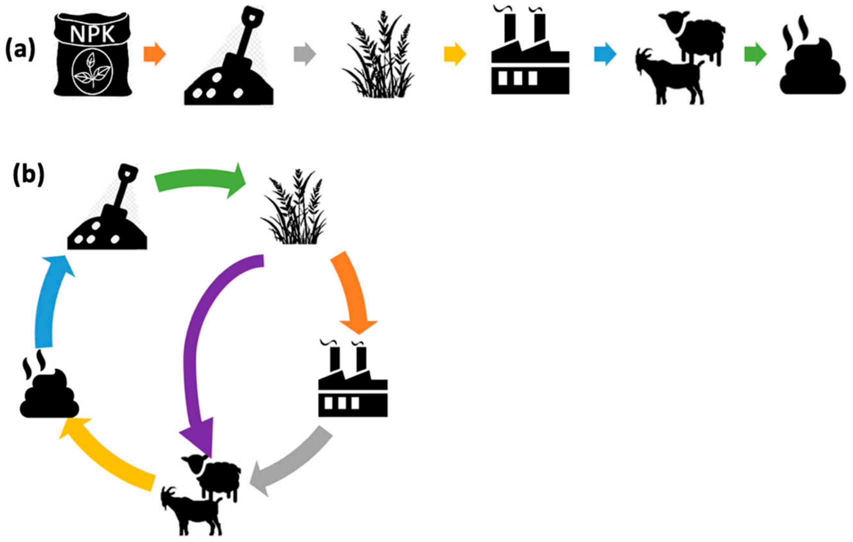

Figure 3. Comparison of linear (**a**) and circular (**b**) economies within a small ruminant production system.

The conversion of nonedible biomass into valuable inputs for animal consumption is an essential aspect of circularity in small ruminant production. Small ruminants are adept at digesting lignocellulosic agroindustrial byproducts, but digestible food waste, such as fruit and vegetable byproducts, can also be used as a feed supplement for ruminants [48–51]. International guidelines for feed safety, such as the Codex Alimentarius (established by the FAO and World Health Organization (WHO)), exist, but regulatory gaps still occur in most LMICs, requiring careful consideration of food waste quality and safety before use as feed.

The focus on circularity may overlook other crucial components of sustainability, such as social and economic considerations [52], particularly in developing nations with limited resources and technology [53]. Further research is needed on the political and social elements of circular agrofood systems, including power dynamics, governance, and stakeholder participation [54], as well as the financial, investment, and scalability models necessary to support these systems [47]. These gaps highlight the significance of adopting a comprehensive and integrated approach when implementing circular principles in the agrofood industry.

Balancing multiple factors and perspectives to form a holistic understanding, we define circularity in small ruminant production as *"the sustainable circular flow of inputs that are scientifically, socially and politically acceptable, agriculturally feasible and economically efficient"* (Figure 4). This definition emphasizes that circularity is not just about recycling or reusing materials but also about ensuring the inputs used in the circular economy are environmentally, socially, and economically sustainable. Scientific acceptability refers to using inputs that have been scientifically tested and proved safe for human health and the environment. Agricultural feasibility refers to using inputs compatible with farming practices that do not harm the natural ecosystems. Social and political acceptability refers to using inputs that are acceptable to the local community and comply with legal regulations and policies. Economic efficiency refers to the use of inputs that are economically viable and provide a net benefit to society.

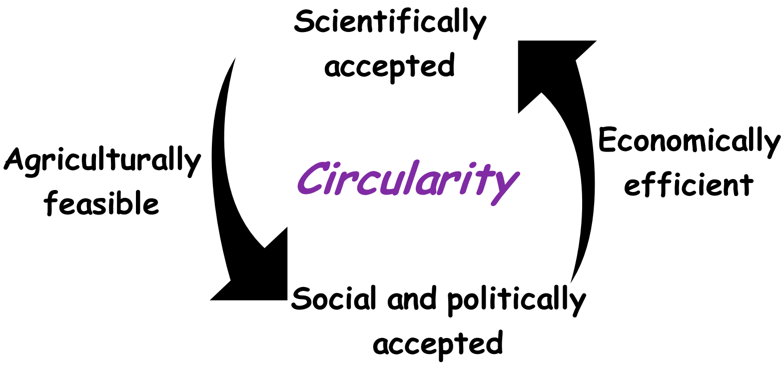

Figure 4. Circularity redefined: closing the loop for a sustainable future.

4. Gliessman's Five Levels of Transition (GLT) Pathways and Related Agroecological Principles as Applied to Small Ruminant Production Systems

Gliessman's five levels of transition provide a useful framework for understanding how agroecological practices can be applied to small ruminant production in LMICs. The framework proposes a two-pronged approach to transition toward agroecology: incremental and transformational (Figure 2). The incremental approach, comprising levels 1 and 2, involves implementing low-risk practices gradually and steadily incorporating more advanced practices over time. It recognizes the importance of starting with simple and low-risk practices that can be easily integrated into existing farming practices, allowing farmers to transition at their own pace and in a way that suits their individual circumstances. This approach provides a supportive and empowering framework to encourage farmers to improve their farming methods while considering the specific challenges and opportunities in their situation.

The transformational approach, comprising the levels from 3 to 5, aims to establish a self-sustaining agroecosystem that integrates multiple agroecological practices and creates complex, multifunctional agroecosystems that benefit both human and environmental health. It requires a significant shift from conventional farming practices and encourages farmers to adopt a more holistic, integrated, and sustainable system. By implementing a range of agroecological practices, farmers can create a more resilient system that can tackle challenges such as climate change, pest outbreaks, and soil degradation. Developing complex and multifunctional agroecosystems can transform the agricultural sector and create a more sustainable future.

The discussion below focuses on eight of the thirteen agroecological principles proposed by HLPE [30] in relation to GLT (Figure 2). Among these principles, seven pertain to the agroecosystem, namely input reduction, animal health, soil health, biodiversity, recycling, synergy, and economic diversity. The eighth principle, cocreation of knowledge, relates to the food system. The utilization of the eight agroecological principles and Gliessman's transition levels can serve as a beneficial framework to facilitate the transition toward sustainable small ruminant production systems in LMICs. It is important to note that these principles and levels are not entirely distinct from one another and may intersect in practical application.

4.1. Level 1: Practices That Increase Efficiency and the Principle of Input Reduction

The initial step in the transition toward agroecology is the Gliessman Transition Level 1 (GLT-1) pathway [31]. This pathway offers a practical and effective approach for farmers to commence transitioning toward agroecology. It emphasizes low-risk practices that can be easily integrated into conventional agriculture. According to research on manure utilization, combining organic and inorganic sources is more effective in meeting crop nutrient requirements than using either source alone (Table 1). This emphasizes the significance of combining several fertilizer sources to improve crop productivity. Moreover, research reveals that push–pull technology (PPT) has demonstrated benefits and effectiveness in the areas where it is used (Table 1). Climate-smart PPT has been shown in many African countries to increase grain output and biomass productivity and to minimize weed and pest infestation. Table 1 shows that harnessing the potential of agroecology for sustainable small ruminant production in African contexts entails recognizing common themes and successful strategies. Integrated approaches combining organic and inorganic inputs are essential. This integration enhances soil fertility, minimizes pest pressures, and bolsters overall productivity. Furthermore, adapting practices to local conditions is paramount. Acknowledging the ecological nuances of specific regions, such as the complexity of landscapes and the presence of pests, ensures that agroecological methods are tailored to maximize their effectiveness.

Diversification is key for sustainable small ruminant production. This involves practices like integrating diverse crop varieties or incorporating different sources of organic matter into the system. Diversifying not only mitigates risks but also enhances the resilience and sustainability of small ruminant farming. Additionally, economic viability must be considered. Sustainable practices should not only boost yields but also improve the economic wellbeing of small ruminant farmers. Raising awareness and disseminating knowledge about these practices among farmers are crucial steps in promoting their adoption. Addressing practical challenges related to manure application, such as bulkiness and transportation costs, can make agroecological methods more accessible and practical for small ruminant producers, further contributing to sustainability. One effective solution is to promote the use of manure locally within mixed-farming systems, minimizing the need for transportation and enhancing soil fertility onsite. This highlights the importance of mixed-farming systems where both livestock and crops are produced, creating a closed-loop agricultural ecosystem.

Previous research has also emphasized the need for a sustainable approach to animal agriculture that considers the ecological interactions required for efficient food and fiber production while reducing the dependence on external inputs [55]. Studies [56–58] have stressed the importance of harmonizing natural resource management, food production, and ecosystem services over the long term and in the face of climate uncertainty.

In low- and middle-income countries (LMICs), small ruminant production systems can benefit from various practices that promote efficiency and yield improvement while reducing input requirements. An example of such practices is the employment of integrated crop–livestock systems, whereby crop residues and byproducts are repurposed as feed for small ruminants [59]. This approach minimizes the need for external feed inputs and boosts soil fertility by reintroducing organic matter into the soil [60,61].

Another beneficial practice in small ruminant production systems is rotational grazing, which involves rotating small ruminants between different paddocks to promote pasture recovery and reduce the risk of overgrazing [62,63]. This technique increases grazing efficiency while enhancing soil health and biodiversity [64,65]. Additionally, adopting agroforestry systems where trees are integrated with silvopastures and livestock can offer supplementary fodder and shade for small ruminants, thus curtailing reliance on external inputs [66,67].

Feeding small ruminants using natural resources and agricultural byproducts saves resources for human food, and such feeding systems can rely on cost-effective sources, such as permanent pastures and rangelands [41]. However, rangeland-based feeding has limitations, such as the need for large areas and the variability in forage amount and quality [23]. Further, alternative feed options, such as straw from crops like maize, millet, and wheat, can serve as supplementary feed for various animals in different agroecosystems, particularly in the dry season when feed is scarce. Additionally, agro-industrial byproducts, such as fruit and vegetable byproducts, can be used as supplementary feed for small ruminants in LMICs [68]. Despite the benefits, it is crucial to acknowledge that conflicting views may arise concerning the implementation of these practices in small ruminant production systems. For instance, feeding small ruminants crop residues means there is competition for the residues that might be important for, for example, the practice of conservation agriculture (CA).

Table 1. Comparative studies on input reduction methods in crop production: effects on yield, soil health, and biodiversity.

Country(s) of Study	Aim(s) of Study	Main Finding(s)	Reference
		Push–Pull Technology (PPT)	
Kenya	Assess the impacts of PPT adoption on economic and social welfare.	Maize yield increased in PPT plots compared to non-PPT plots. PPT system benefitted fodder production through direct sales and livestock products.	[69]
Kenya, Uganda, Tanzania	Assess climate-smart PPT's impact on maize infestation and farmers' perceptions of its effectiveness in east Africa against fall armyworm.	Fall armyworm infestation in East Africa was reduced using climate-adapted push–pull system, reducing maize damage and boosting farmers' perceptions of its effectiveness.	[70]
Uganda	Assess PPT adoption's impact on Ugandan smallholder farmers' welfare.	With the expansion of PPT land, average maize grain production (kg/unit land area), average household income, and average per capita food intake increased.	[71]
Kenya	Compare the performance of PPT to common maize-based cropping systems.	PPT enhanced grain yield, biomass productivity, and reduced weed infestation.	[72]
Ethiopia	Contrast the robustness of PPT farming systems with that of conventional farming systems.	No evidence of positive impact of PPT on pest and weed control due to lack of a severe weed infestation. PPT improved fodder production but not maize yield.	[73]
Kenya, Tanzania, Ethiopia	Assess farmers' readiness to adopt climate-smart PPT in eastern Africa, including knowledge dissemination strategies and projected impact.	Financial analysis showed positive technology benefits from controlled Striga and stemborers, improving soil fertility, outweighing costs compared to farmers' practices, and improving cereal yields.	[74]
Ethiopia	Evaluate push–pull systems' agronomic and pest suppression potential in complex landscapes with companion crops.	Push–pull helped decrease stemborer infestation in intermediate-complexity landscapes with no dominant host plants or perennials. Common bean repelled stemborer effectively, potentially replacing *Desmodium* in areas with Striga infestations. It increased general predator abundance and egg predation rate compared to solely maize or maize intercropped with *Desmodium.*	[75]
Kenya	Compare male and female field plots to examine the adoption of push–pull pest management technology and sustainable farming practices in western Kenya.	Econometric analysis showed no gender heterogeneity in PPT adoption. Jointly managed plots received more animal manure, soil, and water conservation measures. There were no gender differences in intercropping, crop rotation, or fertilizer use. The analysis showed a considerable association between PPT and agricultural technology, implying equal promotion.	[76]
Malawi	Examine PPT performance in different agroecological zones.	Study confirmed the benefits of technology in terms of stemborer and Striga control.	[77]

Table 1. *Cont.*

Country(s) of Study	Aim(s) of Study	Main Finding(s)	Reference
		Manure Application	
Nigeria	Assess NPK fertilizer and poultry manure's impact on cassava, maize, and melon yields.	Poultry manure and chemical fertilizer produced higher yields than sole application of each.	[78]
Zimbabwe	Examine the impact of cattle manure and inorganic fertilizer on maize yield.	Compared to control treatments, applying 2.5 t/ha cattle manure enhanced grain weight, grain, and stover yields by 29.7 percent. Continuous manure application at 5.0 t/ha with no inorganic fertilizer considerably improved yields. The combined treatments outperformed the separate treatments in terms of yield.	[79]
Senegal	Analyze the impact of organic and mineral fertilizer on weed flora in a peanut crop.	Weed density was unaffected by fertilization type. Cattle manure treatment had the highest dry weight of grasses at 40 days, followed by inorganic fertilizer at 15.2 g/m.	[80]
Not applicable	Discuss the components of integrated nutrition management and their impact on maize crop productivity.	Compared to the solo use of organic and inorganic fertilizers, integrated nutrient management improved maize production, absorption of nutrients, and economic return.	[81]
Uganda	Evaluate cattle manure and inorganic fertilizer usage in central Ugandan smallholder farms.	Cattle manure application resulted in high yields and reduced production costs. Major problems of cattle manure use included weight and bulkiness, labor, insufficient quantities, and high transportation and application costs. Most farmers supplemented with other animal manures but never used inorganic fertilizer due to costs and lack of capital.	[82]
Nigeria	Evaluate maize growth and yield using fortified organic fertilizers vs. inorganic fertilization.	Combining poultry manure and chemical fertilizer improved maize nutrient availability and performance.	[83]
Nigeria	Examine the impact of combining ammonium nitrate and goat manure treatment on soil nutrient availability and okra performance.	The highest plant height, leaf area, and leaf count were reached using 8 t/ha^{-1} goat manure + 200 kg/ha^{-1} urea fertilizer. With 8 t/ha^{-1} goat manure + 200 kg/ha^{-1} urea fertilizer, there was a significant increase in fruit weight, flowering days, number, diameter, and length.	[84]
Ethiopia	Evaluate the impact of cow manure and inorganic fertilizer on potato growth and yield.	Integrated farmyard manure and commercial NP fertilizers improved potato tuber yield, potentially reducing production costs. The integrated approach enhanced soil properties for sustainable crop production.	[85]
Uganda	Examine combined cattle manure and mineral fertilizers on *Pennisetum purpureum* fodder growth characteristics.	Sole application of composted cattle manure or combination with mineral fertilizers improved the growth of *Pennisetum purpureum* fodder. Cattle manure and mineral fertilizers produced similar fodder quantities. A combination of composted cattle manure and mineral fertilizers reduced fertilizer costs.	[86]

Table 1. *Cont.*

Country(s) of Study	Aim(s) of Study	Main Finding(s)	Reference
Kenya	Investigate the long-term impacts of organic and inorganic soil fertilization on soil organic matter content functional groups and the relationship between the composition of soil organic matter content functional groups and maize (*Zea mays*) grain yields.	Long-term use of organic fertilizers alone or combined with inorganic fertilizers increased maize yield and soil C sequestration potential.	[87]
Kenya	Measure soil greenhouse gas (GHG) emissions in central Kenya using static chambers during maize cropping seasons with four soil amendment treatments: animal manure, inorganic fertilizer, mixed manure, and no N control.	Animal manure amendment increased CO_2 emissions, N_2O emissions, and maize yields but had the lowest N_2O yield-scaled emissions. Manure and inorganic fertilizer significantly increased CH_4 uptake and N_2O yield-scaled emissions. While animal manure may raise total GHG emissions, the concurrent rise in maize yields resulted in lower yield-scaled GHG emissions.	[88]
Ethiopia, Ghana, Kenya, Malawi, Nigeria, Rwanda, Tanzania, Uganda, Zambia, Zimbabwe	Quantify increased grain yield, rain usage efficiency, and nitrogen (AEN) and phosphorus (AEP) agronomic efficiency through integrated soil fertility management (ISFM). Determine ideal soil fertility management conditions. Contrast yield responses to soil fertility management with and without the use of cattle manure only.	ISFM treatments improved grain yields by 3 t ha^{-1} more than cattle dung or inorganic fertilizer alone. Compared to greater application rates, sole application of cattle dung produced lower yields but higher AEN and AEP.	[89]
Ethiopia	Review the contribution of integrated nutrient management practices for sustainable maize crop productivity.	Combined application of inorganic fertilizers with different sources of organic manures enhanced crop productivity, nutrient uptake, and soil nutrient status in maize-based cropping systems.	[90]
Egypt	Examine different fertilizer effects on maize yield growth, productivity, and quality.	Organic materials yielded more, and combined use reduced chemical fertilizer costs and environmental hazards. Best practice: use of a combination of sheep manure, compost, and Ureaform to achieve high maize growth, yield, and quality and improved soil properties	[91]

4.2. Level 2: Substitution of Agroecological Inputs and Practices and the Principle of Improving Animal Health

Gliessman Transition Level 2 (GLT-2) of agroecological transition involves substituting conventional inputs and practices with sustainable alternatives [31]. Agroecological principles strive to replace harmful inputs, such as chemical fertilizers overutilization, and pesticides, by adopting the use of biofertilizers, e.g., animal manure and plant bioactive compounds, and traditional remedies to address common ailments in small ruminant production systems, including diarrhea and parasitic and respiratory infections [92,93]. In terms of a better animal health outcome, several strategies that substitute conventional inputs are shown in Table 2. Additionally, integrating probiotics and other microbial supplements (e.g., direct-fed microbials) can optimize gut health in small ruminants, enhancing nutrient absorption and reducing the risk of disease occurrence [94–96] (Table 2). The various agroecological methods and strategies outlined in Table 2 exhibit a shared emphasis on holistic and natural approaches to enhance small ruminant health and productivity. These include integrated farming systems with rotational grazing, utilization of organic acids, integration of plant bioactive compounds, and the application of probiotics and prebiotics. Despite regional variations, the common objective across these methods is to optimize animal health, immunity, and growth. They collectively highlight the potential of agroecological approaches in promoting sustainable and environmentally friendly small ruminant production worldwide, with the aim of reducing parasitism, enhancing nutrient utilization, and fostering healthier grazing environments.

In organic sheep-farming systems, practices like regular pasture rotation can effectively reduce nematode larvae [97]. Alternating grazing between cattle and sheep can also reduce parasite burdens in sheep. Additionally, feeding lambs with chicory or tannin-rich plants like sulla or wilted cassava foliage can enhance their health and decrease their dependency on chemical drugs [98,99]. Additionally, allowing animals to exhibit self-medication behavior by ensuring they have access to multispecies forages typically part of their diet that contain bioactive ingredients can improve their health [100,101].

Incorporating agroecological practices in small ruminant production systems can involve the use of improved breeding and selection techniques to develop more resilient and disease-resistant animals. This can be accomplished through selective breeding programs targeting desirable traits like disease resistance, fecundity, and growth rate. Using indigenous and local breeds that are naturally adapted to local environments and often more disease-resistant can lessen reliance on external inputs like anthelmintics and antibiotics. Goats, for instance, are highly adaptable to harsh conditions and can conserve urine during droughts, making them an ideal option for arid environments [10,102]. Furthermore, native breeds and species that have evolved in tropical climates are typically more resistant to endoparasites and ticks [97,103,104]. Selective breeding programs can help increase the resistance of sheep to nematodes, which has been proved through classical quantitative methods [105].

Agroecological animal health management uses sustainable and holistic methods to maintain and improve the health and welfare of farm animals, taking into account the interconnections between animals, the environment, and human society, also known as the 'One Health concept'. According to the WHO [106], the One Health concept emphasizes human, animal, and environmental health interconnection. Agroecological animal health management aligns with this concept by recognizing that animal health and welfare are directly linked to the health of the surrounding ecosystem and human communities. The use of sustainable and holistic methods in agroecology promotes a healthier environment, which in turn benefits both animal and human health.

Table 2. Examples of substitution of agroecological inputs and practices used to improve small ruminant health.

Strategy	Interventions	Impact	References
Farming system	Multispecies livestock system, rotational grazing	Cograzing lambs with cattle reduced nematode eggs and gastrointestinal nematode excretion; rotational grazing reduced fecal egg excretion and mortality.	[107,108]
Organic acids	Use of formic acid, fumaric acid, malic acid, formic acid, and their combinations	Reduced ruminal microbiota, digestibility, and proteolysis while increasing methane emission and total gas production.	[109,110]
Plant bioactive compounds	Use of condensed tannins, medicinal plants, chicory	Improved feed intake, growth, immunity, and reproduction and reduced emissions and parasitism.	[92,98,111,112]
Probiotics and prebiotics	Use of direct-fed microbials (DFMs), Rumen Enhancer (RE)3, lactic acid bacteria as putative probiotic, dry yeast with viable yeast cell	Enhanced ruminal acidosis, immune response, gut health, and productivity and reduced pathogen emissions; maintained balance, improved growth performance, and potentially replaced antibiotics.	[94,95,113–118]

4.3. Level 3: Redesigning Agroecosystems

Gliessman Transition Level 3 (GLT-3) represents a major shift in the design of agroecosystems. This pathway involves diversifying farm operations and managing the interactions between agroecosystem components [41]. The objective is to establish a self-sufficient, resilient, and sustainable agroecosystem that embodies the principles of agroecology and supports both human and planetary health [119]. This pathway offers a vision for a more holistic, integrated, and sustainable future of agriculture that aligns with the principles of agroecology. By developing complex, multifunctional agroecosystems, farmers have the power to reform agriculture and create a more sustainable future for everyone.

This level is vital for achieving agroecological transitions as it emphasizes the integration of diverse components and the promotion of biodiversity, synergy, soil health and recycling. The agroecological principle of synergy emphasizes the importance of creating mutually beneficial relationships between different components of the agroecosystem, while biodiversity preservation helps to maintain ecological resilience and improve overall ecosystem function and recycling, promoting sustainability and reducing waste through closed nutrient cycles. Gliessman's step-by-step transition approach recommends the incorporation of small ruminants as a practical and effective way for farmers to transition toward more sustainable and resilient agroecosystems that benefit both animal and human health.

4.3.1. The Principles of Preserving Biodiversity, Synergy, and Soil Health in Redesigning Agroecosystems

Several agroecological practices and techniques can be used to redesign agroecosystems for greater biodiversity conservation. One such practice is the integration of small ruminants into agroforestry systems. Agroforestry involves the deliberate planting of trees, shrubs, and other perennial plants into crop and animal-farming systems to provide multiple benefits, such as soil conservation, improved microclimate, and enhanced biodiversity [120–122]. Various authors [123–126] have examined how agroforestry systems contribute to biodiversity and have identified five major roles: providing habitats for species that can tolerate some disturbance; preserving germplasms of sensitive species; reducing the rates of natural habitat conversion; creating connectivity between habitat remnants; and providing other ecosystem services. Agroforestry systems that integrate trees and shrubs with grazing animals not only promote biodiversity conservation but also provide additional income streams for farmers through the production of fruits, nuts, and timber [122].

Other practices, such as rotational grazing practices, which allow pasturelands to rest and recover, and intercropping, where multiple crops are grown together, improve soil health by increasing the diversity of plant species, improve nutrient cycling, reduce soil erosion, and promote biodiversity conservation [127–129]. Integrating goats or sheep with cattle in agroecosystems through rotational grazing can improve pasture biodiversity and enhance the nutritional quality of forage for animals, reducing the risk of parasite and pathogen infestations [22,108]. Further, animals can be raised in intercropping systems to graze on crop residue, contributing to soil fertility and pest management. By incorporating a variety of forage species (e.g., alfalfa, sainfoin, birdsfoot trefoil, ryegrass, and clover) into pastures, a more diverse and nutritious diet can be provided to animals and can promote biodiversity in the ecosystem, as well as helping to make the pastures more climate-resilient [130–132]. Integrating multiple livestock species into crop production or agroforestry systems, such as using chickens to control pests in orchards or goats, sheep, and cows to fertilize fields, may increase system effectiveness and decrease the requirement for synthetic inputs [108].

The effectiveness of agroecological practices in enhancing and preserving biodiversity in livestock production can be a complex and controversial topic. Some studies have suggested that agroecological approaches aiming to promote ecological processes and reduce external inputs can positively impact biodiversity in livestock systems [24,133–135].

For example, agroforestry systems combining trees and livestock grazing can improve biodiversity and help maintain landscape diversity [24]. However, other studies have highlighted the challenges of balancing livestock production with biodiversity conservation objectives in agroecological systems [136]. For example, grazing livestock can negatively impact sensitive ecosystems and species, and it can be challenging to manage grazing intensity and timing to minimize these impacts [136–138]. In addition, agroecological approaches may require more land to produce the same amount of food as intensive systems, leading to land use change and fragmentation of natural habitats [139].

The efficiency of agroecological methods in improving, and sustaining biodiversity in livestock production is influenced by various contextual factors, including the specific production system, the surrounding landscape and environment, and the goals and values of the stakeholders involved [140–142]. Therefore, it is essential to carefully consider the trade-offs and synergies between livestock production and biodiversity conservation in each context and to use a participatory and adaptive approach to decision making that takes into account the diverse perspectives of different stakeholders.

Agroecology can also be integrated at the landscape or supply chain level by linking large-scale crop and livestock production through trade in feed or manure [143]. For example, integrating livestock into cropping systems can result in soil fertilization through manure, weed control through grazing, and reduced reliance on synthetic inputs. Additionally, crop residues can feed the animals, creating a symbiotic relationship between crops and livestock, leading to improved productivity and sustainability. Incorporating agroforestry practices, such as trees, into the farming landscape can bring multiple benefits, such as shade and habitat for animals and diversifying the production system to include fruit and timber products.

To adopt agroecology and the principle of synergy into small ruminant production systems, farmers can take practical steps such as integrating cropping and livestock husbandry, using compost or vermicompost made from animal waste, incorporating agroforestry practices, promoting biodiversity, and managing water effectively. These actions can create positive interactions between different components of the production system, leading to increased productivity, sustainability, self-sufficiency, and resilience.

Soil health plays a vital role in the redesign of agroecosystems, as healthy soil supports better plant growth, nutrient cycling, water retention, and overall ecosystem functioning. In sustainable small ruminant production, agroecological practices that prioritize soil health can lead to more resilient and productive systems. For instance, introducing livestock into crop fields for grazing or using crop residues as feed can improve soil health. Livestock contributes to nutrient recycling through manure deposition, which enriches the soil. Integrating trees with forage crops and small ruminants, as seen in agroforestry systems, can improve soil health by increasing organic matter through leaf litter and root decomposition. Trees also help prevent soil erosion and contribute to nutrient cycling. Further practices, such as planting cover crops between forage crops, help protect the soil from erosion, improve soil structure, and enhance microbial activity. Leguminous cover crops can fix nitrogen, reducing the need for synthetic fertilizers.

4.3.2. Redesigning Agroecosystems and the Principle of Recycling

GLT-3 emphasizes the importance of recycling in achieving sustainable agroecosystems [31]. The goal of agroecological practices is to imitate natural ecosystems and boost the recycling of nutrients, water, and biomass, resulting in improved resource utilization and decreased waste and pollution [144]. Recycling can be achieved both on the farm and at the larger landscape level by integrating various components and activities.

The utilization of organic materials and byproducts in small ruminant systems through feed recycling is a key component of sustainable agriculture. This approach involves using farm and local waste to produce feed for animals rather than relying solely on purchased feed. Doing so promotes closed nutrient cycles, reduces waste, and enhances farm efficiency and autonomy, leading to a more sustainable and resilient food system.

Agroecological animal husbandry practices play a critical role in promoting recycling. For example, silage production from crop residues and forages, composting of food waste and manure, vermiculture, insect production, and incorporating agroforestry can all contribute to producing high-quality feed for small ruminants while reducing waste and enhancing soil health and fertility. Feed recycling in small ruminant systems offers multiple benefits beyond environmental sustainability, including reducing costs for farmers and increasing their resilience to market and climate fluctuations. Farmers can reduce their dependence on purchased inputs and improve their self-sufficiency by utilizing on-farm and locally available waste to produce animal feed. This can contribute to developing more equitable and sustainable food systems.

The ideal method for feed recycling in agroecological systems remains a matter of debate, and there are various challenges and potential risks to consider. For example, there may be concerns about the nutritional value of the recycled feed and potential risks associated with feeding recycled materials from unknown sources (Table 3). To address these concerns, strict sanitation and monitoring protocols must be implemented to ensure the safety and quality of the feed. It is also important to note that the most appropriate approach to feed recycling depends on the unique goals, resources, and limitations of the agricultural system.

Table 3. Risks associated with feeding recycled material from unknown sources in agroecological systems.

Potential Risks	**Explanation**	**References**
Contaminants and toxins	Recycled feed from unknown sources may contain contaminants, pesticides, heavy metals, or toxins that could negatively impact animal health.	[145–149]
Disease transmission	Feeding recycled materials from unknown sources can introduce infectious diseases and pathogens into a herd or flock, leading to disease outbreaks.	[150–152]
Imbalanced nutritional composition	The nutritional content of recycled feed may not be well-balanced, lacking essential nutrients or having an inappropriate nutrient ratio for livestock.	[153]
Spread of antimicrobial resistance	Feeding recycled materials can contribute to the spread of antimicrobial resistance, making infections harder to treat in both animals and humans.	[154]

Despite these challenges, the benefits of feed recycling in agroecological systems are undeniable. For example, it can reduce costs, improve efficiency, promote self-sufficiency, increase biodiversity, and reduce the environmental impact of small ruminant production. Additionally, feed recycling can help small ruminant farmers become more resilient to market and climate shocks as they become less reliant on purchased inputs.

4.4. Level 4: Reconnecting Producers and Consumers and the Principles of Economic Diversity and Cocreation of Knowledge

Gliessman’s Transition Level 4 (GLT-4) in agroecology emphasizes the need for reconnection between producers and consumers of food [31]. The agroecological principles of economic diversity and cocreating knowledge align with this transition level and emphasize the importance of involving all stakeholders in developing and implementing agricultural practices.

Further, GLT-4 endeavors to establish a direct link between food producers and consumers by creating alternative food networks [31]. In this transformational approach, priority is given to direct sales through channels such as farmers’ markets, community-supported agriculture, and other direct-marketing methods to promote fairness and justice [41]. The focus is on fostering closer and more transparent relationships between producers and consumers and breaking down existing barriers between them. Producers can receive a fair price for their products through direct sales channels.

By engaging in economic diversity, farmers can broaden their revenue sources, thereby lowering their vulnerability to market swings, climatic variability, and other risks [155]. By participating in multiple income-generating activities, farmers spread their risk and decrease their dependence on a single source of income [156]. This risk diversification promotes economic stability and resilience across the board. Diversifying products and income streams positively impact farmers' market access and bargaining power. Offering a variety of products allows farmers to cater to diverse consumer demands and tap into different market opportunities (Table 3).

Cocreation of agricultural knowledge is gaining recognition as a more effective and sustainable approach than traditional top-down knowledge transfer methods [157,158]. This is because cocreation involves the active involvement and collaboration of stakeholders, including farmers, researchers, extension agents, and others, in designing and implementing sustainable agriculture systems [159,160]. By engaging farmers and other stakeholders in the cocreation process, there is a better understanding of local knowledge, needs, and challenges, which leads to more relevant and context-specific solutions. This approach also promotes the empowerment of farmers and enhances their capacity to make informed decisions about their farming practices and to adapt to changing conditions [161,162].

Demonstration farms are also an effective method of cocreation in agriculture [163,164]. They serve as platforms for testing and demonstrating sustainable agriculture practices and technologies [164]. By involving farmers and other stakeholders in establishing and managing demonstration farms, they can gain hands-on experience and knowledge of sustainable practices and technologies, which can then be adapted and applied to their farms.

To better integrate these practices into African food systems for agroecological transitions in small ruminant production, there needs to be greater collaboration between farmers, researchers, and policymakers. This can be achieved through farmer field schools (FFSs), participatory research and extension approaches (PREAs), and agroecology networks [161,165,166]. Farmer field schools bring together small ruminant farmers to share knowledge and experiences, while PREAs involve farmers in research activities to cocreate knowledge. Agroecology networks connect small ruminant producers with researchers, extension officers, and other stakeholders to facilitate the cocreation of knowledge. Policymakers in African countries should prioritize a tailored implementation of agroecological practices, aligning strategies with each nation's distinctive socioeconomic, environmental, and cultural contexts. This can be achieved through investments in localized research initiatives, fostering collaboration with local agricultural experts and communities to identify region-specific challenges and solutions. Adequate resources should be allocated to strengthen extension services, ensuring the widespread dissemination of knowledge about sustainable small ruminant farming practices.

There are different perspectives regarding cocreation in the context of livestock production in agroecology. While cocreation has the potential to lead to more sustainable and equitable livestock systems by involving farmers and other stakeholders in the process, some challenges and limitations need to be considered. One of the main challenges of cocreation in livestock production is the complexity and diversity of livestock systems. Livestock production systems can vary significantly in terms of species, breeds, production objectives, and cultural and social contexts [3]. This complexity can make it challenging to engage stakeholders in the cocreation process and develop locally relevant and socially acceptable solutions.

It is essential to acknowledge that cocreation may not always result in the most effective or efficient solutions [167]. The cocreation process often involves compromises and trade-offs, which can lead to solutions that may not fully address the needs and objectives of all stakeholders [168]. Cocreation can be a valuable approach in livestock production in agroecology, but it is essential to consider the challenges and limitations and to carefully assess whether it is the most appropriate approach in a given context. Alternative strategies, such as top-down policy or bottom-up grassroots organizing, may also be necessary for some scenarios [158,169–172].

4.5. Level 5: Global Reform and the Principle of Cocreation of Knowledge

Cocreation of knowledge is a vital principle in the transition toward sustainable, equitable, and resilient agroecosystems. Gliessman's Transition Level 5 (GLT-5)—global reform across food environments and food supply chains—highlights the importance of knowledge cocreation on a global scale [31]. GLT-5 is a transformative approach to building a new global food system that embodies the values of involvement, locality, fairness, and justice. This pathway represents a fundamental change in how food production, distribution, and consumption are approached. This level focuses on transforming food systems to address global challenges such as climate change, food insecurity, and social injustice, and the cocreation of knowledge is a critical component of this transformation. The GLT-5 pathway also prioritizes fairness and justice, including food sovereignty, empowering communities to manage their food systems and supporting fair trade and other initiatives that strive for an equitable distribution of resources and benefits within the food system.

Adopting agroecological practices in small ruminant production in LMICs can promote the sustainable use of natural resources, support small-scale farmers' livelihoods, and enhance farming systems' resilience to climate change. The Via Campesina food sovereignty [173–178], Food Justice Movement [179,180], and Slow Food movement are initiatives promoting sustainable agriculture and food systems. They advocate for the rights of small-scale farmers to access land, water, and resources, as well as recognize and protect traditional knowledge and practices. They also encourage producing and consuming healthy, locally grown food that is culturally appropriate and environmentally sustainable.

Other movements in sub-Saharan Africa working toward this goal include the Alliance for Food Sovereignty in Africa (AFSA), a network of small-scale farmers, pastoralists, and indigenous peoples advocating for policies and practices supporting agroecology and food sovereignty. The AFSA prioritizes environmental sustainability, social equity, and economic viability in community-based approaches to small ruminant production. The Comprehensive Africa Agriculture Development Program (CAADP)—African Union Agenda 2063 initiative aims to enhance agricultural productivity and food security across the continent by adopting sustainable agriculture practices.

Similarly, the Enhanced Smallholder Agribusiness Promotion Program (E-SAPP) of the International Fund for Agricultural Development (IFAD) supports small-scale farmers and rural entrepreneurs in developing profitable and sustainable agribusinesses. In addition, the Global Alliance for Climate-Smart Agriculture (GACSA) promotes the adoption of climate-smart agriculture practices that enhance food security, resilience, and productivity while reducing greenhouse gas emissions and contributing to climate change adaptation.

The transition to level 5 of agroecology in small ruminant production in sub-Saharan Africa requires a multistakeholder approach involving farmers, government agencies, civil society organizations, and private sector actors. Working together to promote sustainable and equitable small ruminant production can result in a more just and resilient food system for all.

5. Perspective on Agroecological Principles Applied to Small Ruminant Systems in Low- and Middle-Income Countries

The practices, benefits, and challenges of implementing the eight agroecological principles as related to the GLT are summarized in Table 4. It is important to note that these practices cannot be implemented in isolation and should be integrated into a broader agroecological approach that takes into account the social, cultural, and economic factors that influence small ruminant production in LMICs. This includes promoting farmer-led research and extension, strengthening local institutions and networks, and supporting policies and regulations that incentivize sustainable and equitable food systems.

Table 4. Summary of Gliessman's level of transition pathways and related agroecological principles as applied to small ruminant systems in low- and middle-income countries (LMICs): practices, benefits and challenges.

Gliessman's Level	Related Principle	Practical Examples	Integration into African Food Systems	Ecological Production Techniques and Opportunities	Benefits	Challenges
Level 1: Practices that increase efficiency	Input reduction	Using local feed sources and reducing reliance on imported feed Reducing the use of chemical fertilizers and pesticides Limiting the use of antibiotics and growth hormones in animal feed Using drought-tolerant forages and pasture management to minimize the use of water and chemical fertilizers	Promoting the use of locally available feed resources, such as crop residues and forage Encouraging farmers to adopt integrated pest management techniques Providing education and training to farmers on the use of natural fertilizers Promoting the use of low-input production systems and developing policies that support input reduction	Agroforestry Rotational grazing Crop–livestock integration	Reduced cost of production Reduced environmental impact Healthier animals Increased resilience to climate change	Limited access to alternative inputs Lack of knowledge and skills to optimize the use of available resources Resistance to transition from conventional practices Limited availability of low-input technologies and knowledge gaps among farmers
Level 2: Substitution of agroecological inputs and practices	Animal health	Using natural remedies and biocontrol agents to treat and prevent disease	Encouraging farmers to adopt natural remedies and supplements Providing education and training on the use of probiotics Conducting research for the creation of evidence of use	Herbal medicine, probiotics, and biocontrol agents	Reduced cost of animal health management Reduced reliance on synthetic inputs	Limited availability of natural remedies Lack of knowledge, skills, and scientific evidence to use natural remedies effectively Limited knowledge of the sustainability of raw materials

Table 4. *Cont.*

Gliessman's Level	Related Principle	Practical Examples	Integration into African Food Systems	Ecological Production Techniques and Opportunities	Benefits	Challenges
Level 3: Redesigning agroecosystems	Synergy, recycling, soil health, preserving biodiversity	Implementing integrated crop–livestock systems and agroforestry Intercropping with legumes to fix nitrogen in the soil Incorporating crop residues into animal feed Composting animal manure and crop residues for use as natural fertilizer Advocacy and policy reform to promote agroecology and biodiversity conservation Encouraging the use of indigenous breeds of small ruminants	Promoting integrated crop–livestock systems and agroforestry to promote ecological processes Encouraging farmers to adopt intercropping practices Providing education and training on crop residue management Promoting the use of composting techniques Promoting the development and implementation of policies that support agroecology and biodiversity conservation Establishing breeding programs for indigenous small ruminant breeds	Agroforestry, integrated crop–livestock systems, conservation agriculture Advocacy and policy reform, participatory governance, ecological intensification	Improved soil fertility, increased biodiversity, reduced environmental impact, improved resilience to climate change Reduced costs Improved animal nutrition Improved environmental sustainability, increased biodiversity, improved livelihoods for smallholder farmers	Lack of knowledge and skills to implement integrated systems, limited access to diverse genetic resources Limited knowledge and understanding of intercropping practices Limited access to appropriate crop residues Limited knowledge and understanding of composting techniques Limited political will and commitment, competing interests and priorities Limited access to breeding programs for indigenous small ruminant breeds Limited interaction within the small ruminant holder value chain stakeholders

Table 4. *Cont.*

Gliessman's Level	Related Principle	Practical Examples	Integration into African Food Systems	Ecological Production Techniques and Opportunities	Benefits	Challenges
Level 4: Re-connection between producers and consumers	Economic diversification, cocreation of knowledge	Raising many species in a pastoral system Sale of animal byproducts Direct marketing Encouraging farmer participation in research and development Facilitating farmer-to-farmer knowledge sharing Developing local markets and value chains Farmer field schools (FFSs) bringing together small ruminant farmers to share knowledge and experiences Participatory research and extension approaches (PREAs) involving farmers in research activities to cocreate knowledge Creation of agroecology networks to connect small ruminant producers with researchers, extension officers, and other stakeholders to facilitate the cocreation of knowledge	Promoting the local animal industry Strengthening small ruminant industry chains and farmer–consumer connections Engaging farmers in research and development projects Providing platforms for farmer-to-farmer knowledge sharing Promoting the development of local markets and value chains through participatory processes Providing support to existing farmer networks in Africa and creating new ones to facilitate knowledge cocreation and sharing Supporting participatory research and extension approaches that involve farmers in the development and dissemination of agroecological practices Developing policies that support knowledge cocreation and sharing between different stakeholders in the food system	Additional income, product diversification, and market expansion Encouraging farmers' markets Participatory research, participatory value chain development Community-supported agriculture	Risk mitigation Increased resilience Multiple strains of income Improved knowledge and understanding of sustainable agricultural practices Increased adoption of sustainable practices Improved access to markets, increased income for smallholder farmers Improved food security for local communities Improved small ruminant production through knowledge cocreation and sharing Increased farmer participation and ownership in agroecological transitions Enhanced livelihoods for small ruminant producers through increased productivity and profitability	Limited resources for research and development Limited access to information and communication technologies Limited infrastructure and access to markets, limited access to financial resources Limited access to knowledge and information among small ruminant farmers in LMICs Limited resources and infrastructure for supporting knowledge cocreation and sharing Limited policy support for the cocreation of knowledge and participation of small ruminant producers in agroecological transitions

Table 4. *Cont.*

Gliessman's Level	Related Principle	Practical Examples	Integration into African Food Systems	Ecological Production Techniques and Opportunities	Benefits	Challenges
Level 5: Global reform	Cocreation of knowledge	The Via Campesina food sovereignty Food Justice Movement Slow Food movement Alliance for Food Sovereignty in Africa (AFSA) Comprehensive Africa Agriculture Development Program (CAADP) International Fund for Agricultural Development (IFAD)—Enhanced Smallholder Agribusiness Promotion Program (E-SAPP) Global Alliance for Climate-Smart Agriculture (GACSA)	Advocating for policies and practices that support agroecology and food sovereignty Promoting community-based approaches to small ruminant production Emphasizing the importance of small-scale producers Prioritizing sustainable, community-based approaches to small ruminant production	Promoting ecological and social sustainability of small ruminant production systems	Creating a more sustainable and equitable food system Benefitting small ruminant producers, consumers, and the environment Supporting small-scale producers	Implementing the fundamental transformation of the entire food system Addressing the root causes of hunger and poverty Requires systemic changes in policies and institutions Resistance from large-scale industrial producers

Analyzing agroecological practices globally reveals consistent patterns, offering insights into sustainable small ruminant production. These patterns connect specific strategies to outcomes, highlighting successful agroecological approaches applicable to countries with similar economic contexts. The practices outlined in Table 4 reflect a universal inclination toward sustainable and natural approaches. One prominent aspect is the emphasis on reducing reliance on chemical inputs, such as feed additives and synthetic medicines. Across diverse regions, there is a shared commitment to adopting local feed sources, natural remedies, and biocontrol agents. This unified approach aims to minimize environmental impact, reduce production costs, and enhance the health and wellbeing of small ruminants. Another focus is on ecosystem health. Recurring strategies include integrating crop–livestock systems, practicing agroforestry, and emphasizing soil health and biodiversity preservation. These practices, seen across continents, signify a global shift toward holistic farming systems. By interweaving crops and livestock, optimizing soil health, and preserving biodiversity, farmers enhance the resilience of their agricultural ecosystems while promoting sustainable practices.

Furthermore, there is a strong emphasis on community engagement and cocreation of knowledge. Direct marketing, farmer-to-farmer knowledge sharing, and participatory research initiatives are prevalent strategies. These methods foster local economies, empower farmers, and enrich agricultural knowledge. By connecting producers and consumers directly and facilitating collaborative learning, communities are better equipped to adopt and adapt agroecological practices. Addressing challenges outlined in Table 4 requires the following:

(i) Skills and capacity building: Strengthening local communities through specialized training programs is critical for unlocking the potential of agroecology in small ruminant farming in African countries. These programs provide practical knowledge to farmers, extension workers, and practitioners, focusing on sustainable livestock management, natural remedies, and ecofriendly pest control techniques. By imparting these skills, individuals can implement agroecological practices effectively, promoting environmentally friendly methods in small ruminant production.

(ii) Research-based knowledge generation: Investing in research focused on traditional natural remedies is vital. Rigorous scientific studies validate indigenous knowledge, refine traditional practices, and enhance their effectiveness. Collaborative research involving researchers and farmers ensures that valuable traditional knowledge is preserved and improved. Sharing research findings through accessible channels equips farmers with practical, evidence-based information, enabling them to use effective natural remedies in small ruminant farming.

(iii) Appropriate technologies: In overcoming challenges in harnessing agroecology for small ruminant production, a strategic focus on appropriate technology is key. Implementing fodder choppers, feed millers, and solar-powered devices ensures sustainable practices. Cooperative-owned machinery use enhances efficiency and accessibility, and it becomes an incentive for further use for other community farmers who may not be preview to its benefits. Education and training programs empower farmers to operate and maintain machinery, while community-owned cooperatives make equipment collectively accessible. Encouraging local innovations fosters tailored solutions and promotes sustainability and productivity in small ruminant farming.

(iv) Knowledge exchange networks and policy support: Creating platforms for sharing knowledge and supportive policies are fundamental. Forums connecting farmers, researchers, and policymakers allow the exchange of best practices. Farmer cooperatives and community-based organizations serve as valuable hubs for sharing knowledge. Policymakers' roles are crucial: policies encouraging sustainable practices and providing financial support create a conducive environment. When these policies align with local needs, they promote the widespread adoption of agroecological methods in small ruminant farming across Africa.

At a broader level, there is a collective push for policy reform and global advocacy. Movements like Food Sovereignty and initiatives like the CAADP reflect a shared vision for systemic agricultural transformation. The goal is to address the root causes of hunger and poverty. By advocating for policies supporting agroecology and promoting equitable food systems, these initiatives aim to create lasting, positive change on a global scale. In summary, the common ground across these agroecological practices lies in the shared commitment to sustainability, natural resource optimization, community engagement, and policy advocacy. These practices represent a united effort to create environmentally friendly, economically viable, and socially equitable small ruminant production systems across diverse LMICs. The challenges, such as limited resources and resistance from existing systems, underscore the need for collaborative efforts and supportive policies to fully leverage the potential of agroecology in small ruminant farming.

Countries with comparable economic contexts can adopt the identified practices tailored to their specific agricultural landscapes. By emphasizing reduced chemical inputs, local resource utilization, ecosystem integration, community engagement, and policy advocacy, similar economies can enhance the sustainability and productivity of their small ruminant production systems. Scientifically analyzing these regularities provides a robust foundation for formulating evidence-based policies and practices, ensuring the widespread adoption of agroecological approaches across diverse regions with similar economic profiles.

6. Concluding Remarks

Our analysis of the application of agroecology to small ruminant production systems in low- and middle-income countries underscores its potential as a valuable approach toward sustainable livestock production. Achieving more agroecological and sustainable small ruminant production systems in these countries necessitates a comprehensive and context-specific systemic approach. This should entail promoting farmer-led research and extension, strengthening local institutions and networks, and supporting policies and regulations that incentivize sustainable and equitable food systems. The eight agroecological principles and Gliessman’s transition levels offer a valuable framework for guiding this transition, with the caveat that these principles and levels are not mutually exclusive and can overlap in practice.

Integrating agroecological practices in small ruminant production systems can significantly contribute to achieving food security and sustainability goals in African food systems. However, scaling up these practices faces several challenges, including limited credit access, land tenure issues, and inadequate extension services. Overcoming these obstacles requires promoting policies that support agroecological transitions and providing technical assistance and training to small-scale farmers.

It is also essential to acknowledge that sustainable and equitable small ruminant production systems require a long-term perspective prioritizing environmental sustainability, animal welfare, and social equity. While there may be trade-offs between short-term economic gains and long-term sustainability, it is crucial to prioritize the health and wellbeing of small ruminants, farmers, and the environment in transitioning toward more sustainable food systems. By adopting a systemic approach that prioritizes sustainability and equity, we can realize the potential of agroecology as a promising approach for sustainable small ruminant production systems in low- and middle-income countries.

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