



(REVIEW ARTICLE)



Enhancing climate resilience and sustainability through agroecology: A review of key principles and recent advances (2020–2025)

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Abstract

Agroecology has emerged as a comprehensive and integrative framework that combines ecological science, traditional knowledge systems, and participatory methodologies to reconfigure food systems in response to the interlinked crises of climate change, biodiversity loss, and socio-economic inequality. This review synthesizes recent scientific developments (2020–2025), examining the core principles of agroecology, its contributions to biodiversity conservation and climate resilience, and its transformative potential in fostering circular sustainability and farmer participation. Drawing on a wide range of global and Mediterranean case studies, including olive-based systems in Turkey, the paper highlights how agroecological practices can reduce dependency on external inputs, promote ecological regeneration, and enhance socio-ecological resilience. The review concludes with a critical discussion on policy integration, knowledge co-production, and enabling conditions for scaling agroecology across both smallholder and commercial farming systems.

Keywords: Agroecology; Climate resilience; Biodiversity; Sustainability; Farmer participation; Knowledge co-production; Ecological principles

1. Introduction

In the context of escalating climate instability, environmental degradation, and deepening socio-economic inequities, agroecology has gained global prominence as a comprehensive and transformative approach to rethinking food and agricultural systems. Departing from the conventional agricultural paradigm which prioritizes yield intensification through synthetic inputs, monocultures, and globalized supply chains—agroecology offers a framework that merges ecological science, traditional and Indigenous knowledge, and participatory governance mechanisms. Its scope extends beyond environmental problem-solving to include a critique of, and response to, the systemic injustices and power imbalances embedded in industrial food systems.

Emerging in Latin America in the late 20th century as both a grassroots movement and a scientific domain, agroecology has evolved into a globally recognized transdisciplinary field that integrates science, place-based farming practices, and social mobilization. Institutions such as the Food and Agriculture Organization (FAO) and the High-Level Panel of Experts (HLPE) on Food Security and Nutrition have acknowledged agroecology's relevance to the Sustainable Development Goals (SDGs) particularly those related to climate action, biodiversity preservation, poverty alleviation, and inclusive rural development.

Agroecology is founded on a series of core principles that include the promotion of biodiversity, closed-loop nutrient cycling, reduction of external input reliance, and the empowerment of smallholder farmers through local autonomy and ecological knowledge. It values context-sensitive solutions over standardized technologies, resilience over productivity

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alone, and food sovereignty over global market dependency. In this regard, agroecology operates simultaneously as a scientific approach, a framework for sustainable practice, and a political project advocating for equity and system-wide transformation.

Over the last three decades, agroecology has undergone significant conceptual and practical expansion. While its early formulations were primarily grounded in ecological theory and localized practice, it now embodies a more integrated response to multi-dimensional global crises, including resource depletion, climate change, biodiversity loss, and socio-political marginalization. Scholars such as Altieri and Gliessman have characterized agroecology as the “ecology of food systems,” reflecting its analytical and normative capacity to address the interdependence of ecological processes and human livelihoods.

Agroecology today is widely recognized as encompassing three interconnected dimensions:

- a scientific discipline advancing ecological approaches to food production;
- a set of agricultural practices rooted in local ecosystems and knowledge systems; and
- a social and political movement committed to transforming the structures of power and inequality in agriculture (Wezel & Soldat, 2009). These dimensions have converged into a pluralistic and evolving paradigm that now serves as a foundation for reimagining agriculture as a site of regeneration, resilience, and justice.

This review focuses on synthesizing recent agroecological research published between 2020 and 2025, with particular emphasis on five interrelated themes:

- The foundational ecological and socio-political principles of agroecology;
- Agroecology’s contribution to biodiversity protection and climate adaptation;
- The role of farmers in co-producing knowledge and leading innovation;
- Agroecological strategies for mitigating and adapting to climate change; and
- Systemic sustainability through circular, regenerative, and low-input systems.

Through this structure, the review highlights the dynamic, multi-scalar nature of agroecological transformation. Rather than treating agroecology as a rigid set of techniques, it frames it as a living framework—adaptive, context-responsive, and deeply tied to cultural, political, and ecological realities.

In addition to synthesizing global literature, this review incorporates region-specific insights, with a focus on Mediterranean farming landscapes and olive-based systems in Turkey. These cases provide valuable evidence of how agroecology can function as both a climate resilience strategy and a tool for social empowerment, particularly in water-scarce, biodiverse, and historically marginalized rural contexts.

Despite growing recognition, agroecology still faces numerous implementation barriers. These include the hegemony of agro-industrial models, fragmented policy environments, limited public investment in agroecological research, and the exclusion of smallholders and Indigenous voices from institutional decision-making. However, the increasing alignment of agroecology with international frameworks—such as the FAO’s Scaling Up Agroecology Initiative, the European Green Deal, and the IPES-Food platform—signals growing momentum for structural transformation.

Ultimately, agroecology provides a compass rather than a one-size-fits-all solution. It guides food systems toward approaches that are ecologically regenerative, socially inclusive, and democratically governed. In a world confronting intertwined environmental and social crises, agroecology represents a scientifically grounded and morally urgent alternative to the status quo.

2. Methodology of the Review

This review is based on a systematic literature analysis of peer-reviewed scientific studies published between January 2020 and March 2025. The literature search was conducted across three major academic databases—Scopus, Web of Science, and Google Scholar—using a combination of keywords including: “agroecology,” “climate resilience,” “biodiversity,” “agroecosystem services,” “participatory farming,” and “agroecological transition.” Boolean operators (AND/OR) were employed to refine search outputs and improve specificity.

To ensure scientific relevance and quality, the following **inclusion criteria** were applied:

- Publications appearing in **Q1 or Q2** journals as ranked in relevant academic databases,
- Research focusing on agroecosystems in the Mediterranean region and the Global South,
- Studies adopting interdisciplinary perspectives, integrating ecological, social, and agronomic dimensions.
- Conversely, the exclusion criteria were:
- Non-peer-reviewed content, including opinion pieces, editorials, and grey literature,
- Publications prior to 2020,
- Technocentric or reductionist approaches lacking an agroecological framing.

In total, 121 scientific articles were reviewed in full. Following thematic screening for relevance, methodological rigor, and conceptual alignment with agroecological principles, 95 studies were selected for in-depth analysis.

3. Scientific Scope and Interdisciplinary Foundations of Agroecology

3.1. The Scope and Scientific Framework of Agroecology

Agroecology transcends the narrow conception of a production model; it is more accurately defined as the *ecology of entire food systems*, integrating ecological processes with social and economic dimensions in a cohesive framework. This review adopts this holistic lens, highlighting the essential role of societal structures and processes in enabling agroecological transformation.

A key challenge inherent in this approach is the capacity to engage with complexity and diversity in a systematic and interdisciplinary manner. Agroecology requires the integration of knowledge not only across agronomic and ecological disciplines, but also between the environmental sciences and the social sciences. This makes it both an epistemological and methodological frontier.

To understand agroecological systems, one must examine biological functions at the plot level such as pollination dynamics, nutrient cycling, pest regulation, and carbon storage while also accounting for broader ecological impacts like biodiversity loss, soil degradation, and climate variability. Equally important are social dimensions including farmers' rights, collective agency, participatory governance, and market structures. These social factors are deeply interwoven with agroecological processes and outcomes.

The academic relevance and growth of agroecology have been well-documented. For example, Wezel and Soldat (2009) provided an early mapping of its intellectual expansion, noting a sharp increase in scholarly contributions since the early 2000s. The ongoing diversification of agroecological research underscores the need to understand the evolution of its thematic scope and disciplinary intersections.

In selecting focal topics for deeper analysis, this review adopted the following prioritization criteria:

- **Scientific Maturity** – The presence of a substantial body of peer-reviewed literature post-2005;
- **Strategic Relevance** – The topic's significance in addressing food system sustainability and reducing environmental harm;
- **Prospective Impact** – Its potential to shape long-term research agendas and policy discussions.

Topics scoring highly across all three dimensions were addressed in Section 3, classified as part of the *agroecological context*. These include systemic drivers that directly or indirectly influence agricultural practices and land use. For instance, the concentration of corporate power in agri-food markets affects pricing mechanisms, farmer decision-making, and input dependency all of which have profound implications for agroecological transitions.

3.2. Core Principles of Agroecology (2020–2025)

This conceptual diagram presents the interrelated dimensions of agroecology discussed throughout this review. At its center lies the concept of Agroecological Transition, which is upheld by seven fundamental domains: Agricultural Practices, Biodiversity, Inputs and Pollution, Livestock Integration, Resource Cycling, Food Access, and Innovation and Social Learning. Each of these elements interacts dynamically, illustrating the systems-based and integrative nature of agroecological thinking.

The Agroecological Nexus Framework articulated in this section captures the multi-dimensional processes necessary for advancing agroecological transitions. At the core, the transition is conceptualized as a continuously evolving process, driven by synergistic interactions across the following key areas:

- **Agricultural Practices:** Incorporation of diversified techniques such as crop diversification, polycultures, agroforestry systems, minimal soil disturbance, and ecological pest control all aimed at reinforcing environmental balance and agroecosystem resilience.
- **Biodiversity:** Promotion of biological diversity at genetic, species, and landscape levels to ensure the functionality, adaptability, and resilience of ecosystems in the face of environmental challenges.
- **Inputs and Pollution:** Efforts to significantly curtail the application of synthetic agrochemicals (e.g., fertilizers and pesticides), with an emphasis on lowering pollution levels and enhancing the use of ecological alternatives to safeguard environmental health.
- **Livestock Integration:** A focus on merging crop and animal systems to optimize nutrient flows, improve soil quality, and strengthen the long-term economic sustainability of farm operations.
- **Resource Cycling:** The development of self-reliant systems through practices like composting, incorporation of green manures, and renewable energy use, all aimed at closing energy, nutrient, and water loops within farming systems.
- **Food Access:** Strengthening decentralized food networks by improving local distribution, ensuring equitable food availability, advancing food sovereignty, and promoting diversity in diets and nutrition security.
- **Innovation and Social Learning:** Encouraging participatory processes such as farmer-to-farmer exchanges, community-driven research, shared knowledge platforms, and capacity-building initiatives to empower producers and communities.

Together, these interconnected domains co-develop over time, reinforcing one another and generating adaptive, inclusive, and resilient agroecosystems. The relationships emphasized in this framework underscore the holistic essence of agroecology, wherein sustainable food futures are shaped through integrated system design rather than fragmented interventions.

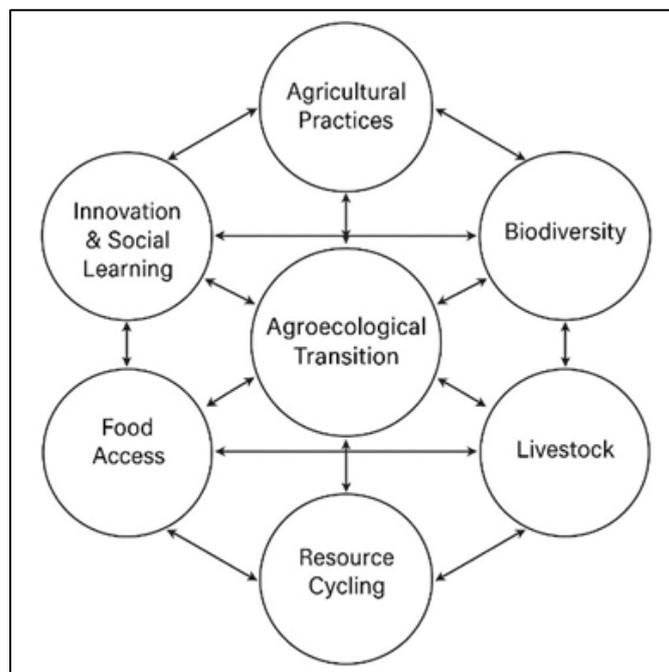


Figure 1 Agroecological Nexus Framework

3.3. Integrating Agricultural and Environmental Sciences

Similar to the foundational principles of ecology, agroecology is rooted in the examination of energy pathways, species interdependencies, and biogeochemical cycles. However, it expands beyond classical ecological inquiry by incorporating the reciprocal interactions between environmental pressures and agricultural production systems.

In the contemporary context, agricultural landscapes are influenced by a complex matrix of local, regional, and global dynamics. Variables such as land-use transformation, climatic shifts, demographic trends, and economic constraints intersect to challenge the adaptive capacity of agroecological systems. As a result, agroecological research must navigate a highly dynamic and often unpredictable environmental landscape.

Central to this endeavor are the concepts of resilience and adaptive capacity, which have become essential analytical tools in sustainability science. Core areas of inquiry include the protection of ecosystem services, the regulation of carbon flows, and the minimization of agriculture's ecological footprint all of which are critical to the advancement of agroecological understanding.

As agriculture is a fundamentally socio-cultural endeavor deeply shaped by and embedded within human institutions, it is imperative that agroecology also engage with societal structures and cultural contexts. This requires moving beyond the conventional dichotomy between nature and society, recognizing instead that human communities exist *within* ecosystems. In this sense, agriculture represents both a cause and a consequence of socio-ecological interactions.

Accordingly, the advancement of agroecological science necessitates the inclusion of social science disciplines, notably environmental sociology, political ecology, and rural development studies. These perspectives offer critical insights into how systemic social inequalities and institutional deficiencies contribute to environmental degradation. Without addressing these structural issues, sustainable agricultural futures cannot be fully realized (Guthman, 2004; Getz et al., 2012).

Thus, agroecology must be viewed not merely as an environmental science, but also as a transformative pathway for reconfiguring socio-ecological relationships. Embedding principles of justice, equity, and participatory agency into sustainability transitions is essential for building agroecological systems that are not only ecologically robust but also socially inclusive and resilient.

Traditional agronomic research has historically emphasized yield optimization at the field scale. In contrast, contemporary agroecological assessments encompass broader spatial dimensions, extending from individual plots to entire landscapes, national territories, and even planetary systems. The intricate interconnections between agricultural activities and ecosystem services necessitate analysis that transcends farm boundaries.

Over the past decade, global change science and a series of high-level international evaluations have drawn attention to the considerable ecological consequences of modern agriculture. These include alterations in land cover, disruptions to ecological processes, and heightened threats to long-term sustainability (IPBES, 2019; Rockström et al., 2020).

Among the most pressing challenges are climate change and increasing water scarcity both of which jeopardize not only ecological stability but also food production and global food security. The reciprocal relationships between farming practices and ecosystem integrity unfold across various spatial and temporal dimensions, necessitating a more comprehensive and dynamic scientific approach.

To respond to this complexity, agroecological research must be reoriented to address multi-scale processes, from molecular-level mechanisms to large-scale landscape dynamics, and across timeframes ranging from immediate reactions to long-term trends. In this evolving framework, landscape-level assessments have emerged as a critical area of inquiry.

Despite notable advancements in the field of landscape ecology, significant knowledge gaps remain, particularly concerning the functioning of ecosystems within heterogeneous agricultural environments (Turner, 2005). Kremen (2005) similarly highlighted the insufficient incorporation of ecosystem service functions into ecological modeling frameworks. However, recent progress has been made, especially in areas such as pollination dynamics (as elaborated in Section 3.2), biogeochemical functioning within agroecosystems (Ahrens et al., 2018), and spatial modeling efforts aimed at balancing biodiversity, ecosystem service provision, and agricultural productivity (Nelson et al., 2019).

4. Biodiversity and Climate Resilience through Agroecological Practices (2020–2025)

Biodiversity is a foundational element in agroecological systems, playing a critical role beyond simply offering genetic resources. It serves as the structural and functional basis for sustaining long-term agricultural viability. Within agroecology, biodiversity is not a secondary benefit, it is the cornerstone of system design. Recent empirical evidence from the 2020–2025 period affirms that diversified farming systems significantly enhance ecological performance, contribute to yield stability, and improve adaptive responses to climatic fluctuations (Tittonell et al., 2020; Barrios et al., 2021).

Agroecology has gained recognition as a transformative paradigm capable of simultaneously addressing interconnected crises related to climate, food, and biodiversity (Tittonell et al., 2023). A recent study published in *Agricultural Systems* emphasizes that agroecological strategies such as polycultures, cover cropping, and agroforestry not only support

climate mitigation efforts but also strengthen adaptive capacities by bolstering ecosystem functions (Tittonell et al., 2023).

4.1. Functional Role of Biodiversity in Agroecology

Agroecological systems foster biodiversity at genetic, species, and ecosystem levels. These multi-tiered forms of diversity perform key ecological services, including pest regulation, nutrient cycling, pollination, and soil regeneration (Altieri & Nicholls, 2022). For instance, intercropping and polyculture strategies support natural enemies of pests, reduce herbivore outbreaks, and minimize the need for synthetic pesticides. Soil microbial diversity is also enhanced in systems that prioritize organic matter retention and crop rotation, improving fertility and resilience against drought (Barrios et al., 2021).

Moreover, the adoption of agrobiodiverse cropping systems, especially those involving traditional and local varieties, contributes to climate adaptation through trait-based selection for heat, drought, and disease resistance (Lin, 2021).

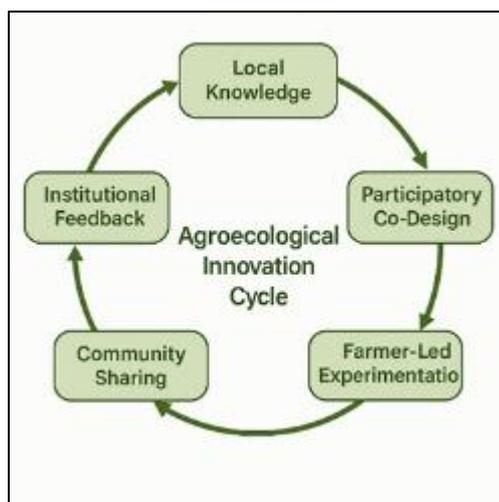


Figure 2 Agroecological Nexus Framework

This conceptual diagram illustrates the interconnected dimensions of agroecology as explored in this review. The central node—Agroecological Transition—is supported by six core domains: Agricultural Practices, Biodiversity, Inputs & Pollution, Livestock, Resource Cycling, Food Access, and Innovation & Social Learning. Each component reinforces and co-evolves with others, reflecting a systems-based and holistic agroecological paradigm.

Agroecology offers substantial advantages in enhancing the resilience of agricultural systems to climate-related disruptions. A key mechanism through which this resilience is achieved lies in the biological diversity and system heterogeneity that agroecological approaches promote. Variability in plant species and farming system configurations introduces redundancy and functional complementarity, which together act as a form of ecological insurance, minimizing risk and facilitating recovery following extreme climatic events (Gliessman, 2021).

One of the cornerstone practices in agroecological design is agroforestry, which plays a pivotal role in mitigating climate impacts. It enhances carbon sequestration, moderates temperature extremes, and improves water cycle regulation, particularly within semi-arid and drought-prone environments (Mbow et al., 2023). These contributions are especially relevant in regions increasingly vulnerable to climate instability.

Moreover, agroecology places emphasis on practices such as the cultivation of perennial species, the use of cover crops, and the implementation of biologically diverse crop rotations. These strategies contribute to the formation of stable microclimates, reduce evapotranspiration rates, and boost soil organic carbon content all of which are essential to both climate change mitigation and adaptive capacity (FAO, 2022).

4.2. Global and Regional Applications

In the Sahel region of West Africa, the technique of farmer-managed natural regeneration has led to the rehabilitation of degraded lands, enhanced water infiltration and retention, and supported the resurgence of biodiversity. This community-led approach exemplifies a grassroots model for building climate resilience (Reij et al., 2021).

Across Latin America, agroecological farms employing diverse agroforestry systems have been associated with improved food sovereignty, ecological balance, and increased household incomes, particularly under conditions of climatic uncertainty and stress (Rosset et al., 2022).

These real-world case studies underscore the potential of biodiversity-centered agroecological systems not only to stabilize agricultural production, but also to fortify the adaptive capacity of rural populations, thereby supporting sustainable livelihoods under climate variability.

4.3. Agroecological Strategies for Climate Adaptation (2020–2025)

4.3.1. Soil Health and Carbon Sequestration

Soil quality stands as a fundamental pillar in the pursuit of climate-resilient agriculture. Agroecological systems contribute significantly to soil health through the use of organic inputs, crop-livestock integration, minimal tillage, and cover cropping practices. These techniques foster microbial biodiversity, improve soil structure, and boost water retention capacity, all of which enhance system resilience (Schreefel et al., 2020).

In addition to stabilizing crop yields under conditions of climatic stress, such improvements also promote carbon sequestration, playing a critical role in offsetting atmospheric carbon dioxide concentrations (Gattinger et al., 2021). By enhancing soil organic matter and creating closed-loop nutrient cycles, agroecology not only decreases dependence on synthetic fertilizers but also establishes ecological buffers that increase resistance to both drought and flooding events.

4.3.2. Water Management and Microclimate Regulation

Water is a key element in climate adaptation, and agroecological approaches offer a variety of strategies to optimize its use. Techniques such as mulching, terracing, intercropping, agroforestry, and rainwater harvesting are central to agroecological water management. These practices help to reduce evapotranspiration, limit surface runoff, and enhance soil infiltration, thus improving water availability and use efficiency (FAO, 2023).

Furthermore, the integration of trees and ground cover vegetation within agricultural landscapes plays an important role in microclimate regulation. This vegetative cover acts as a buffer against temperature extremes and wind desiccation, thereby supporting more stable growing conditions (Altieri & Nicholls, 2022).

Among these practices, agroforestry has emerged as particularly effective in retaining soil moisture and reducing heat stress, especially in dryland farming systems across diverse regions including Africa, Asia, and Latin America (Mbow et al., 2023).

4.3.3. Diversification as a Resilience Strategy

Agroecosystem diversification enhances resilience by fostering ecological redundancy and enabling functional complementarity. The incorporation of multiple crop types, livestock species, trees, and even aquatic organisms such as fish into farming systems helps mitigate risks associated with pest outbreaks, disease pressures, and extreme weather events (Lin, 2021).

This biodiversity creates greater adaptive flexibility, allowing farming communities to better respond to changing environmental conditions and resource fluctuations. Unlike monocultures, which concentrate risk in a single species or production cycle, diversified systems spread risk both spatially and temporally functioning as a form of natural insurance against systemic shocks.

5. Agricultural Production Systems and Practices

Globally, agricultural systems exhibit a remarkable range of productivity outcomes, management styles, and ecological contexts. While this review primarily focuses on temperate agricultural systems, it also draws upon agroecological case studies from tropical regions, including Latin America, Sub-Saharan Africa, and Southeast Asia (Altieri et al., 2020; Gliessman, 2022).

Beginning in the mid-20th century, agricultural systems underwent a profound shift towards specialization and intensification. The increasing reliance on external inputs such as hybrid seed varieties, synthetic fertilizers, pesticides, and fossil fuel-based technologies led to substantial gains in crop productivity. Between 1960 and 2000, for instance, global food output more than doubled. However, this progress was accompanied by serious environmental trade-offs,

notably disruptions to nitrogen and phosphorus cycles and a significant erosion of biodiversity (Foley et al., 2011; Erisman et al., 2013).

The intensification model has frequently undermined natural ecological processes and curtailed the use of on-farm recycling practices. Standardization of high-yielding cultivars, the decline of integrated crop-livestock systems, and the widespread expansion of monocultures have collectively increased the ecological fragility of these production models (Garnett et al., 2020). As a result, such systems have become heavily dependent on external chemical inputs and are often less resilient to environmental or economic shocks.

In contrast, agroecology presents a viable alternative to these systemic vulnerabilities. In an era characterized by volatile energy costs, climate instability, and resource scarcity, the agroecological paradigm promotes diversified, context-specific, and low-input farming systems. These approaches aim to build ecological resilience, decrease reliance on external inputs, and restore key ecosystem functions through methods such as polyculture, cover cropping, and integrated farming (FAO, 2022).

Rather than optimizing for maximum input use, agroecology advocates for a process-oriented design, wherein nutrient cycling, pest regulation, and energy flow are managed through ecological services rather than through synthetic interventions. This systems-based approach supports long-term sustainability, particularly under conditions of environmental uncertainty and socio-ecological stress.

Recent studies reinforce agroecology's potential as a comprehensive solution to the interconnected crises of climate change, food insecurity, and biodiversity loss. For example, global case studies presented by Tiftonell et al. (2023) reveal that agroecological strategies such as polyculture, agroforestry, and the use of cover crops can significantly improve systemic resilience and ecosystem functioning, thereby offering integrated responses to multiple sustainability challenges.

5.1. Nutrient Inputs, Outputs, and Pollution

Nitrogen (N) is widely recognized as one of the most limiting macronutrients in global agricultural production. The development of the Haber-Bosch process often cited as one of the most transformative scientific innovations of the 20th century enabled the industrial fixation of atmospheric nitrogen into ammonia, revolutionizing fertilizer production. However, this technology is highly energy-intensive, relying predominantly on fossil fuels, and constitutes a major source of greenhouse gas (GHG) emissions (Erisman et al., 2008).

Although the widespread adoption of synthetic nitrogen fertilizers has played a crucial role in boosting global food output, it has also introduced serious ecological repercussions. Overapplication of nitrogen leads to the leakage of reactive nitrogen compounds into the atmosphere, soil, and water bodies, exacerbating issues such as eutrophication, denitrification, and increased GHG release (Galloway et al., 2003; Sutton et al., 2011).

Erisman et al. (2013) describe this escalating condition as a "nitrogen-saturated planet," and projections for the future paint a troubling picture. According to Bouwman et al. (2017), if current practices persist, achieving a significant reduction in nitrogen pollution by the year 2050 appears highly improbable without profound structural and technological transformations.

In parallel, phosphorus (P) represents another critical nutrient constraint, particularly acute in tropical regions where soils are often deficient in available phosphorus. The non-renewable nature of phosphate rock reserves results in volatile pricing and growing global interest in nutrient recovery and recycling technologies (Cordell et al., 2009). The limited availability of accessible phosphorus presents a direct threat to long-term global food security, reinforcing the urgency of nutrient circularity within agroecological systems.

Within this context, the recycling of nitrogen and phosphorus at both the farm and regional scales is fundamental to building sustainable agricultural models. A nuanced evaluation of how various management strategies impact both productivity and environmental integrity is essential for the development of sound, forward-looking policy interventions.

Key considerations include:

Farmers' choices are heavily influenced by market prices, input accessibility, and institutional policy frameworks.

Navigating the trade-off between economic viability for farmers and environmental sustainability remains a central challenge.

The complexity of these interactions has led to increased reliance on bioeconomic modeling to assess policy impacts and optimize outcomes. For example, evaluations of ethanol production policies in the United States reveal that corn-based biofuel incentives although initially intended to promote sustainable energy may in fact contribute to greater GHG emissions by intensifying land-use pressures (Searchinger et al., 2008). These findings underscore the unintended consequences of strategies overly reliant on external inputs, and highlight the need for integrated agroecological planning.

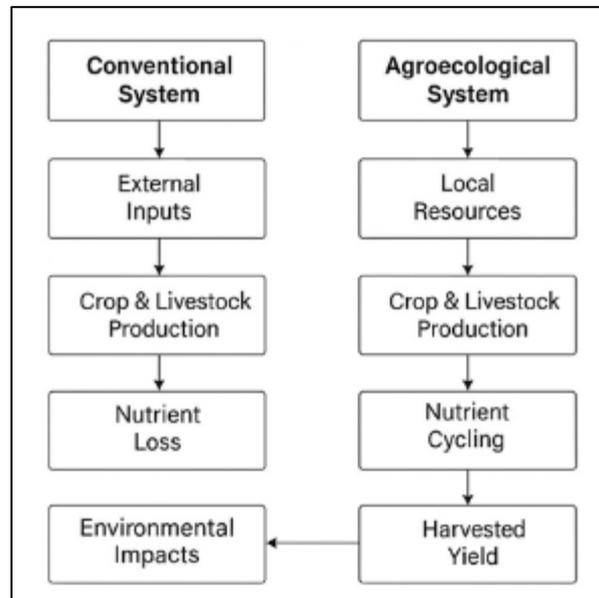


Figure 3 Agroecological Nexus Framework

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5.2. Agricultural Biodiversity

Agricultural biodiversity is one of the foundational pillars of agroecology, contributing directly to both productivity and resilience. Diversity at the genetic, species, and habitat levels supports a range of ecosystem services, including soil health, pest suppression, pollination, water regulation, and nutrient cycling (Altieri, 1999; Kremen et al., 2012).

Beyond productivity, biodiversity increases system stability and resistance to biotic and abiotic stress. Genetic diversity, in particular, plays a crucial role in enhancing resilience to plant diseases and pests. The temporal and spatial rotation of crop genotypes is shown to reduce vulnerability while supporting natural defenses (Zhu et al., 2000; Tooker et al., 2021).

Shelter habitats for natural enemies within agricultural landscapes are essential for maintaining biological control. Biodiversity in farming systems encompasses not only crop species, but also beneficial soil microbes, pollinators, predators, and non-harvested companion species. However, today, nearly 90% of global food production depends on only 103 crop species (FAO, 2021; IPES-Food, 2016).

This homogenization is linked to practices such as monocropping, habitat destruction, intensive tillage, and overuse of agrochemicals—all of which reduce biodiversity and impair ecosystem services. In summary:

- Yield-maximizing systems often ignore ecological side-effects.
- Biodiversity loss destabilizes ecological functions and jeopardizes long-term productivity.
- Pollinators (e.g., bees) are harmed by habitat loss and intensified farming.

- Soil biota such as nematodes and beneficial fungi are disrupted by synthetic inputs and disturbance, weakening belowground ecosystem function.

Moreover, chemical pesticides designed for target pests often suppress beneficial species as well, creating a cycle of dependency and ecological fragility (Gurr et al., 2016). Agroecology addresses this challenge through ecosystem-based pest management, promoting habitat diversification, natural enemy enhancement, and low-input strategies.

One notable example is the "push-pull" strategy, which manipulates insect behavior by using repellent intercrops to "push" pests away from the main crop and attractant border plants to "pull" them toward a trap crop. Such strategies exemplify the potential of agroecological design to foster ecological balance and reduce chemical reliance (Khan et al., 2008).

Fernandez & Khosla (2023) underline the essential role of biodiversity in agroecological frameworks, particularly emphasizing improved pest control, pollination efficiency, and nutrient cycling, thereby enhancing system circularity and reducing external input dependency.

5.3. Landscape-Level Dynamics and Ecological Engineering

The restoration of ecological processes within agricultural landscapes requires deliberate strategies aimed at reestablishing trophic interactions, particularly those between predators and their prey, as well as improving resource use efficiency across spatial scales. A case in point is the movement of predatory nematodes, which can be impeded if organic residues are buried too deeply or if root systems lack sufficient density. To address such challenges, several key agroecological practices are recommended:

- Maintaining surface organic residues through mulching while minimizing disruptive tillage operations.
- Enhancing root zone nutrient density via targeted irrigation and planting strategies that favor deep rooting.
- Stimulating populations of root-associated predators through the incorporation of cover crops and diversified rotational systems.
- Inoculating transplants with beneficial rhizosphere microorganisms to boost soil biological activity.
- Supporting upper trophic organisms (e.g., birds, spiders, beneficial insects) by applying ecological engineering approaches at both the field and broader landscape levels.

Although organisms like pollinators and natural enemies in the aboveground environment tend to be relatively mobile, soil-dwelling biota disperse at much slower rates. As a result, the successful facilitation of biological connectivity in agroecosystems depends on intentional spatial planning. Practices such as hedgerow planting, cover cropping, intercropping, and enhancing functional biodiversity contribute to the development of ecological corridors and networked habitat structures (Tscharntke et al., 2012).

Nonetheless, it is important to acknowledge that simultaneous optimization of all ecosystem services is often unfeasible due to trade-offs between different functions and temporal or spatial limitations. Therefore, managing agricultural systems at the landscape scale, in coordination with supportive policy frameworks, becomes crucial in pursuing multi-functionality and resilient agroecosystem design over the long term.

6. Livestock Systems: Environmental Impacts and Health Dimensions

Animal agriculture constitutes a fundamental pillar of global food systems and must be assessed in tandem with its environmental externalities and public health implications. For example, in the United States, nearly 50% of total grain production is allocated to animal feed. Yet, only an estimated 30% of the nitrogen (N) applied to these feed crops is absorbed by the animals. The remaining nitrogen is released into the environment primarily through manure and urine, where it is often lost via ammonia volatilization or runoff into aquatic ecosystems, thereby contributing to both air and water pollution (Bouwman et al., 2013).

One of the key challenges stems from the geographical decoupling of feed production and livestock rearing, which complicates efforts to close nutrient loops. In contrast, integrated crop-livestock systems offer more coherent pathways for nutrient recycling and efficiency. A pertinent example is swine production, where excess phosphorus (P) remains a notable environmental issue. The low bioavailability of phytate-bound phosphorus in conventional feed grains often leads to over-supplementation, resulting in high phosphorus concentrations in manure and subsequent environmental loading. Mitigation strategies include the use of phytase enzymes and the cultivation of low-phytate crop varieties to reduce phosphorus waste (Sharpley et al., 2004).

Moreover, livestock systems are major sources of greenhouse gas (GHG) emissions, predominantly through enteric methane production in ruminants. Life Cycle Assessment (LCA) studies on beef production indicate that methane emissions, expressed in CO₂-equivalent terms, range between 5.9 and 7.2 kilograms per kilogram of live weight, depending on whether the system is grain-fed or pasture-based. These figures vary significantly across geographies from 5.0 kg/kg in more extensive African systems to values exceeding 20 kg/kg in highly industrialized contexts such as Japan (Gerber et al., 2013).

Modifications to animal diets and pasture management techniques have shown potential for mitigating methane output (Hristov et al., 2013). According to Herrero et al. (2010), mixed crop-livestock systems, particularly in the Global South, could simultaneously contribute to enhanced food security and reduced environmental degradation.

Nonetheless, there remain considerable knowledge gaps in quantifying and tracking the environmental consequences of livestock production. Gill et al. (2010) have emphasized the need for an integrated global framework that connects issues of food system resilience with GHG mitigation strategies.

Another pressing concern is the widespread use of antibiotics in intensive animal farming. The deployment of antibiotics as growth promoters has been directly linked to the emergence of antibiotic-resistant pathogens, posing serious risks to public health. While the European Union prohibited such practices in 1999, these methods continue to be prevalent across many developing countries (Van Boeckel et al., 2015).

Addressing these concerns calls for a global governance approach involving cross-sectoral collaboration among veterinary, agricultural, and healthcare institutions. Agroecological approaches to livestock rooted in ecological harmony, animal welfare, and closed-loop nutrient management offer a more sustainable and health-conscious pathway for the future of food systems.

6.1. Resource Cycling: Nutrients, Energy, and Water

Agricultural systems that rely heavily on intensive management practices have been shown to significantly disrupt the natural cycling of nutrients, water, and energy. Contemporary production models, which depend on substantial external inputs, have frequently displaced ecologically balanced flows in favor of chemically driven alternatives. While these approaches have often succeeded in boosting yields in the short term, they have also eroded the regenerative capacities of agroecosystems over time (Foley et al., 2011; Altieri & Nicholls, 2020).

Take nitrogen as an example: a large proportion of the nitrogen applied in the form of chemical fertilizers fails to be absorbed by crops. Instead, it is lost through leaching or volatilization, entering surrounding ecosystems where it contributes to problems like eutrophication and groundwater contamination. Research shows that only approximately 4% of the nitrogen applied ultimately reaches human food consumption, underscoring the inefficiency and ecological cost of such systems (Erisman et al., 2008; Sutton et al., 2011).

In addition to nutrient losses, practices such as intensive tillage, chemical pesticide application, and inefficient irrigation can severely affect soil health, disrupting microbial diversity, degrading soil structure, and diminishing subterranean ecosystem functions. When biological functions are replaced with synthetic inputs, the system becomes more fragile and increasingly dependent on external support mechanisms (Kremen et al., 2012).

From an energy standpoint, conventional agriculture exhibits a high reliance on fossil fuels, not only for the production of synthetic fertilizers but also for irrigation infrastructure, mechanized equipment, and the long-distance transport of agricultural goods. This dependency renders food systems highly vulnerable to energy price fluctuations and supply chain instability (Pimentel & Pimentel, 2008).

In stark contrast, agroecological systems strive to rebuild and close internal cycles of key resources through a variety of methods, including:

- Nutrient recycling on the farm, using compost, green manures, and livestock waste;
- Biological nitrogen fixation, facilitated by leguminous crops and beneficial soil microbes;
- Water harvesting and conservation-oriented farming techniques;
- Mixed cropping systems and spatial diversification to reduce erosion and nutrient runoff;
- Incorporation of renewable energy sources, such as solar-powered irrigation systems.

However, transforming resource cycles is not purely a matter of technical redesign. It also requires institutional reform, economic restructuring, and cultural shifts. For instance, the stigmatization of organic waste such as manure, often seen as a liability rather than a resource, presents a social and perceptual barrier to circularity. In addition, market distortions and lack of supportive policies hinder the transition toward regenerative nutrient management.

There exists a stark imbalance: while some areas face nutrient overloads due to livestock concentration or industrial waste others suffer from severe nutrient deficits and chronic food insecurity. Agroecology provides place-based solutions that seek to balance agricultural productivity with ecological stewardship (Tittonell, 2013).

Ultimately, reconnecting crop and livestock systems, enhancing agrobiodiversity, and empowering farmers to lead localized innovations in nutrient and water governance are essential steps in building circular, resilient food systems that remain within planetary ecological boundaries.

6.2. Food Access and Local Food Systems

Within agroecological frameworks, food access is considered a foundational principle one that goes beyond mere availability to encompass affordability, nutritional quality, cultural relevance, and social justice. The concept of food security, which gained prominence during the global food crises of the 1970s, has gradually evolved into a more comprehensive, multi-dimensional construct emphasizing the importance of sustainable and equitable access to food resources (FAO, 2021; HLPE, 2020).

In many industrialized countries, alternative models such as urban agriculture, community-supported agriculture (CSA), and household gardening have become increasingly popular as responses to concerns over food quality, transparency, and local resilience. Nonetheless, a persistent paradox remains: the very individuals responsible for food production farmers frequently experience food insecurity themselves, particularly in economies that are heavily reliant on market-driven, input-intensive agricultural models (De Schutter, 2014).

In developing regions, smallholder farming communities navigate a complex landscape in which they are tasked with both ensuring household food self-sufficiency and engaging competitively with globalized agricultural markets. This dual pressure often produces conflicting development outcomes, wherein export-oriented growth strategies undermine local food sovereignty and disrupt ecological balances (Altieri & Toledo, 2011).

Therefore, any agroecological examination of food systems must extend its scope beyond biophysical efficiency to include the social and institutional architectures that govern how food is produced, distributed, and consumed. Notably, research indicates that local food systems are not inherently superior in terms of greenhouse gas (GHG) emissions when compared to imported food. Instead, outcomes are shaped more critically by variables such as energy input efficiency, farming techniques, and the design of supply chains (Edwards-Jones et al., 2008; Canfora, 2016).

In response to these complexities, discourse has progressively shifted from the paradigm of “food security” to that of “food sovereignty” a rights-based framework emphasizing the ability of communities and peoples to define their own food and agricultural systems. This includes the right to produce culturally appropriate food, control local resources, and resist the commodification and industrialization of food systems (La Vía Campesina, 2020).

Organizations such as La Vía Campesina position agroecology not only as a practical or technical solution, but also as an instrument for political resistance, social justice, and cultural preservation. According to Perfecto et al. (2009), agroecological sustainability can only be realized when it is firmly grounded in social movements that advocate for the protection of peasant livelihoods and the revitalization of local food traditions.

Consequently, the development of agroecological food systems must prioritize community empowerment, inclusive governance mechanisms, and redistributive policies. These components are not merely supplementary, they are essential to the long-term sustainability, adaptability, and equity of agroecological systems.

7. Innovation and Social Learning

The transformation toward agroecological systems involves more than the adoption of new technologies; it is deeply rooted in processes of innovation that are participatory, adaptive, and grounded in social contexts. In contrast to conventional top-down models of technological dissemination, agroecological innovation is characterized by its emergence from local knowledge systems, collaborative experimentation, and peer-to-peer learning among farmers, researchers, and community members (Altieri & Nicholls, 2017; Pimbert, 2018).

This type of innovation is inherently place-based and evolves through hands-on learning. It embodies not only new techniques, but also new forms of relationships between people and ecosystems, between producers and researchers, and between productive practices and cultural values. As such, social learning becomes a key strategy for building collective resilience and problem-solving capacity in the face of environmental degradation, economic volatility, and institutional rigidity (Leeuwis & Aarts, 2011).

Agroecology actively supports the creation of “innovation platforms” spaces that convene diverse stakeholders to co-generate context-specific knowledge. Examples include Farmer Field Schools, community seed banks, participatory plant breeding initiatives, and living laboratories. These platforms facilitate not only technical skill-building, but also social empowerment, with particular benefits for women, indigenous peoples, and other historically marginalized groups (FAO, 2019; World Bank, 2020).

Social learning also plays a pivotal role in the scaling of agroecological approaches. In this context, scaling is not simply the geographic replication of practices or technologies, but the expansion of values, relational dynamics, and governance frameworks that align with equity and ecological stewardship. According to Mier y Terán et al. (2018), enabling such scaling efforts requires a supportive institutional environment, including flexible funding systems, inclusive policies, and formal acknowledgment of agroecology within national and global agendas.

Moreover, agroecological innovation often entails a redefinition of success indicators. Rather than focusing solely on yield per hectare, success is increasingly measured by metrics such as ecosystem vitality, social cohesion, nutritional diversity, and cultural resilience (HLPE, 2019). These alternative indicators reflect a holistic understanding of sustainability that transcends productivity metrics alone.

Ultimately, advancing innovation within agroecology is not about substituting one dominant system for another. It is about creating open and pluralistic pathways toward sustainable futures that are co-designed and led by the people inhabiting and cultivating rural territories. In this light, **grassroots innovation and collective learning** are not peripheral they are **core drivers of agroecological transformation**.

7.1. Farmer Participation and Knowledge Co-Creation in Agroecology (2020–2025)

Within the agroecological paradigm, farmers are recognized not merely as recipients of technological innovation but as active co-creators of knowledge and key agents of transformation in the development of sustainable agriculture. In sharp contrast to top-down agricultural extension systems, agroecological research and practice are grounded in participatory approaches that prioritize local knowledge, hands-on learning, and inclusive governance structures (Coolsaet, 2020; Wittman & Blesh, 2022).

Creating an enabling policy environment is essential for supporting and scaling agroecological transitions. Prominent international frameworks including the FAO’s Scaling Up Agroecology Initiative and the European Union’s Green Deal (Farm to Fork Strategy) have explicitly incorporated agroecological principles into their sustainability agendas. According to Rodriguez & Martinez (2024), these strategies aim to reduce dependence on agrochemicals, conserve biodiversity, and empower smallholder farmers, reflecting the importance of coherent, multilevel policy design in facilitating comprehensive agroecological change.

In agroecology, farmer participation is not an optional or peripheral component it constitutes a core organizing principle that reshapes conventional ideas about how agricultural knowledge is generated, exchanged, and applied. Rather than promoting passive adoption of pre-packaged solutions, agroecological transformation depends on collaborative, iterative processes in which farmers are central agents of experimentation and learning. In this setting, knowledge is not delivered from expert to practitioner; it is co-produced through mutual dialogue, contextual understanding, and adaptive practice.

The value of such participatory approaches in advancing agroecological innovation is demonstrated by recent empirical studies. For example, Greco et al. (2024) explored a participatory action research project implemented in Western Sicily, where partnerships between farmers and researchers led to the co-development of locally adapted practices. The study found that such collaborations significantly increased the adoption, effectiveness, and long-term sustainability of agroecological interventions, while simultaneously enhancing livelihood resilience and ecological outcomes in the region.

Through this case, Greco et al. (2024) emphasized the transformative role of farmer-scientist partnerships in shaping agroecological transitions. Their findings illustrate that co-creation of knowledge not only leads to more relevant and sustainable agricultural practices but also strengthens the social fabric necessary for systemic change in rural areas.

7.2. From Technology Transfer to Participatory Innovation

The transition from conventional, linear models of technology dissemination to co-creative, iterative innovation processes marks a fundamental shift within agroecological practice. Approaches such as Participatory Action Research (PAR), Farmer Field Schools (FFS), and campesino-a-campesino (farmer-to-farmer) networks exemplify how farmers engage not just as recipients, but as active developers, testers, and disseminators of agroecological knowledge and practices (Rosset & Altieri, 2020).

This participatory orientation enhances not only the local applicability and resilience of practices but also strengthens social learning, community empowerment, and long-term adaptive capacity. In many contexts across the Global South, participatory methodologies have enabled smallholder farmers to maintain control over seeds, land, and their traditional knowledge systems, thus resisting the homogenizing forces of industrial agriculture (Van der Ploeg et al., 2024).

Recent studies further reinforce the value of participatory innovation. For instance, Tittonell et al. (2023) demonstrate that agroecological strategies such as polyculture, agroforestry, and cover cropping simultaneously address the intersecting crises of climate change, food insecurity, and biodiversity loss. Their findings highlight the potential of such practices to substantially improve ecosystem functions and agroecosystem resilience.

7.3. Co-Creation of Knowledge: Bridging Scientific and Local Expertise

Agroecology emphasizes the synergistic integration of formal scientific inquiry with local, Indigenous, and experiential forms of knowledge. This approach to co-creation is grounded in the belief that scientific rigor and cultural relevance are not contradictory, but rather mutually enriching (Bezner Kerr et al., 2021). Collaborative processes involving farmers, academics, civil society organizations, and policymakers have yielded tailored solutions that align both with ecological sustainability and social equity.

Emerging studies also highlight the role of digital tools and open platforms in fostering distributed innovation systems. For example, Delgado et al. (2023) underline how mobile technologies, community-based communication channels, and open-access knowledge platforms have enhanced farmer-to-farmer learning across geographical and cultural boundaries. These tools not only facilitate real-time data exchange but also democratize access to agronomic information, enabling bottom-up innovation.

Furthermore, Fernandez and Khosla (2023) provide a comprehensive assessment of the importance of agricultural biodiversity within agroecological frameworks. Their work underscores how biodiversity contributes to key ecosystem services such as natural pest control, pollination, and nutrient cycling. Their analysis demonstrates that agrobiodiverse systems enhance ecological circularity, thereby reducing dependence on synthetic inputs and strengthening the system's capacity to adapt to environmental stresses.

7.4. Gender, Equity, and Youth Engagement

Agroecology's participatory and inclusive foundation paves the way for greater involvement of historically marginalized groups, especially women and youth. Research has demonstrated that women's engagement in agroecological learning processes and leadership roles contributes to increased farm diversification, improved food system resilience, and enhanced household nutrition and food security (Bezner Kerr et al., 2022). Similarly, youth-led agroecological movements are on the rise—particularly in areas experiencing rural outmigration providing environmentally responsible livelihood options and fostering local stewardship.

Participation in agroecology also carries political significance, as it challenges systemic patterns of exclusion along gender, socioeconomic, and generational lines. Despite their critical roles in seed preservation, soil fertility management, and family nutrition, women are often sidelined in mainstream agricultural advisory systems. Agroecology, through its inclusive values, offers a platform for women's leadership, voice, and knowledge validation (Bezner Kerr et al., 2022). In parallel, youth participation in agroecological systems supports rural revitalization and intergenerational continuity, especially in regions grappling with aging farming populations and youth disinterest in conventional agriculture.

Furthermore, agroecology reinforces community-based adaptation (CBA) strategies by nurturing local institutions, strengthening social capital, and promoting collective learning infrastructures. Organizations such as farmer unions, women-led cooperatives, and Indigenous collectives have harnessed agroecological principles to reclaim food sovereignty, conserve seed diversity, and adapt to localized climate stresses (Bezner Kerr et al., 2024). These bottom-up mechanisms are particularly impactful in regions where formal adaptation policies are lacking or ineffective, demonstrating the value of community-driven climate resilience.

7.5. Participatory Approaches: Shifting the Research Paradigm

Agroecological research increasingly adopts participatory methods that depart from conventional, top-down models of experimentation and knowledge transfer. Techniques such as Participatory Action Research (PAR), Farmer Field Schools (FFS), and the Campesino-a-Campesino approach place farmers at the center of innovation, recognizing them as co-investigators who contribute to research design, data interpretation, and local adaptation of new practices (Rosset & Altieri, 2020).

This participatory paradigm strengthens the social legitimacy and contextual fit of agroecological innovations, thereby improving both adoption rates and the long-term sustainability of interventions (Wittman & Blesh, 2022). Through farmer-led experimentation, communities build adaptive capacities and gain a sense of ownership, which are crucial in the face of climate variability, market fluctuations, and ecological uncertainties.

Beyond technical outcomes, participatory methodologies contribute to the formation of collective agency, fostering solidarity networks, reciprocal support systems, and peer learning cultures (Coolsaet, 2020). These social dynamics not only reinforce the resilience of agroecological systems but also serve as the foundation for democratic and transformative agricultural transitions.

7.6. Co-Production of Knowledge: Bridging Epistemologies

Agroecology embraces an epistemologically pluralistic approach, valuing diverse forms of knowledge that range from formal scientific inquiry to Indigenous, traditional, and experiential understandings. This inclusive perspective is vital for crafting solutions that are both ecologically appropriate and culturally relevant, particularly in complex and varied agroecosystems (Bezner Kerr et al., 2021). Through co-production of knowledge, farmers and researchers collaboratively identify key challenges, design context-specific experiments, and jointly assess outcomes. The result is a set of practices and innovations that are not only environmentally robust, but also socially accepted and legitimized by local communities.

Contemporary research also emphasizes the transformative potential of digital technologies in supporting knowledge co-creation. For instance, Delgado et al. (2023) highlight how open-source mobile applications, community radio programs, and digital data-sharing platforms are being employed to link geographically dispersed farmer groups, monitor field-level performance, and enable real-time peer-to-peer learning.

These tools are increasingly instrumental in democratizing agricultural innovation, allowing farmers to play an active role in generating, validating, and disseminating agroecological knowledge. As such, bridging epistemologies is not simply a theoretical exercise it is a practical foundation for inclusive, adaptive, and resilient agroecosystem transformation.

8. Case Study: Mediterranean Olive Systems under Agroecological Transition

The cultivation of olives in the Mediterranean particularly within the **semi-arid zones of Turkey**—serves as a compelling example of how agroecological approaches can be mobilized to adapt agricultural systems to increasing climate pressures. In the Aegean region, olive groves are increasingly affected by extended drought periods, soil degradation, and the limitations of monoculture systems that depend on external inputs. However, the transition toward agroecologically informed practices, including cover cropping, rainwater harvesting, intercropping with aromatic herbs like lavender and rosemary, and the establishment of participatory farmer learning groups, has begun to yield promising outcomes.

Among the noteworthy efforts is the “LivingLav” project in Western Anatolia, which merges regenerative agroforestry principles with women-led cooperative structures. The initiative has contributed to tangible improvements in soil organic matter content, erosion control, and yield stability, especially among heirloom olive cultivars. In addition, community-centered training programs have empowered female farmers by offering education on agroecological methods, composting, and on-farm biodiversity management.

This localized, socially embedded approach illustrates agroecology's multifaceted value not only in fostering environmental resilience but also in promoting food sovereignty, gender equity, and community self-determination all of which are central pillars of the agroecological movement.

8.1. Case Study: Enhancing Agroecological Resilience through the LivingLav Project, Western Anatolia, Turkey

The Mediterranean basin, typified by semi-arid climatic conditions and frequent drought events, presents a range of challenges for agricultural production particularly for olive cultivation, which traditionally requires substantial water inputs. The LivingLav Project, launched in Western Anatolia, Turkey in 2022, represents a pioneering example of applying agroecological design to improve both ecological functionality and climate resilience in olive-based systems.

By incorporating elements of permaculture and agroforestry, the project has introduced aromatic intercrops such as lavender (*Lavandula angustifolia*), rosemary (*Rosmarinus officinalis*), and sage (*Salvia officinalis*) into existing olive orchards. This strategy has resulted in enhanced soil structure, erosion mitigation, and biodiversity enrichment, partly through the attraction of beneficial insects and natural pollinators, reducing the need for synthetic inputs.



Figure 4 LivingLav Project Reports, 2023; Field Observations and Interviews, Olive Research Institute, İzmir-Turkey, 2024

A distinguishing feature of LivingLav is its strong commitment to social sustainability, with a specific focus on empowering women farmers. The project has supported the formation of women-led agricultural cooperatives, which play active roles in decision-making, cultivation planning, and the marketing of value-added products derived from aromatic crops. Through a combination of educational workshops and participatory training, these women have gained skills in organic compost production, rainwater collection techniques, and strategic biodiversity planning, contributing significantly to both ecological integrity and social equity.

Initial findings from the project point to increased soil moisture retention, improved organic matter levels, and enhanced resilience to drought stress demonstrating agroecology's tangible contributions to climate adaptation. Additionally, the project has yielded important social outcomes, such as expanded economic opportunities for women, strengthened community bonds, and broader adoption of sustainable farming practices within the region.

In this way, the LivingLav initiative exemplifies how agroecological innovation when paired with inclusive, community-led processes can address the interconnected challenges of climate change, ecological degradation, and rural inequality across the Mediterranean landscape.

9. Sustainability and Ecological Circularity in Agroecological Systems (2020–2025)

In agroecology, sustainability is not viewed as a static goal, but rather as a continuous and dynamic process involving ecological regeneration, resource renewal, and socio-economic inclusion. The agroecological framework prioritizes closed-loop systems, reduction of external input dependence, and the emulation of natural cycles thereby fostering self-reliant agricultural ecosystems that are ecologically balanced, economically sound, and socially equitable.

9.1. Closing Nutrient and Energy Loops

One of the hallmark characteristics of agroecology is its focus on internal nutrient cycling. Instead of relying on synthetic fertilizers, agroecological systems utilize organic residues, livestock manure, green manures, and compost to sustain soil fertility (Tiftonell, 2020). These systems also integrate crop and livestock production, allowing waste from one subsystem to be repurposed as a resource for another thereby closing both nutrient and energy loops (Gosnell et al., 2021).

By reducing the use of fossil fuels, shortening transportation distances, and minimizing chemical input requirements, agroecological systems significantly lower their carbon and ecological footprints. These efficiencies not only aid in climate mitigation efforts but also offer economic advantages, particularly for smallholder and resource-limited farmers.

9.2. Regenerative Practices and Long-Term Viability

Agroecology aligns closely with regenerative agricultural principles, aiming not just to maintain current ecosystem function, but to actively restore degraded ecological processes. Practices such as minimal tillage, agroforestry, use of green manures, polycultures, and perennial cropping systems contribute to the rebuilding of soil organic carbon, enhanced biodiversity, and the stabilization of water cycles (Schreefel et al., 2020).

These systems offer increased resilience against environmental disturbances such as droughts, pests, and resource scarcity—thereby safeguarding long-term food production and promoting responsible land stewardship (IPES-Food, 2021). Over time, regenerative agroecological models reduce the reliance on costly external inputs, enhancing their viability under conditions of market volatility and economic uncertainty.

9.3. Economic and Social Dimensions of Sustainability

Agroecological sustainability encompasses not only ecological parameters but also economic self-sufficiency and social justice. Initiatives such as community-supported agriculture (CSA), localized market systems, and producer cooperatives contribute to shorter supply chains, which in turn reduce post-harvest losses, greenhouse gas emissions, and support rural incomes (Rosset et al., 2023).

Additionally, agroecology emphasizes participatory governance, equitable land access, and inclusive involvement of women and youth in agricultural decision-making factors that are critical to building resilient and cohesive rural communities (Méndez et al., 2022). Rather than optimizing singular variables like crop yield, agroecology promotes multifunctionality, integrating considerations of nutrition, cultural identity, equity, and ecosystem health as equally important pillars.

9.4. Strengthening Agroecological Transitions through Integrated Policy Frameworks

Despite the broad benefits offered by agroecological systems across ecological, economic, and social domains, their widespread implementation is contingent upon the development of supportive and coherent policy environments. In recent years, several global initiatives have incorporated agroecological principles into strategic frameworks aimed at transforming food systems.

For instance, the FAO's Scaling Up Agroecology Initiative, launched in 2018 and continually evolving, has positioned itself as a major driver of systemic transformation. It seeks to promote biodiversity, sustainable farming practices, and empowerment of family farmers, while advocating for inclusive policy-making, capacity development, and cross-sectoral collaboration all aligned with the ethos of agroecology.

Similarly, the European Union's Green Deal and the associated Farm to Fork Strategy (European Commission, 2020) integrate agroecological thinking into their broader vision for sustainable food systems. These frameworks aim to reduce pesticide and fertilizer use, expand organic farming, and foster biodiverse landscapes thereby aligning agricultural development with ecological and public health goals.

Beyond these, the International Panel of Experts on Sustainable Food Systems (IPES-Food) emphasizes the urgency of addressing deep structural barriers, such as market consolidation, unbalanced power relations, and inadequate public funding. Recent recommendations from IPES-Food call for redirecting agricultural subsidies away from industrial models toward agroecologically diverse systems, investing in public-sector agroecological research, and facilitating market access for small-scale producers through infrastructure and financing reform (Rodriguez & Martinez, 2024).

Embedding these international policy agendas within national and regional contexts, such as in the Mediterranean, can facilitate the upscaling of agroecological innovations like those observed in the LivingLav Project in Turkey. Effectively aligning national agricultural strategies with agroecological principles is therefore critical to ensuring a transition toward climate-resilient, ecologically sound, and socially just food systems.

10. Discussion

Over the last five years, a growing body of evidence has consolidated agroecology's status not only as a rigorous scientific framework but also as a social movement and a credible policy approach capable of driving comprehensive food system transformation. Agroecology merges ecological understanding with participatory governance, gender equity, traditional and cultural knowledge, and economic justice thus offering a holistic and systemic alternative to the input-intensive, industrialized agriculture paradigm.

Despite gaining substantial traction in both academic circles and grassroots movements, agroecology still faces several structural obstacles that hinder its large-scale adoption. Among the most prominent barriers are the entrenchment of agro-industrial corporations, policy frameworks that favor monocultures and export-driven production, the exclusion of small-scale producers from decision-making platforms, and the decline of public extension services. Moreover, successful agroecological transition typically demands time, capacity building, and institutional trust all of which may be insufficient or absent, especially in fragile or under-resourced rural environments.

To enable agroecology to evolve beyond experimental niches and pilot projects, it must be embedded in coherent policy systems, cross-sectoral partnerships, and inclusive research structures. Critical strategies include redirecting subsidies from conventional agriculture toward regenerative and diversified practices, investing in farmer-led innovation, and integrating agroecology into formal education, especially in rural communities. Empowering youth and women through agroecological training is essential for fostering long-term stewardship, autonomy, and resilient local food systems.

In Mediterranean regions, such as the olive-producing landscapes of Turkey, agroecological approaches provide context-sensitive strategies to confront both climatic challenges and social inequalities. Techniques like cover cropping, composting, intercropping with medicinal and aromatic plants, and rainwater harvesting have demonstrated tangible benefits for soil fertility, water conservation, and reduced reliance on synthetic inputs. Beyond environmental gains, agroecology contributes to social resilience by promoting women's leadership and revitalizing local food traditions.

Looking forward, the scaling of agroecology will hinge on the alignment of three transformative pillars:

- Scientific integrity, which embraces epistemological diversity and emphasizes local adaptation;
- Policy integration, which realigns public incentives with the goals of ecosystem sustainability;
- Grassroots empowerment, which positions farmers as co-designers—not merely adopters of sustainable futures.

Agroecology is not presented as a universal or one-size-fits-all solution but it functions as a guiding framework, a compass pointing toward systems that restore ecosystems, foster inclusion, and nurture both human and planetary well-being.

To embed agroecology more deeply within agricultural and food governance, it is essential to build stronger synergies with existing international initiatives. The FAO's Scaling Up Agroecology Initiative calls for transformative reforms in agriculture through inclusive governance, targeted investments, and cross-sector dialogue. In parallel, the European Union's Green Deal and its Farm to Fork Strategy promote chemical input reduction, biodiversity enhancement, and support for smallholder farming principles that closely mirror those of agroecology.

The International Panel of Experts on Sustainable Food Systems (IPES-Food) also underscores the need to dismantle entrenched barriers in global food governance such as market concentration, power asymmetries, and the lack of public investment in sustainable alternatives. Their recent policy recommendations advocate for the development of territorial food systems, reallocation of subsidies, and the creation of farmer-centered research and support mechanisms, particularly within agroecologically aligned frameworks (Rodriguez & Martinez, 2024).

In the context of Mediterranean agricultural systems, including those found in Turkey, integrating agroecology into national rural development plans, Common Agricultural Policy (CAP)-style instruments, and climate adaptation strategies could lay the foundation for more equitable, sustainable, and climate-resilient food systems.

Rodriguez and Martinez (2024) have emphasized that for agroecology to contribute meaningfully to sustainable development, it must be embedded within global policy frameworks, such as the EU Green Deal and the FAO's Agroecology Initiative. Their findings stress the urgency of systemic policy transformation, enabling agroecological practices to flourish at local, regional, and global levels thereby contributing to key global targets, including SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

11. Conclusion

This review highlights the pivotal role of agroecology in enhancing climate resilience and promoting sustainable food systems by integrating ecological principles, farmer knowledge, and participatory approaches. Synthesizing recent developments from 2020 to 2025, it underscores agroecology's capacity to reduce reliance on external inputs, regenerate ecosystems, and strengthen socio-ecological networks, particularly in olive-based and Mediterranean systems. The analysis also emphasizes the importance of supportive policies and collaborative knowledge production in enabling widespread adoption. By demonstrating the practical and transformative potential of agroecology, this study contributes to bridging science and practice for more equitable and resilient agricultural futures. It will benefit society by guiding decision-makers, researchers, and farmers toward sustainable transitions, while setting a path for scaling agroecological innovations globally.

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