

Agroecology and Sustainable Farming Systems: Recent Research Developments

P. Thukkaiyannan^{1*}, Naval Kishore Meena², Lucy Kumari³

¹Associate Professor (Agronomy), Maize Research Station Vagarai, Palani (Tk) Dindigul Dt. 624613, Tamilnadu

²Ph.D. Scholar, Department of Horticulture (Fruit Science), RCA, MPUAT, Udaipur-313001, Rajasthan

³Ph.D. Scholar, Department of Horticulture, PG College of Agriculture, Dr Rajendra Prasad Central Agriculture University Pusa Bihar

*Corresponding Author E-mail: thukkaiyannan@tnau.ac.in

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ABSTRACT

Agroecology has emerged as a transformative framework for redesigning agricultural systems that integrate ecological principles with sustainable farming practices. This review examines recent research developments (2020–2025) in agroecological approaches, encompassing diversified cropping systems, biological pest management, soil health enhancement, agroforestry, climate-smart agriculture, and the integration of digital technologies. Evidence from large-scale field trials demonstrates that agroecological practices enhance biodiversity, improve soil organic carbon, increase pollinator populations, and strengthen crop resilience against climate variability. However, economic viability often depends on policy support and agri-environmental subsidies. The review highlights the role of integrated pest management within a One Health framework, the carbon sequestration potential of agroforestry systems, and emerging precision agroecology tools incorporating IoT sensors and artificial intelligence. Future research priorities include long-term field experiments, scaling strategies for smallholder systems, and enabling policy frameworks to facilitate the widespread transition to sustainable farming.

Keywords: *Agroecology; Sustainable agriculture; Climate-smart farming; Biodiversity conservation; Soil health.*

INTRODUCTION

The global agricultural system stands at a critical juncture, facing the simultaneous challenges of feeding a growing population projected to exceed 9.7 billion by 2050,

adapting to the accelerating impacts of climate change, and reversing decades of environmental degradation caused by conventional farming practices (Franzluebbers et al., 2020).

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Conventional agriculture, characterized by monoculture cropping, heavy reliance on synthetic fertilizers and pesticides, and intensive tillage, has contributed to soil degradation, biodiversity loss, water pollution, and greenhouse gas emissions that collectively threaten the long-term sustainability of food production systems (Altieri & Nicholls, 2020). 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 these interlinked crises (Uckun, 2025). The Food and Agriculture Organization of the United Nations (FAO) has endorsed the 10 Elements of Agroecology—including diversity, synergies, efficiency, recycling, resilience, and co-creation of knowledge—as an analytical framework to support the transformation of agriculture and food systems (Barrios et al., 2020). Unlike narrow technical solutions, agroecology addresses productivity, environmental health, and social equity

concerns simultaneously, offering viable pathways for sustainable intensification (Sethuraman et al., 2021).

Recent years have witnessed significant advances in agroecological research, from large-scale field trials demonstrating the biodiversity and yield benefits of nature-friendly farming (Rothamsted Research, 2025) to the integration of artificial intelligence and IoT-based precision tools into agroecological systems (Eze et al., 2025). This review synthesizes the most recent research developments in agroecology and sustainable farming systems, examining key thematic areas including diversified cropping systems, soil health management, biological pest control, agroforestry, climate-smart agriculture, and the emerging role of digital technologies. The objective is to provide a comprehensive overview of the current state of knowledge and identify priorities for future research and policy development.



Figure1. Aerial view of a diversified agroecological farming landscape showing intercropping, agroforestry, and wildflower strips

2. Diversified Cropping Systems and Biodiversity

Crop diversification represents one of the most fundamental agroecological practices for enhancing soil health, boosting productivity, and building system resilience. Diversification

methods include intercropping, crop rotation, polyculture, and the integration of cover crops, each contributing distinct ecological benefits to farming systems (Frontiers, 2024). Polyculture, which involves cultivating diverse crops together or in rotation, fosters

biodiversity enhancement, nutrient cycling, and natural pest control, creating more stable and resilient agroecosystems compared to monoculture approaches (Wilson & Lovell, 2016).

A landmark four-year study conducted across 17 commercial arable farms in England by the UK Centre for Ecology and Hydrology (UKCEH) and Rothamsted Research provided compelling evidence for the efficacy of agroecological diversification (Rothamsted Research, 2025). The study tested three systems: standard business-as-usual (BAU) intensive methods, an “Enhancing Ecosystem Services” approach using wildflower margins and cover crops, and a “Maximising Ecosystem Services” model that additionally incorporated in-field wildflower strips and farmyard manure application. Results demonstrated that the ecological systems significantly increased earthworm populations, pollinator abundance (including bees and hoverflies), and natural pest predators such as ladybirds, lacewings, and spiders, while reducing pest aphid and snail populations. Cereal and oilseed rape yields also increased under these nature-based systems due to improved pollination and natural pest control.

Agrobiodiversity serves as a critical tool for reducing production risks and increasing adaptive capacity under changing environmental conditions. Diverse crop rotations, such as the corn-soybean-wheat rotation widely adopted in the United States, enhance soil fertility by varying nutrient demands and reducing pest buildup (Mirsky et al., 2013; & Huang et al., 2021). In tropical regions, intercropping with aromatic herbs such as *Ocimum basilicum* and *Mentha* spp. has been shown to repel pests by masking volatile olfactory cues, thereby diminishing infestation levels while simultaneously improving overall agroecosystem resilience (Tscharnkte et al., 2024).

3. Soil Health Enhancement and Carbon Sequestration

Soil health encompasses the physical, chemical, and biological well-being of soils, and forms the foundation upon which

sustainable agricultural productivity depends. Agroecological approaches focus on building soil health through practices that enhance soil organic matter, promote beneficial microbial communities, improve soil structure, and maintain nutrient cycling processes (El-Ramady et al., 2014). Carbon sequestration and soil health are closely linked: increasing organic matter in soils not only stores atmospheric carbon but also improves soil structure, water-holding capacity, and nutrient availability (Frontiers, 2024).

Recent field experiments have confirmed the synergistic effects of organic farming and conservation tillage on soil health. Guo and Lincy (2025) reported that in semi-arid agroecosystems, organic production systems enhanced microbial biomass and nutrient turnover, strip-tillage improved soil structure and water retention, and the combination of both approaches produced synergistic improvements in crop productivity and water use efficiency. The Rothamsted study similarly found that soils under the maximised ecological system showed the greatest carbon gains, with both ecological systems demonstrating increases in earthworm populations and beneficial soil organisms (Rothamsted Research, 2025).

Agroforestry systems offer particularly promising pathways for carbon sequestration. A comprehensive review by the International Journal of Plant and Soil Science (2025) confirmed that agroforestry enhances soil organic carbon stocks through long-lived vegetation cover, extensive root systems, and continuous litter inputs. Compared to traditional monocropping, agroforestry provides long-term ecological services through soil stabilization, erosion prevention, and nutrient cycling, while simultaneously diversifying income streams and improving food security for smallholder farmers. These findings are corroborated by research demonstrating that agroforestry can serve as an effective climate action strategy, enhancing carbon stocks, improving soil quality, and fostering biodiversity (Journal of Forestry, 2025).

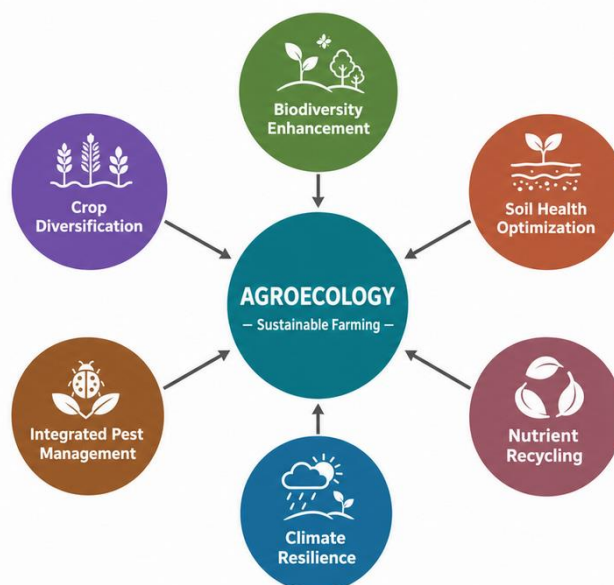


Figure2. Core principles and components of agroecological farming systems
(Adapted from FAO, 2018; Wezel et al., 2024)

4. Integrated Pest Management and Biological Control

Integrated Pest Management (IPM) has evolved significantly within the agroecological framework, moving beyond conventional approaches toward a holistic, systems-based methodology that emphasizes biological control, habitat management, and ecosystem services. Recent advances highlight the growing importance of conservation biological control, which involves the management of agricultural landscapes to promote natural enemy populations and suppress pest outbreaks without chemical interventions (ACS Omega, 2024). Strategies include the establishment of wildflower margins, hedgerows, and beetle banks that provide habitat for predatory insects, parasitoids, and pollinators.

A groundbreaking development in IPM research is the proposed integration with the One Health framework. Khan et al. (2025) introduced a Climate-Smart One Health IPM roadmap that combines ecological, environmental, and socio-economic factors while considering human, animal, soil, and water health within the agricultural environment. This framework employs Systems Thinking and System Dynamics methodologies to comprehend complex

interactions in climate-affected agricultural systems, alongside Digital Twin technology for real-time, data-driven pest management. The roadmap optimizes resource allocation, fosters biodiversity, mitigates climate impact, and prevents zoonotic diseases through adaptive pest management practices.

Practical applications of biological pest management have demonstrated measurable benefits. The Rothamsted field trials showed that ecological farming systems significantly increased populations of natural pest predators, including ladybirds, lacewings, and spiders, which in turn reduced pest aphid and snail biomass in ecologically managed plots (Rothamsted Research, 2025). These findings confirm that managing farmland habitats for wildlife is not in direct conflict with food security but can support sustainable production by providing natural pest control services that could potentially substitute for chemical pesticides.

5. Climate-Smart Agriculture and Agroecological Adaptation

Climate-smart agriculture (CSA) represents a forward-thinking approach that addresses food insecurity and climate change simultaneously, aligning closely with agroecological principles. The FAO identifies three main objectives of CSA: sustainably increasing

agricultural productivity and incomes, adapting to and building resilience against climate change, and reducing greenhouse gas emissions (Action Against Hunger, 2025). Agroecological practices contribute to all three objectives through carbon sequestration in soils, reduced dependence on synthetic inputs, implementation of agroforestry systems, and diversified cropping strategies that enhance system resilience (Muhie, 2022).

The role of agroecology in climate change mitigation operates through multiple pathways. Cover cropping captures atmospheric carbon dioxide and mitigates soil erosion during fallow periods. Crop rotation and diversification interrupt disease and pest cycles, diminishing reliance on synthetic pesticides and fertilizers while enhancing nutrient cycling and curtailing nitrous oxide emissions (Tariq et al., 2019). Agroforestry systems contribute to greenhouse gas

reduction by maintaining permanent tree cover that continuously sequesters carbon in both above-ground biomass and below-ground root systems.

An emerging concept in the intersection of agroecology and water management is “multiservice irrigation,” proposed by researchers in Nature (2025). This framework reconceives irrigation not merely as a water delivery mechanism for yield maximization but as a means of providing multiple ecosystem services, including enhanced soil health, biodiversity support, and nutrient cycling. The multiservice irrigation framework aligns irrigation practices with agroecological goals, recognizing that practices such as no-till farming, cover cropping, and polycultures fundamentally alter soil-water-plant interactions in ways that require rethinking conventional irrigation scheduling, dosing, and technique.

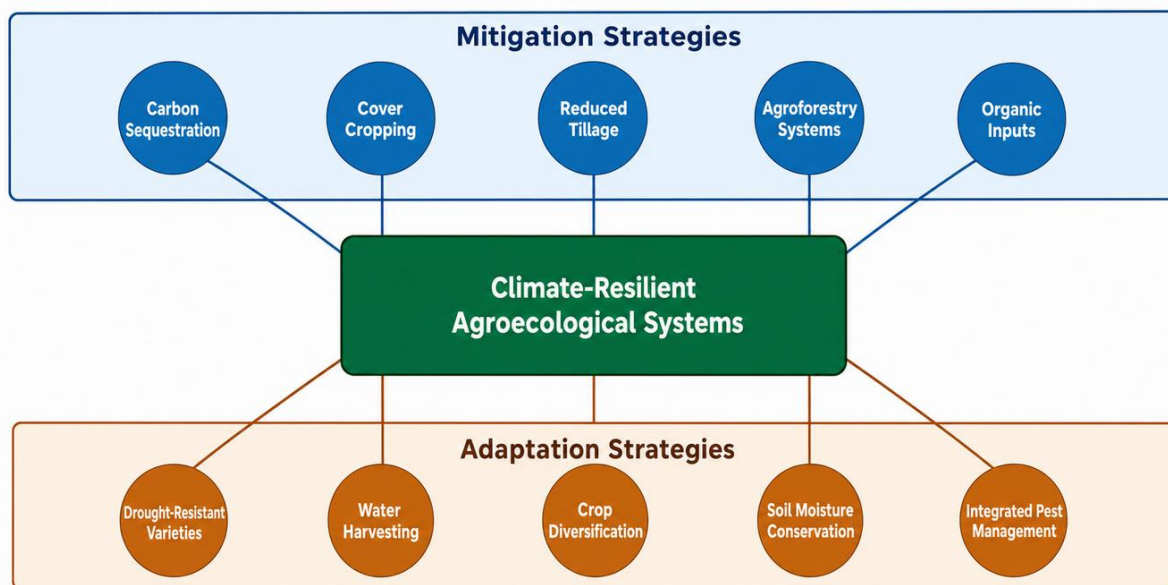


Figure3. Agroecological strategies for climate change mitigation and adaptation (Adapted from Wezel et al., 2024; Uckun, 2025)

6. Digital Technologies and Precision Agroecology

The integration of digital technologies into agroecological systems represents one of the most dynamic and rapidly evolving research frontiers. Precision agroecology combines IoT sensors, machine learning algorithms, and data

analytics to optimize ecological farming practices while maintaining the core principles of biodiversity, minimal external inputs, and system resilience (Eze et al., 2025). AI-powered crop health analysis uses real-time sensor data and camera imagery to assess plant health, monitor irrigation levels, and optimize

crop quality, while predictive yield analytics combine weather forecasts with historical crop performance data to guide management decisions (Robovision, 2025).

Digital Twin technology has emerged as a particularly promising tool for agroecological pest management. By creating virtual replicas of agricultural systems that incorporate real-time environmental data, Digital Twins enable farmers to simulate different management scenarios, assess their outcomes, and optimize resource utilization before implementing changes in the field (Khan et al., 2025). This technology facilitates adaptive management by continuously updating models to reflect changing conditions and emerging pest dynamics.

The adoption of these technologies in agroecological contexts offers significant advantages over their application in conventional systems. McKinsey's Global Farmer Insights 2024 survey indicates that digital agronomy and precision agriculture hardware are the most sought-after technologies globally, with adoption growing steadily, particularly in countries with larger farm operations (AgTech Breakthrough, 2025). However, ensuring equitable access to these technologies for smallholder farmers remains a critical challenge that requires targeted policy interventions and capacity-building programmes.

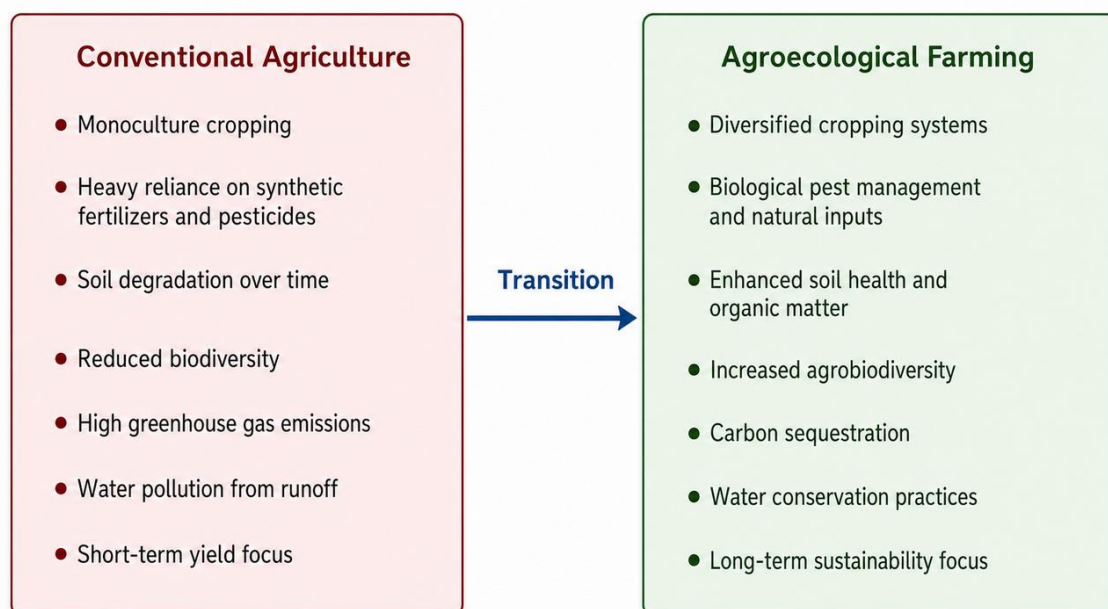


Figure 4. Comparative overview of conventional agriculture and agroecological farming systems (Adapted from Altieri & Nicholls, 2020; Gliessman, 2015)

CONCLUSION

This review demonstrates that agroecology has matured from a set of ecological principles into a comprehensive, evidence-based framework for transforming agricultural systems toward sustainability. Recent research developments across multiple domains—from large-scale field trials confirming biodiversity and yield co-benefits to the integration of advanced digital technologies—provide robust scientific support for the transition from conventional to agroecological farming

systems. Key findings indicate that diversified cropping systems enhance pollinator populations and natural pest control; soil health management through organic inputs and conservation tillage improves carbon sequestration and microbial activity; integrated pest management within a One Health framework offers sustainable alternatives to chemical-dependent approaches; and agroforestry systems provide significant carbon sequestration alongside livelihood diversification.

However, critical challenges remain. The economic viability of agroecological transitions often depends on agri-environmental subsidies, as demonstrated by the Rothamsted trials where ecological systems required policy support to achieve financial parity with intensive farming. Scaling agroecological practices to commercial farming operations requires addressing institutional barriers, market access constraints, and knowledge gaps among practitioners. Future research should prioritize long-term multi-site field experiments, the development of context-specific transition pathways for diverse agroecological zones, and the design of enabling policy frameworks that incentivize sustainable practices while supporting farmer livelihoods. The convergence of traditional ecological knowledge with modern precision technologies offers particularly promising avenues for developing resilient, productive, and equitable agricultural systems capable of meeting the food security challenges of the twenty-first century.

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