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# EXTENSION SERVICES FOR SUSTAINABLE AGRICULTURE IN INTEGRATING AGROECOLOGY AND INDIGENOUS KNOWLEDGE: A REVIEW

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**ABSTRACT**

21st-century sustainable agriculture requires innovative and participatory methods that integrate productivity with environmental integrity. This review critically assesses the contributions of agricultural extension services towards enabling the incorporation of agroecological concepts and indigenous knowledge systems for the promotion of sustainable and resilient farming. Agroecology focuses on ecological relationships and diversity, whereas indigenous knowledge, based on centuries of localized practice, provides insightful experiences into climate resilience, natural resource management, and crop diversity. The research examines participatory extension approaches that enhance farmers' empowerment, facilitate co-learning, and secure traditional practices' preservation and utilization in tandem with scientific innovation. It brings to the fore the importance of farmer innovation, community-based seed banks, organic soil fertility management, and locally evolved crop varieties in building sustainability. In addition, it addresses the role of policy support, capacity development, and reorientation of extension curricula towards pluralistic knowledge systems. Through the interaction between modern science and traditional wisdom, extension services can act as a bridge to innovate ecologically responsible, culture-appropriate, and socially just farming systems.
***Keywords*** **:** Agroecology, Indigenous Knowledge, Extension Services, Sustainable Farming, Farmer Field.

## Introduction

The mounting environmental degradation, loss of biodiversity, and climate uncertainty have revealed the weaknesses of traditional input-based agriculture (Rahman, and Rahman, 2015). These issues call for a paradigm shift to sustainable and ecologically based farming systems. Agroecology becomes an integral approach that combines ecological science with farming practices to develop more resilient and environmentally conscious production systems (Altieri *et al*., 2015). It is known not just as a science but also as a collection of practical approaches and a grass-root movement favoring sustainability (Altieri, 2015).

Concurrently, indigenous knowledge, founded on generations of observation, experimentation, and innovation by local farming people, provides localized, low-cost, and ecologically evolved solutions for sustainable agriculture (Gonsalves, 2005). These knowledge systems are uniquely helpful in managing natural resources, maintaining diversity, and adapting to climatic variability.

Agroecological practices value ecosystem-based methods that embrace natural processes like soil fertility restoration, natural pest suppression, and effective water use (Otieno, 2024). Through reduced use of synthetic inputs and increased ecosystem service provision, agroecology provides a sustainable route to food security, environmental sustainability, and climate resilience (Mrunalini *et al*., 2022). Extension services can be a game-changer in upscaling these principles through knowledge sharing, training, farmer field schools, and inclusive innovation platforms (Nagothu *et al*., 2018).

Analyze the key role of agricultural extension services in advancing sustainable agriculture through the incorporation of agroecological principles and traditional knowledge systems (Prajapati *et al*., 2025). Highlight successful participatory extension approaches that empower farmers, encourage collaborative learning, and enable effective knowledge exchange between scientific and traditional systems (Adefila *et al*., 2024). Emphasize the major challenges and constraints experienced in integrating agroecology and indigenous knowledge into extension systems, and suggest feasible solutions to overcome these obstacles. Establish future directions and strategic proposals for enhancing extension systems to enhance the adoption and scaling-up of agroecological and indigenous farming practices (Ewert, 2023).

Agroecology is the use of ecological principles in agricultural systems. As more specifically defined by Francis *et al*. (2003), it is the integrated study of food system ecology, combining biophysical, economic, and social aspects. What sets agroecology apart is its integrated style it focuses on comprehending the relationships within agriculture and its wider context. A developing responsiveness in many sectors academic, political, and practical towards the pressures and principles of agroecology marks its growing influence and pertinence in contemporary agricultural debates (Wezel *et al*., 2009).

Extension services are the key as the interface between scientific research, policy, and farming communities (Darr *et al*., 2013). By linking formal scientific knowledge to traditional practices, extension systems can promote participatory learning, stimulate innovation, and enable large-scale adoption of sustainable farming methods (Braun *et al*., 2000). Integration of agroecology and indigenous knowledge through extension services is therefore the key to promoting long-term agricultural sustainability and resilience (Prajapat *et al*., 2025).

## Concept of Sustainable Agriculture

As the global population continues to grow, the demand for food, fiber, and other agricultural products is also rising significantly (Westcott, and Trostle, 2012). To meet this growing need while addressing environmental and socio-economic challenges, sustainable agriculture has become an essential strategy. It offers solutions to pressing issues such as biodiversity loss, soil degradation, erosion, salinity, climate change, water scarcity, and the economic hardships faced by smallholder farmers (Hossain *et al*., 2020). The idea gained widespread attention after the 1987 Brundtland Report, which emphasized the broader goal of sustainable development. Sustainable agriculture refers to a long-term, integrated system of crop and livestock production that seeks to: Meet the increasing demand for food and fiber, safeguard environmental health and preserve natural resources, use non-renewable and on-farm resources efficiently, Ensure the economic sustainability of farming systems, and enhance the well-being of farmers and the wider community (Brodt *et al*., 2011).

At its core, sustainable agriculture promotes the use of farming practices that maintain soil fertility, conserve water, reduce greenhouse gas emissions, and protect biodiversity (Lal, 2008). Common practices include conservation tillage, crop rotation and diversification, agroforestry, organic farming, integrated pest management (IPM), and the use of renewable energy in agriculture (Jasrotia *et al*., 2023).

## Importance of Sustainable Agriculture

Sustainable agriculture is important in balancing the ideals of environmental protection with the need to produce safe, healthy, and adequate food (Umesha *et al*., 2018). With the world's population still growing, embracing sustainable farming methods becomes more imperative not only to provide food security but also to safeguard the ecological health of our planet (Nicolétis *et al*., 2019). The importance of sustainable agriculture can be explained by the following major objectives:

**Assuring food, feed, fiber, and energy security:** One of the major objectives of sustainable agriculture is to grow sufficient amounts of food, animal feed, natural fibers, and renewable energy in order to satisfy the needs of an increasing world population without

depleting the natural resources of the planet (Chen and Zhang, 2015).

**Conservation of the environment and natural resources:** Sustainable agriculture stresses the conservation of the environment. It attempts to maintain soil fertility, save water bodies, preserve biodiversity, and minimize pollution using environmentally friendly farm practices (Rehman *et al*., 2022).

**Sustaining economic viability of farming systems:** Farming systems need to be economically viable if they are to be truly sustainable. Sustainable agriculture ensures there are stable livelihoods for the farmer through resilient production systems with less dependence on expensive external inputs and better market access (Singh *et al*., 2011)

**Encouraging effective use of resources:** Sustainable agriculture promotes effective and responsible use of non-renewable resources, including fossil fuels and synthetic chemicals, while fostering on-farm recycling of resources. It also incorporates natural biological processes and cycles, including nutrient cycling, nitrogen fixation, and predator–prey relationships, to minimize environmental impact (Stagnari *et al*., 2010).

Through fulfilling these goals, sustainable agriculture does not only satisfy current needs but also ensures the ability of future generations to fulfill their own, so as to create an equitable relationship between people and nature.

**Enhancing farmers' and society's quality of life:** Finally, sustainable agriculture promotes social sustainability as it enhances the welfare of rural people. It fosters equitable labor practices, promotes community involvement, and supports the health and nutrition components through the provision of healthy food (Rai *et al*., 2023).

**Table 1 :** Government Schemes Enhancing Extension Services for Sustainable Farming Integrating Agroecology and Indigenous Knowledge

| Government Scheme | Key Features and Role in Extension Services |
|---|---|
| **Paramparagat Krishi Vikas Yojana (PKVY)** | Promotes organic farming through cluster-based participatory models; supports farmer training, demonstrations, and organic certification. |
| **National Agroforestry Policy** | Encourages integration of trees and shrubs in farming systems; provides extension support for agroforestry and indigenous species conservation. |
| **Mission Organic Value Chain Development for North Eastern Region (MOVCDNER)** | Focuses on organic farming promotion emphasizing local knowledge and traditional crops; facilitates capacity building, extension, and market linkages. |
| **Soil Health Card Scheme** | Provides farmers with soil nutrient status to optimize input use; extension services promote ecological nutrient management and reduce chemical use. |
| **National Innovations on Climate Resilient Agriculture (NICRA)** | Supports research-extension-farmer linkage for climate-smart farming, including traditional adaptation; encourages participatory research and farmer field schools. |
| **Krishi Vigyan Kendra (KVK) Network** | Key extension platform delivering location-specific technologies; integrates local knowledge through farmer training, demonstrations, and participatory learning. |
| **Rashtriya Krishi Vikas Yojana (RKVY)** | Provides flexible funding for innovative extension projects, including agroecological practices and documentation of local knowledge; supports state-led sustainable agriculture initiatives. |
| **National Mission on Sustainable Agriculture (NMSA)** | Promotes integrated farming, water conservation, and organic practices through extension and capacity building; encourages use of indigenous varieties and traditional pest management. |
| **Paramparagat Krishi Vikas Yojana (PKVY) and Participatory Guarantee Systems (PGS)** | Provides community-based certification systems validating indigenous and organic farming; supports participatory documentation and knowledge sharing among farmers. |
| **Deendayal Antyodaya Yojana – National Rural Livelihoods Mission (DAY-NRLM)** | Empowers rural women and farmers via self-help groups; promotes peer-to-peer learning and dissemination of indigenous practices. |
| **Digital India Initiatives – eNAM, Kisan Call Centers, and Mobile Apps** | Uses ICT tools for knowledge dissemination, market linkages, and advisory services integrating local and scientific knowledge. |

## Agroecology their Principles and Significance

Agroecology is a holistic discipline that uses ecological principles to develop sustainable agricultural systems through planning and management. Agroecology goes beyond farms to encompass landscapes, ecosystems, and the socio-cultural aspects of food production, distribution, and

consumption (Thomas and Kevan, 1993). Agroecology understands farming to be a complex and dynamic system that is intricately connected to natural ecosystems and human societies. Through the combination of these principles, agroecology provides a route to productive, environmentally friendly, and equitable food systems that are sustainable (Snapp, 2017). Extension services in agriculture have a key role to support agroecological changes through their contributions to knowledge transfer, fostering experimentation by farmers, and the interface between scientific and traditional knowledge systems. The key principles of agroecology are:

**Diversity:** Agroecology focuses on the promotion of biological and genetic diversity in agricultural systems. Crop diversification, intercropping, agroforestry, and the utilization of local and traditional varieties of crops increase ecosystem resilience, boost productivity, and enhance resistance to pests, diseases, and climate stresses (Snapp, 2017).

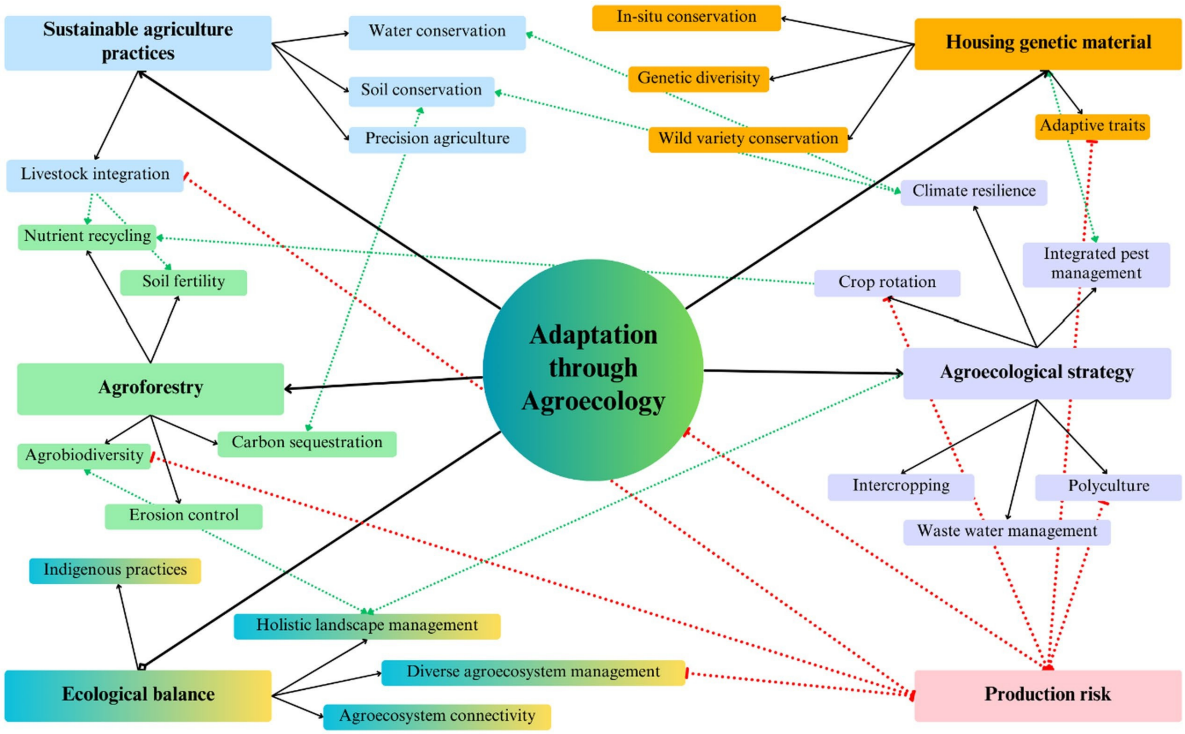



**Fig. 1 :** Adaptation of different Agroecology

**Synergy:** By promoting synergistic relationships among various components of the agroecosystem such as crops, livestock, beneficial soil organisms, and natural pest predators agroecological systems can optimize resource use and ecological functions. These interactions contribute to improved soil fertility, pest suppression, and nutrient cycling (Nicholls *et al.*, 2017).

**Efficiency:** Agroecological approaches seek to minimize reliance on external, non-renewable inputs through optimizing the efficiency of natural processes. These involve utilizing ecosystem services like biological nitrogen fixation, organic matter decomposition, and natural pest control to reduce the use of synthetic fertilizers and pesticides (Wojtkowski, 2006).

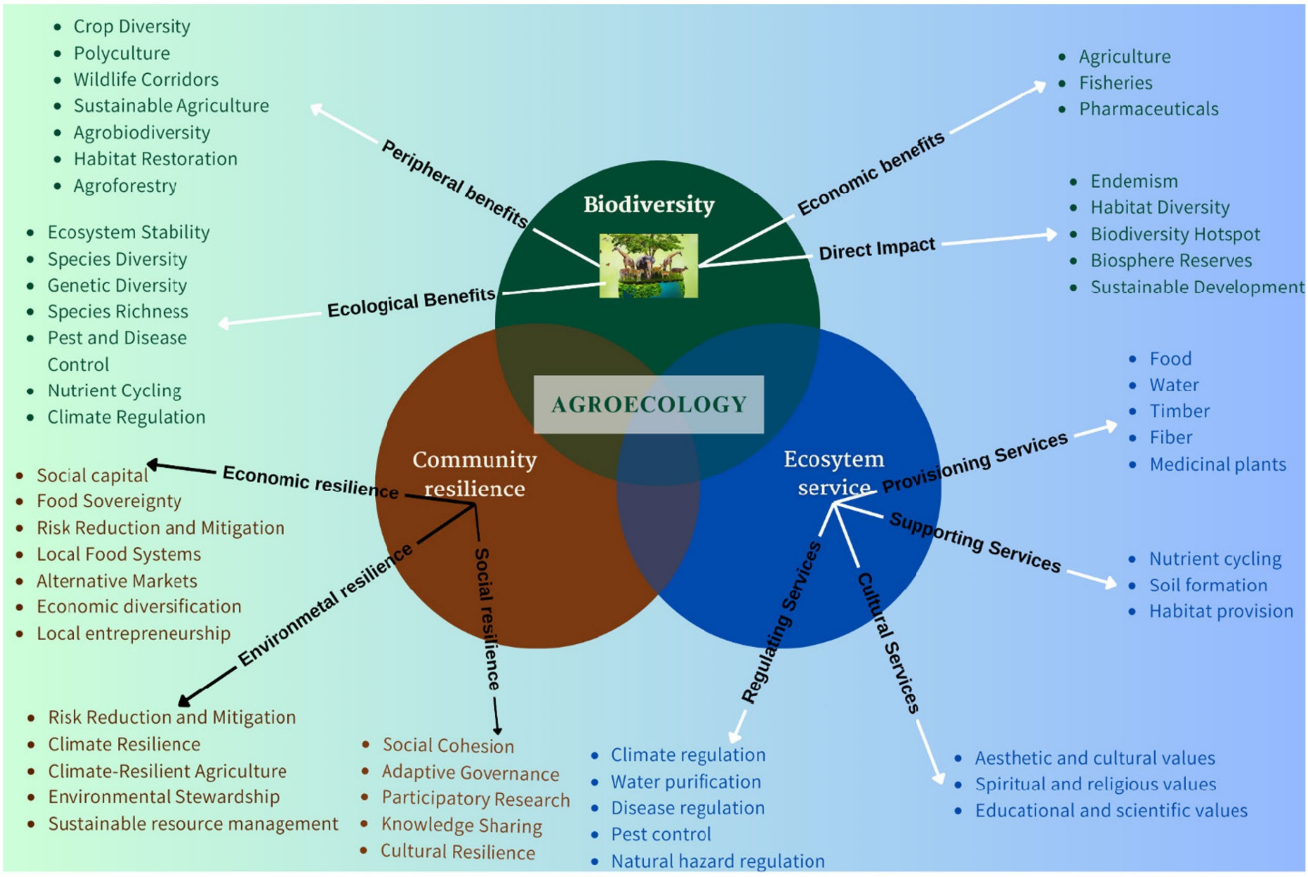
**Resilience:** Making farming systems more resilient is a central agroecological objective. Diverse agroecosystems can better absorb environmental shocks and socio-economic stresses, e.g., drought, pest infestations, market instability, or policy uncertainty. Resilience comes from ecological diversity, adaptive management, and robust community networks (Wezel *et al.*, 2020).

**Recycling:** Agroecology encourages the internal circulation of nutrients, water, and organic matter within the farm system. Production practices like composting, green manuring, and integrating livestock enable the closing of nutrient loops, minimize waste, and enhance soil fertility, thus enhancing environmental sustainability and conserving resources (Brym, and Reeve, 2016).

**Co-creation and Sharing of Knowledge:** One of the salient characteristics of agroecology is its emphasis on participatory practices that integrate scientific knowledge and farmers' experience-based knowledge. Agroecology involves the co-creation of socially appropriate and locally adapted agricultural practices through collaborative innovation, farmer field schools, and community learning (Altieri, 2019).

## Agroecology's Contribution to Climate Change Mitigation

Agroecology has an important role in reducing climate change through the establishment of a synergistic relationship between carbon storage and soil fertility. Agroecology focuses on environmentally friendly practices like cover crops, reduced tillage, crop rotation, and natural inputs, which enhance soil fertility as well as facilitate the capture and storage of atmospheric carbon dioxide ($CO_2$) (Giri and Madla, 2017). These methods help reduce greenhouse gas emissions and increase the resilience of agricultural systems to climatic uncertainty. As a locally adapted and community-led strategy, agroecology presents a sustainable route towards climate action its potential, however, hinges on the presence of enabling policies, institutional arrangements, and access to sufficient resources (Snapp *et al.*, 2021).




(Source, Vikas, and Ranjan, 2024)

**Fig. 2 :** Agroecology component

## Carbon Sequestration in Agriculture

Carbon sequestration is the technique of capturing and storing atmospheric carbon dioxide ($CO_2$) over a long duration (Lal, 2009). In agriculture, this process is mainly the trapping of carbon in soils, plant biomass, and other natural systems. Enhancing the organic matter content of soils is one of the most efficient ways to do this (Mohammadi *et al.*, 2011). Methods like the use of cover crops, the reduction of soil disturbance by lowered tillage, and adding organic amendments such as compost and manure greatly aid in this process (Nogia *et al.*, 2016). These methods not only increase the ability of the soil to sequester carbon but also result in improved soil structure, enhanced water holding capacity, and overall improved crop productivity thus bringing climate mitigation in balance with sustainable agricultural growth.

## Indigenous Knowledge in Agriculture

Indigenous agricultural knowledge is the customary, community-oriented understanding and experience that has been cultivated, honed, and transmitted across generations of farmers (Laforge, 2017). It is embedded in local culture, nature, and spiritual belief, thus being strongly adaptive, context-specific, and sustainable.

One of the identifying features of indigenous knowledge is its local character. It is shaped in direct response to the particular environmental conditions, agro-climatic zones, and cultural heritage of an area (Bogale and Bikkiko, 2018). Experiential and observational learning underpin this system of knowledge, with farmers culling lessons from centuries of working with their land and natural resources. It is embedded in culture and frequently tied to rituals, beliefs, and customs, and generally transmitted by community interaction and communication rather than education (Chwe, 2013). Notably, indigenous knowledge is dynamic, allowing people to adapt to environmental fluctuation and social transformation through the passage of time.

Some examples of indigenous farming practices are numerous and widespread. Farmers in most parts of the world employ traditional pest deterrents, such as neem extract, ash, or cow urine, to manage pests in an environmentally friendly and affordable way. Intercropping or the cultivation of two or more crops simultaneously has been used to minimize pest occurrence, increase soil fertility, and optimize land use efficiency for a long time (Huss *et al*., 2022). Local seed preservation methods, such as the use of natural preservatives such as ash or keeping seeds in clay pots, ensure seed quality and genetic purity. In addition, applying the lunar calendar in directing planting and harvesting operations is a widespread customary practice that synchronizes agriculture operations with nature (Sivasankar and Thimmaiah, 2021).

The importance of indigenous knowledge in contemporary agriculture is that it enhances agrobiodiversity conservation and adaptation to climate change. Most traditional farming systems include the production of a range of diverse and locally adapted crops that are tolerant to biotic and abiotic stresses (Altieri, and Nicholls, 2017). The diversity of such crops is important for the maintenance of food security under varying climatic conditions (Muluneh, 2021). In addition, indigenous knowledge systems ensure sustainable resource management, reduce dependency on external inputs, and enhance ecological balance.

Agroecology is a system that incorporates ecological principles into farming systems to attain sustainability in the long term. It calls for prioritizing biodiversity, applying crop rotation, soil health improvement, and natural pest control (Yadav *et al*., 2021). Agroecological practices also prioritize agroforestry, the integration of trees into agricultural landscapes, and the application of indigenous and local knowledge systems for decision-making and innovation (Saliu *et al*., 2023).

This nature-based approach to agriculture has several advantages, such as enhanced food security, biodiversity conservation, and reduction of climate change effects. By minimizing the use of chemical inputs and promoting ecosystem-based management, agroecology reduces the environmental impact of agriculture while promoting the health of ecosystems and human beings (Patel *et al*., 2020). Additionally, it encourages robust farming systems that can effectively cope with environmental shocks, along with enhancing social fairness, rural livelihoods, and cultural heritage (Reyes *et al*., 2020). Essentially, agroecology provides a revolutionary remedy to tackle interconnected global issues like food shortages, loss of biodiversity, and climate change prioritizing the health of ecosystems and human livelihoods equally (De La Riva *et al*., 2023).

## Global Challenges: The Interlinkages of Food, Water, and Environmental Security

Currently, the world is confronted by interlinked challenges that threaten food and water system stability. Climate change and global warming are interfering with natural patterns of weather, resulting in extreme weather events like droughts, floods, and storms. These events have a devastating impact on agricultural production, thus increasing the exposure of already vulnerable food systems (Tofu *et al*., 2022).

Loss of biodiversity also aggravates these issues. As habitats contract and deteriorate, the vital ecological services they offer, e.g., pollination, nutrient cycling, soil formation, and regulation by natural enemies, are progressively jeopardized. Besides, extensive application of agrochemicals, as much as it aims to increase crop yields, may have disparate unintended consequences on both environmental and human health. Exposure to agrochemicals has been credited with water pollution, soil erosion, and harmful health impacts (World Health Organization, 2021).

In order to meet these pressing challenges, it is vital to embrace agricultural practices that coexist with nature. This calls for urgent and concerted action to protect food and water security, bring back ecological

balance, and deal with the complex relationships between human activities and natural systems (Mishra *et al*., 2021). Agroecology, which stresses sustainability, resilience, and community participation, is a potential solution toward attaining these worldwide objectives.

**Extension Services' role in Sustainable Agriculture**

Extension services for agriculture have traditionally bridged the gap between research organizations and the farming community, making farmers aware of scientific information, better technology, and the best farming practices (Prajapati *et al*., 2025). Yet in sustainable agriculture, the call is increasing to move beyond the conventional top-down extension models to more participatory and inclusive methods that see farmers as co-creators of knowledge not simply as recipients (Lubell and McRoberts, 2018).

In conventional extension models, information and technologies are generally passed on in a linear way from scientists to extension agents and from there to farmers. These strategies tend to emphasize productivity gains through external inputs and uniform practices, with little regard for local knowledge, agroecological diversity, or socio-cultural contexts (Lubell *et al*., 2014).

Conversely, participatory extension models seek to foreground collaboration, discussion, and learning among farmers, researchers, and extension workers (Kaur, and Kaur, 2018). Participatory extension models seek to empower farmers by engaging them actively in decision-making, problem-solving, and innovation generation. Participatory approaches are especially well-suited to support agroecological farming and the integration of indigenous knowledge since they are local reality-based and sensitive to the needs and experiences of farmers (Cremilleux *et al*., 2023). Extension services perform a number of crucial functions to promote sustainable agriculture:

**Knowledge Diffusion and Capacity Development:** Extension agents bring about the diffusion of scientific as well as local knowledge to farmers. They create training activities, workshops, and demonstrations that enhance farmers' technical capacity to undertake sustainable practices like organic farming, integrated nutrient management, and agroforestry (Williamson, 2002). Extension is also responsible for imparting education to farmers on climate-resilient practices, conservation of biodiversity, and sustainable resource utilization.

**Enabling Farmer-Led Innovation:** Participatory extension strategies foster innovation from the ground up by giving due recognition to farmers' experiential knowledge. Extension systems can empower farmer innovators by way of exposure visits, fairs on innovation, and documentation of innovative local practices with success stories. This enables adaptive and scalable solutions that are responsive to local agro-ecological conditions (Dolinska and d'Aquino, 2016).

**Promoting Local Experimentation and Farmer Field Schools (FFS):** Extension activities increasingly facilitate tools like Farmer Field Schools, where farmers undergo experiential, season-long learning and experimentation (Braun, 2000). These schools promote peer-to-peer learning, critical thinking, and ecological literacy so that farmers can experiment and improve sustainable practices under actual field conditions.

**Connecting Farmers to Markets and Policy Assistance:** Apart from knowledge exchange, contemporary extension systems assist in connecting farmers to value chains, markets, and enabling policy frameworks. They can aid in the establishment of producer groups, encourage certification of organic or fair-trade products, and lobby for policies that favor agroecological change and indigenous rights to farm (Raynolds, 2000).

By embracing participatory and inclusive approaches, extension services can become a game-changer in the upscaling of sustainable agriculture. Not only do they serve as knowledge brokers but also as innovation facilitators, partners, and empowers essentials for the transition to equitable and resilient food systems.

**Function of Agricultural Extension in Encouraging Organic Farming**

Agricultural extension has a crucial role in guiding traditional farming systems into sustainability through promoting the uptake of climate-resilient and resource-conserving farm practices (Raynolds *et al*., 2000). Of these, organic agriculture has become a critical pillar in sustainable agriculture. It offers an environmentally friendly alternative to traditional farming systems through its focus on soil health, conservation of biological diversity, ecological balance, and minimum use of synthetic chemical inputs (Lorenz & Lal, 2022).

The successful transition to organic farming is not a change in the method of farming but involves overall comprehension of ecological functions, exposure to advanced technologies, and conducive institutional and policy environments (Wijeratne *et al*., 2024). Extension systems of agriculture serve as the catalyst for this change through the two-way transfer of information from scientific research centers to farming communities. With focused outreach, extension

professionals facilitate the promotion of innovative organic agricultural methods, input management advice, and advising farmers to deal with complex regulatory structures necessary for organic certification (Arowosegbe *et al*., 2024).

In addition, extension services have an important role in building capacity through training farmers, conducting field demonstrations, and exposing them to experiences of successful organic farms (Allahyari, 2009). They also provide advice on planning crops, pests, and nutrient management based on organic concepts, and help connect farmers with organic markets. This not only improves the economic resilience of farmers but also leads to environmental sustainability and better food quality (Allahyari *et al*., 2009)

Organic agriculture has its foundation in the central tenants of building soil fertility, building biological diversity, promoting natural pest control, and reducing dependence on chemical inputs (Kumari *et al*., 2023). Though it has many advantages better soil, environmental conservation, and improved food health the adoption has remained low. Its hindrances come in the form of a lack of knowledge among farmers, restricted access to technical information, poor market linkages, and the time-consuming procedure of procuring organic certification (Santacoloma, 2007).


(Source : Kumar *et al*., 2025)

**Fig. 3:** Benefits of organic farming

Here, agricultural extension presents itself as a strategic facilitator by taking on these issues directly. It provides farmers with experiential learning, enhances their confidence levels in embracing organic methods, and assists them during the transition process. Extension agents also serve as link persons in engaging community-based farmer associations, making government schemes accessible, and for developing organic value chains (Rickards *et al*., 2025).

## Key Elements of Agricultural Extension in Organic Farming

Agricultural extension is a critical component supporting the transition to organic farming by facilitating linkages between scientific information and field-level application (Prajapati *et al*., 2025). The key elements of agricultural extension in the case of organic farming are as follows:

### Capacity Building and Skill Development

Extension services focus on building the capacity of farmers by organizing training programs, workshops, and field demonstrations that educate them on organic farming principles and techniques such as composting, green manuring, and the use of biopesticides (Bažok *et al*., 2022). These efforts enhance farmers' competencies in areas like soil health management, biological pest control, crop rotation, and the organic certification process.

### Awareness Generation

A critical function of extension is to create awareness among farming communities of the environmental, economic, and health advantages of organic agriculture (Alotaibi *et al*., 2021). This is done through several avenues, such as mass media campaign, local sensitization campaigns, farmer field

schools, and participatory rural appraisal (PRA) techniques.

### Technology Transfer

Extension agents enable the use of organic technologies created by research centers, such as organic fertilizers, pest control measures, and disease-resistant crops. They also provide demonstrative use of low-cost, environmentally friendly substitutes for synthetic inputs to foster sustainable agriculture (van Bruggen *et al*., 2016).

### Advisory and Diagnostic Services

Extension agriculture offers on-time and local advice to farmers regarding different practices of organic farming (Gikunda *et al*., 2021). It further assists them with soil testing, identification of pests and diseases, and advice on organic remedies specific to their requirements.

### Market Linkages and Value Addition

Extension services aid farmers in accessing organic markets through linking them with buyers, retailers, and certifying organizations (Barrett *et al*., 2001). They also facilitate activities such as value addition, packaging, branding, and marketing to enable farmers to get improved prices for their organic products.

### Certification and Policy Support

One of the primary roles of extension is to lead farmers through the procedure of getting organic certification, either by way of Participatory Guarantee Systems (PGS) or India's National Programme for Organic Production (NPOP). Extension staff also publicize respective government schemes, subsidies, and policy programs favoring organic farming (Hill, 2016).

### Participatory and Group Approaches

Extension promotes the development of collective institutions like Farmer Producer Organizations (FPOs), cooperatives, and self-help groups (SHGs) to allow for group learning, procurement of inputs, and improved market access. Participatory extension approaches like Farmer Field Schools (FFS) and experiential learning methods are also encouraged to improve farmer participation (Malik and Kajale, 2024).

### Monitoring and Feedback Mechanisms

The effectiveness of the extension interventions is ensured by regular monitoring and evaluation. The farmers' feedback is applied to improve strategies and facilitate adaptive learning, hence ensuring constant improvement in organic farming practices (Bouttes, *et al*., 2019).

### Connectivity to Research and Institutions

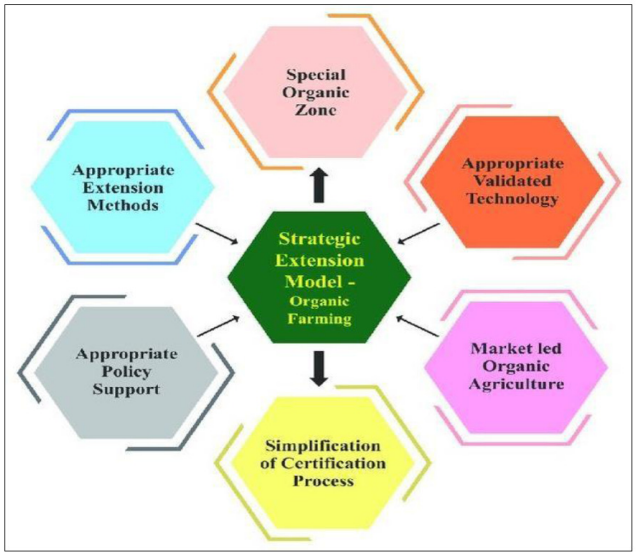
Extension activities try to consolidate the linkage between research institutions, NGOs, certification bodies, and farmer communities. Research, extension, and farmer linkage models are encouraged to develop context-related innovations for organic farming (Braun *et al*., 2000).

**Table 2 :** Key aspects of agricultural extension in organic farming

| Aspect | Role in Organic Farming | Challenges | Future Prospects |
|---|---|---|---|
| **Knowledge Dissemination** | Educates farmers on organic practices, soil health, and sustainability. | Low awareness and limited access to reliable information. | Digital learning platforms, AI-driven advisory services. |
| **Technology Adoption** | Promotes climate-smart and eco-friendly techniques like IPM, biofertilizers. | Resistance to new techniques due to lack of training. | Integration of precision farming, IoT, and automation. |
| **Capacity Building** | Provides training programs, field demonstrations, and workshops. | Insufficient extension personnel and funding. | Public-private partnerships for extensive farmer training. |
| **Policy Support** | Advocates for organic farming incentives and certification simplifications. | Bureaucratic hurdles and high certification costs. | Streamlined certification processes, subsidies for organic inputs. |
| **Market Linkages** | Connects farmers with organic markets, cooperatives, and consumers. | Limited access to premium organic markets. | E-commerce platforms, blockchain for supply chain transparency. |
| **ICT in Extension** | Uses mobile apps, AI chatbots, and digital advisory services for real-time support. | Digital illiteracy and lack of internet infrastructure. | Expansion of mobile- based and cloud computing services. |
| **Sustainability Practices** | Encourages agroforestry, crop rotation, and natural pest control. | Climate variability affecting productivity. | Climate-resilient crop varieties and integrated organic systems. |
| **Farmer Empowerment** | Enhances decision-making, self-reliance, and cooperative development. | Dependency on subsidies and lack of institutional support. | Strengthened farmer-led participatory models and rural entrepreneurship. |

(Source, Kumar *et al*., 2025)

In conclusion, a proper agricultural extension system is essential for organic farming upscaling. By closing the knowledge gap, enhancing institutional support, and improving market integration, extension services enable farmers to adopt sustainable agrisystems that ensure livelihoods alongside environmental well-being.




(Source, Kumar *et al*., 2025)

**Fig. 4:** Strategic Extension Model for Empowering Farmers through Organic Farming (Paramasivam *et al*., 2022)

## Strategic Extension Model towards Empowering Farmers through Organic Farming

A strategic extension model is an overarching framework towards empowering farmers by promoting the implementation of organic farming practices that lead towards enhanced livelihood security and environmentally sustainable living. Paramasivam *et al*. (2022) explain that the model encompasses several elements of knowledge extension, skill acquisition, institutional assistance, and linkage with the market to create a seamless shift from conventional to organic farming.

The model is participatory in nature, where farmers are not mere passive recipients of information but active collaborators in the process of learning and decision-making. It incorporates need-based training, on-farm demonstrations, and farmer field schools to raise awareness and technical skills in organic farming techniques like composting, biofertilizer application, integrated pest management, and crop rotation.

In addition, the strategic extension model encourages development of and strengthening in Farmer Producer Organizations (FPOs), Self-Help Groups (SHGs), and community-based groups for enhanced collective action, enhanced bargaining capacity, and ease of access to inputs, credit, and organic markets (Röling and Pretty, 1997). It also includes provisions for certification assistance, value addition, branding, and direct marketing of organics for enhanced price realization (Lohr, 1998).

Significantly, the model aims at harmonization with policy structures and government programs facilitating promotion of organic farming, ensuring institution convergence and intervention sustainability. By synthesizing scientific information with local improvements and indigenous wisdom, this model not only strengthens the economy of farmers but also promotes environmental resilience and rural development (Šūmane *et al*., 2018).

Effectively, the strategic extension model offers an integrated process for enhancing farmers' ability to uptake organic farming, increasing income security, minimizing reliance on external inputs, and developing sustainable agricultural development.

## Synthesizing Agroecology and Indigenous Knowledge through Extension

Synthesis of agroecology and indigenous knowledge systems in extension services is crucial in advocating for sustainable, context-appropriate, and agroecologically resilient agricultural practices (Kuria *et al*., 2025). Participatory, inclusive, and culturally appropriate extension programs are more efficient in acknowledging the worth of conventional practices and improving them with science-based innovations.

## Participatory Approaches

Participatory methods are at the heart of effective integration. Farmer Field Schools (FFS) is an example, where farmers go through experiential, season-long learning in their own fields. Farmers develop their capacity for agroecological practices and corroborate traditional methods through joint observation, experimentation, and collective reflection (Lacombe *et al*., 2018). FFS platforms promote critical thinking and support peer learning, providing the positive environment for integrating modern ecological knowledge with indigenous know-how.

Equally, Participatory Rural Appraisal (PRA) allows communities to diagnose their own agricultural situations, problems, and resources using mapping, ranking, and group discussion. This facilitates the extension agents in understanding local realities and designing interventions accordingly, with a culture and ecology focus (Easdale *et al*., 2020).

Community seed banks and knowledge sharing platforms are key grassroots institutions that maintain local crop varieties and traditional farming wisdom. These platforms enable farmers to conserve agrobiodiversity, share resilient seeds, and record region-specific practices, thus strengthening community-based agroecological transitions.

**Capacity Building and Sensitization**

Successful integration also involves specific capacity development and sensitization. Education of extension workers in agroecological concepts, ethnobotany, and indigenous knowledge systems gives them the necessary instruments to identify, respect, and strengthen traditional practices (Kumar *et al*., 2021). In addition, involving indigenous leaders and seasoned farmers as co-trainers or resource persons in training improves credibility, local commitment, and bridging between formal and informal knowledge systems.

**Documentation and Validation**

An important advancement towards the validation of indigenous practices is the systematic recording of indigenous agro-ecological knowledge (Alzate *et al*., 2019) Traditional techniques pertaining to pest management, seed choice, irrigation, and soil fertility maintenance are recorded. After recording, the practices can be scientifically tested to determine their effectiveness, flexibility, and possibility of large-scale application. Through joint validation procedures, extension services can improve and increase effective traditional innovations while maintaining their cultural significance (Adefila *et al*., 2024).

**Policy and Institutional Support**

Institutional and policy-level interventions play a pivotal role to establish an enabling environment for integration of agroecological and indigenous knowledge. Bottom-up extension planning, where farmers are directly involved in program design and implementation, guarantees relevance and ownership. Governments and development agencies must facilitate policy frameworks that promote agroecological transitions, like subsidies for organic inputs, recognition of traditional seed systems, and promoting biodiversity-enhancing practices (MacPherson, 2024). In addition, incorporating indigenous knowledge into national extension curricula and research programs will ensure long-term sustainability and universality in agricultural growth.

**Case Studies and Success Stories**

Examples of effective mainstreaming of agroecology and indigenous knowledge within extension systems provide important lessons and insights for scaling up sustainable agriculture practices. These case studies illustrate how participatory strategies, enabling policies, and community participation can bring about transformative change.

**Andhra Pradesh Community Managed Natural Farming (APCNF), India**

The Andhra Pradesh Community Managed Natural Farming (APCNF) programme is one of the world's largest agroecological shifts. Applied on millions of hectares and by thousands of farmers, APCNF prioritizes low-cost, environmentally friendly practices based on the wisdom of local know-how. The program encourages methods like mulching, intercropping, indigenous cow-based preparations (like Jeevamrutha), and non-pesticidal management. Extension support comes through farmer-to-farmer communication, women self-help groups, and village-level resource persons. The success of APCNF results from its participatory nature that respects local knowledge, improves soil fertility, minimizes external input reliance, and enhances farmers' livelihoods and climate resilience.

**Zai Pits in Burkina Faso**

Zai pits, a time-tested water harvesting and soil fertility method, have been revived and up-scaled through extension-driven interventions across Burkina Faso's semi-arid areas. Zai pits are excavating small planting holes that focus organic material and water, thus restoring degraded land and raising crop yields. First practiced by a handful of indigenous farmers, it spread with the encouragement of local extension agents and development initiatives. By linking indigenous ingenuity with new extension outreach, communities have restored millions of hectares of dry land, boosted food production, and established drought resilience. The case illustrates how identification and support for indigenous practices result in sustainable land use.

**Sikkim Organic Mission, India**

The Sikkim Organic Mission was a policy-based program that was able to convert the entire state of Sikkim into a certified organic agriculture area by adopting traditional farming techniques and modern organic norms. Extension activities played a key role in educating farmers, encouraging composting, indigenous pest management, and organic certification processes. Local wisdom was utilized to develop organic practices adapted to the agro-climatic and cultural conditions of the state. Capacity building, economic incentives, and high-level political will were

part of the mission, transforming Sikkim into a worldwide model for organic and sustainable agriculture. It exhibits the strength of policy environment support in institutionalizing traditional wisdom and agroecology at scale.

**Challenges and Limitations**

Though the integration of agroecology and traditional knowledge by extension services holds a promising key to sustainable farming, there are a number of challenges and limitations that still stand in the way of its universal application and institutionalization.

**Knowledge Gap among Extension Workers**

One of the major obstacles is the scant expertise of extension workers in perceiving and disseminating agroecological concepts and traditional knowledge systems. Most agricultural extension training curriculum and programs are still very much focused on conventional, input-based farming paradigms. It follows that many extension agents are not adequately aware, capable, or confident to work with traditional approaches or to manage participatory learning situations. Closing this knowledge divide will involve targeted reorientation and capacity-building interventions with a focus on ecological literacy and cultural sensitivity.

**Institutional Resistance to Non-Conventional Practices**

Institutional resistance and skepticism regarding non-conventional farming methods are another major impediment. Most public and private agricultural institutions remain wedded to technology-centric, high-input, standard-output solutions, and tend to belittle traditional knowledge as unscientific or archaic. Such resistance is further enhanced by strong research agendas and bureaucratic extension procedures that sideline local experimentation and farmer innovation. Transcending these attitudes requires institutional reforms at the system level, cross-disciplinary teamwork, and enhanced farmer-researcher-extension interfaces.

**Lack of Documentation of Indigenous Knowledge**

Though rich and contextually relevant, indigenous farm knowledge is not well documented, but passed orally from one generation to another and in danger of being forgotten. The lack of formal documentation and validation systems constrains the documentation and incorporation of local practices into formal extension systems. Moreover, since there are no records, it is difficult to spread and scale these practices outside their original locality. There exists an urgent imperative for collective action to document, assess, and conserve indigenous knowledge in a culturally sensitive and scientifically excellent way.

**Policy and Funding Biases Toward Industrial Agriculture**

Policy and funding environments in most nations still tilt towards industrial, monoculture-based agricultural systems, frequently excluding ecological and traditional methods. Subsidies on chemical inputs, yield maximization priorities, and encouragement of export-oriented production systems circumvent the advancement of agroecology and traditional practices. Investment deficits in community-driven extension services, participatory research, and agroecological training further curtail the ability of farmers and extension workers to shift towards sustainable systems. These biases are addressed by aligning agricultural policies and fund priorities towards supporting localized, low-cost, and environmentally friendly innovations.

**Way Forward**

Strengthening the integration of agroecology and local knowledge in sustainable agriculture requires a multi-faceted and inclusive strategy. Extension systems need to change to become more responsive, participatory, and adaptive to local ecological and cultural situations. The following strategic directions are recommended towards initiating this change:

**Curriculum Reform in Extension Education**

There is a pressing necessity to reform and update extension education curricula to include agroecological approaches and indigenous knowledge of farming. Agricultural universities and training centers need to integrate modules on agroecology, traditional ecological knowledge (TEK), participatory approaches, and social learning processes into formal training courses. Such reform will assist in developing the next generation of extension professionals who are ecologically aware, culturally attuned, and better positioned to facilitate sustainable and resilient agriculture.

**Public-Private Partnerships in Sustainable Farming Initiatives**

Public institutions, non-governmental organizations, and private stakeholders can come together to form synergies for facilitating agroecological transitions. PPPs can facilitate scaling of successful indigenous practices, farmer innovation platforms, and community-based extension model

resource mobilization. Public-private partnerships must focus on equity, transparency, and farmers' empowerment, with the local community at the center of planning and decision-making.

**Use of ICT Tools for Documentation and Dissemination**

Information and Communication Technologies (ICTs) provide useful resources for recording, storing, and sharing indigenous agricultural knowledge. Mobile applications, digital narratives, online archives, and radio shows are able to close the intergenerational and geographical gap by sharing indigenous practices with a wider public. Interactive platforms can also support timely exchange of knowledge between farmers, researchers, and extension workers, enabling co-creation and innovation.

**Policy Advocacy for Inclusive Extension Models**

A durable change must have effective policy advocacy so that extension systems become inclusive and farmer-led. Policymakers must appreciate and reward farmers not as mere receivers of technology but as guardians and co-producers of information. This involves the promotion of decentralized, demand-driven extension strategies that are consistent with agroecological philosophies. It also means institutional support for farmer field schools, community seed banks, and knowledge-sharing networks. Policies must be realigned to offer incentives for ecologically friendly practices, safeguard intellectual property rights to indigenous knowledge, and provide fairly equal access to extension services.

**Future Directions**

In the future, a number of good areas will help improve agroecology and indigenous knowledge integration through extension services in order to promote sustainable agriculture in the world.

**Scaling Up Digital and Mobile-Based Extension Tools**

The increased availability of digital technologies provides an unprecedented chance to take agroecological and indigenous expertise to marginal and geographically isolated farming communities. Mobile applications, SMS advisories, interactive voice response systems, and web platforms can provide site-specific information, enable real-time decision-making, and foster knowledge exchange community-based. Horizontal scaling of such digital extension systems will enhance accessibility and equity in agricultural extension.

**Strengthening Farmer Networks and Cooperatives**

The establishment and nurturing of farmer networks, cooperatives, and community organizations can promote peer-to-peer learning and collective innovation. These systems allow farmers to exchange traditional practices, test in collective ways, and upscale locally adapted agroecological approaches. Organized farmer groups can also promote increased market access, input sourcing, and advocacy, enhancing overall rural resilience.

**Integration of Agroecological Education in Formal Curricula**

Integration of agroecology and indigenous knowledge into formal agricultural instruction and extension training will make these methods mainstream. Integration of these subjects at the undergraduate, graduate, and professional levels will provide a constant source of extension agents and scientists well-equipped to facilitate transitions toward sustainable farming based on ecological and cultural principles.

**More Research on Scientific Verification of Traditional Practices**

Thorough scientific assessment and verification of traditional farming practices are necessary to ensure greater support among policymakers, researchers, and farmers. Interdisciplinary research that honors the local knowledge systems but incorporates modern scientific approaches has the potential to produce rigorous evidence of effectiveness, which can lead to integration into policy guidelines and extension advice.

**Policy Reforms for Inclusive Extension Services**

Last but not least are policy reforms focused on prioritizing inclusive, bottom-up extension models. Identifying farmers as agent knowledge holders and co-producers and offering institutional and financial support for community-based extension methods will ensure sustainable livelihoods and ecological stewardship. Policies must also protect intellectual property rights on indigenous knowledge and encourage agroecological transitions.

**Table 3 :** Challenge and future prospects in Enhancing Extension Services for Sustainable Farming Integrating Agroecology.

| Aspect | Challenges | Future Prospects |
|---|---|---|
| **Knowledge & Capacity** | - Limited awareness and understanding of agroecology and indigenous knowledge among extension workers. - Insufficient training on participatory and inclusive extension approaches. | - Curriculum reform to include agroecology and indigenous knowledge in extension education. - Capacity building through continuous training and involvement of indigenous experts. |
| **Institutional Support** | - Resistance from conventional agricultural institutions toward non-conventional farming practices. - Lack of policy support for agroecological and indigenous extension models. | - Policy advocacy for inclusive extension models that recognize farmers as knowledge holders. - Encouragement of bottom-up extension planning and institutional flexibility. |
| **Documentation & Validation** | - Inadequate systematic documentation and scientific validation of indigenous practices. - Loss of traditional knowledge due to modernization and urban migration. | - Use of ICT tools to document, disseminate, and preserve indigenous knowledge. - Increased research on scientific validation of traditional methods. |
| **Funding & Resources** | - Funding biases favoring industrial agriculture and high-input farming systems. - Limited resources allocated for agroecological extension and farmer participatory programs. | - Promotion of public-private partnerships to support sustainable farming initiatives. - Allocation of dedicated funds for participatory and agroecology-focused extension activities. |
| **Farmer Engagement** | - Limited farmer participation in extension program design and implementation. - Challenges in scaling up local knowledge-sharing platforms and farmer networks. | - Strengthening farmer networks and cooperatives for peer-to-peer learning and wider knowledge exchange. - Adoption of participatory extension tools like Farmer Field Schools and community seed banks. |
| **Technology Integration** | - Limited access and digital literacy for remote and marginalized farming communities. | - Expansion of mobile and digital extension tools tailored for agroecology and indigenous knowledge sharing. - Development of user-friendly ICT platforms to enhance connectivity and learning. |

## Conclusion

The marriage of agroecological principles and indigenous knowledge through responsive, participatory, and inclusive extension services is a key route toward sustainable agriculture. This convergence empowers farmers by authenticating their experiential wisdom, scaling up their capacities for adaptation, and enhancing resilient farming systems that preserve biodiversity and natural resources. Extension systems are central to the intermediary function in bringing scientific knowledge and traditional practices together, enabling co-creation of locally appropriate innovations. For agri-transformation to be sustainable, extension services need to move away from traditional top-down approaches and adopt farmer-led strategies that respect cultural heritage and environmental sustainability. Strengthening this integrated setup will go a long way in achieving food sovereignty, environmental sustainability, and sustainable rural livelihoods.

## References

Adefila, A. O., Ajayi, O. O., Toromade, A. S., & Sam-Bulya, N. J. (2024). Integrating traditional knowledge with modern agricultural practices: A sociocultural framework for sustainable development. *Journal of Sustainable Agriculture and Development*.

Allahyari, M.S. (2009). Agricultural sustainability: Implications for extension systems. *African Journal of Agricultural Research*, **4**(9), 781-786.

Allahyari, M. S., Chizari, M. & Mirdamadi, S. M. (2009). Extension-education methods to facilitate learning in sustainable agriculture. *Journal of Agriculture & Social Sciences*, **5**(1-2), 27-30.

Alotaibi, B. A., Yoder, E., Brennan, M. A., & Kassem, H. S. (2021). Perception of organic farmers towards organic agriculture and role of extension. *Saudi Journal of Biological Sciences*, **28**(5), 2980-2986.

Altieri, M. A. (2019). Agroecology: principles and practices for diverse, resilient, and productive farming systems. In *Oxford Research Encyclopedia of Environmental Science*.

Altieri, M.A., & Nicholls, C.I. (2017). The adaptation and mitigation potential of traditional agriculture in a changing climate. *Climatic change*, *140*, 33-45.

Altieri, M. A., Nicholls, C. I., Henao, A., & Lana, M. A. (2015). Agroecology and the design of climate change-resilient farming systems. *Agronomy for sustainable development*, **35**(3), 869-890.

Alzate, C., Mertens, F., Fillion, M., & Rozin, A. (2019). The study and use of traditional knowledge in agroecological contexts. *Revista de La Facultad de Ciencias Agrarias UNCuyo*, **51**(1), 337-350.

Arowosegbe, O. B., Alomaja, O. A., & Tiamiyu, B. B. (2024). The role of agricultural extension workers in transforming agricultural supply chains: Enhancing innovation, technology adoption, and ethical practices in Nigeria. *World Journal of Advanced Research and Reviews*, **23**(3), 2585-2602.

Barrett, H. R., Browne, A. W., Harris, P. J. C., & Cadoret, K. (2001). Smallholder farmers and organic certification: Accessing the EU market from the developing world. *Biological agriculture & horticulture*, **19**(2), 183-199.

Bažok, R., Čačija, M., Karoglan Kontić, J., Kramarič, M., Lemić, D., Stolz, M., & Takács, E. (2022). Training manual for plant protection in organic farming.

Bogale, H. D., & Bikiko, S. S. (2018). The role of indigenous knowledge in climate change adaptation: The case of Gibe Woreda, Hadiya Zone, Ethiopia. *International journal of environmental protection and policy*, **5**(6), 104-113.

Bouttes, M., Darnhofer, I., & Martin, G. (2019). Converting to organic farming as a way to enhance adaptive capacity. *Organic Agriculture*, **9**, 235-247.

Braun, A. R., Thiele, G., & Fernández, M. (2000). Farmer field schools and local agricultural research committees: complementary platforms for integrated decision-making in sustainable agriculture.

Brodt, S., Six, J., Feenstra, G., Ingels, C., & Campbell, D. (2011). Sustainable agriculture. *Nat. Educ. Knowl*, **3**(1).

Brym, Z. T., & Reeve, J. R. (2016). Agroecological principles from a bibliographic analysis of the term agroecology. *Sustainable Agriculture Reviews: Volume* **19**, 203-231.

Chen, H. G., & Zhang, Y. H. P. (2015). New biorefineries and sustainable agriculture: Increased food, biofuels, and ecosystem security. *Renewable and Sustainable Energy Reviews*, **47**, 117-132.

Chwe, M. S. Y. (2013). *Rational ritual: Culture, coordination, and common knowledge*. Princeton University Press.

Cremilleux, M., Michaud, A., Cayre, P., Martin, B., Rigolot, C., & Michelin, Y. (2023). Combining systemic and pragmatic approaches for the holistic diagnosis of a farm in agroecological transition in a health context. *Frontiers in Sustainable Food Systems*, **7**, 875820.

Darr, D., Hoffmann, V., & Helmle, S. (2013). Extension services for rural development. In *Forests and rural development* (pp. 205-240). Berlin, Heidelberg: *Springer Berlin Heidelberg*.

de la Riva, E. G., Ulrich, W., Batáry, P., Baudry, J., Beaumelle, L., Bucher, R., *et al*. (2023). From functional 605 diversity to human well-being: a conceptual framework for agroecosystem 606 sustainability. *Agric. Syst.* 208:103659.

Dolinska, A., & d'Aquino, P. (2016). Farmers as agents in innovation systems. Empowering farmers for innovation through communities of practice. *Agricultural systems*, **142**, 122-130.

Easdale, M. H., Pérez León, N., & Aguiar, M. R. (2020). Strains in sustainability debates: traditional ecological knowledge and western science through the lens of extension agents in a pastoral region. *Rural Sociology*, **85**(1), 57-84.

Ewert, F., Baatz, R., & Finger, R. (2023). Agroecology for a sustainable agriculture and food system: from local solutions to large-scale adoption. *Annual Review of Resource Economics*, **15**(1), 351-381.

Francis, C., Lieblein, G., Gliessman, S., Breland, T. A., Creamer, N., Harwood, R., Salomonsson, L., Helenius, J., Rickerl, D., Salvador, R., Wiedenhoeft, M., Simmons, S., Allen, P., Altieri, M., Flora, C., & Poincelot, R. (2003). Agroecology and agroecosystems: The ecology of food systems. *Journal of Sustainable Agriculture*, **22**(3), 99–118.

Gikunda, R. M., Lawver, D. E., Baker, M., Boren-Alpizar, A. E., & Guo, W. (2021). Extension education needs for improved adoption of sustainable organic agriculture in Central Kenya.

Giri, R.K.K.V., and Madla, V. R. (2017). Study and evaluation of carbon sequestration using remote sending and GIS: a review on various techniques. *Int. J. Civil Eng. Technol.* **8**, 287–300.

Gonsalves, J. F. (2005). *Participatory research and development for sustainable agriculture and natural resource management: a sourcebook* (Vol. 1). IDRC.

Hill, J. K. (2016). Organic agriculture in India and participatory guarantee systems (PGS): A case study from West Bengal. *Jharkhand Journal of Development and Management Studies*, **14**(2), 7037-7055.

Hossain, A., Krupnik, T. J., Timsina, J., Mahboob, M. G., Chaki, A. K., Farooq, M.,... & Hasanuzzaman, M. (2020). Agricultural land degradation: Processes and problems undermining future food security. In Environment, Climate, Plant and Vegetation Growth (pp. 17-61). Cham: *Springer International Publishing*.

Huss, C. P., Holmes, K. D., & Blubaugh, C. K. (2022). Benefits and risks of intercropping for crop resilience and pest management. *Journal of economic entomology*, **115**(5), 1350-1362.

Jasrotia, P., Kumari, P., Malik, K., Kashyap, P. L., Kumar, S., Bhardwaj, A. K., & Singh, G. P. (2023). Conservation agriculture based crop management practices impact diversity and population dynamics of the insect-pests and their natural enemies in agroecosystems. *Frontiers in Sustainable Food Systems*, **7**, 1173048.

Kaur, K., & Kaur, P. (2018). Agricultural extension approaches to enhance the knowledge of farmers. *International Journal of Current Microbiology and Applied Sciences*, **7**(2), 2367-2376.

Kumar, A., Kumar, S., Komal, Ramchiary, N., & Singh, P. (2021). Role of traditional ethnobotanical knowledge and indigenous communities in achieving sustainable development goals. *Sustainability*, **13**(6), 3062.

Kumar, C., Kumar, M., & Kumar, D. (2025). The Extension Services in Advancing Organic Farming: A Global Perspective. *Journal of Scientific Research and Reports* **31**(3): 96-106

Kumari, S., Kumar, R., Chouhan, S., & Chaudhary, P. L. (2023). Influence of various organic amendments on growth and yield attributes of mung bean (*Vigna radiata* L.). International Journal of Plant & Soil Science, **35**(12), 124-130.

Kuria, A. W., Pagella, T., Muthuri, C. W., & Sinclair, F. L. (2025). Revisiting agroecological transitions in Rwanda a decade later: the role of local knowledge in understanding the crop diversity–food security–land degradation nexus. *Frontiers in Agronomy*, **7**, 1537012.

Lacombe, C., Couix, N., & Hazard, L. (2018). Designing agroecological farming systems with farmers: A review. *Agricultural systems*, **165**, 208-220.

Laforge, J. (2017). Farmer knowledge in alternative agriculture: Community learning and the politics of knowledge.

Lal, R. (2008). Soils and sustainable agriculture. A review. *Agronomy for Sustainable Development*, **28**, 57-64.

Lal, R. (2009). Sequestering atmospheric carbon dioxide. *Critical Reviews in Plant Science*, **28**(3), 90-96.

Lohr, L. (1998). Implications of organic certification for market structure and trade. *American Journal of Agricultural Economics*, **80**(5), 1125-1129.

Lorenz, K., & Lal, R. (2022). Combining conventional and organic practices to reduce climate impacts of agriculture. In Organic Agriculture and Climate Change (pp. 201-218). Cham: *Springer International Publishing.*

Lubell, M., & McRoberts, N. (2018). Closing the extension gap: Information and communication technology in sustainable agriculture. *California Agriculture*, **72**(4).

Lubell, M., Niles, M., & Hoffman, M. (2014). Extension 3.0: Managing agricultural knowledge systems in the network age. *Society & Natural Resources*, **27**(10), 1089-1103.

MacPherson, J. (2024). Addressing uncertainty and normativity in agricultural sustainability assessment: the example of agricultural digitalization.

Malik, S., & Kajale, D. (2024). Empowering small and marginal farmers: Unveiling the potential and addressing obstacles of farmer producer organizations in India. *Research on World Agricultural Economy*, **5**(1), 32-47.

Mishra, B. K., Kumar, P., Saraswat, C., Chakraborty, S., and Gautam, A. (2021). Water security in a changing environment: concept, challenges and solutions. Water 13:490.

Mohammadi, K., Heidari, G., Khalesro, S., & Sohrabi, Y. (2011). Soil management, microorganisms and organic matter interactions: A review. *African Journal of Biotechnology*, **10**(86), 19840.

Mrunalini, K., Behera, B., Jayaraman, S., Abhilash, P. C., Dubey, P. K., Swamy, G. N., ... & Srinivasa Rao, C. (2022). Nature-based solutions in soil restoration for improving agricultural productivity. *Land Degradation & Development*, **33**(8), 1269-1289.

Muluneh, M. G. (2021). Impact of climate change on biodiversity and food security: a global perspective—a review article. *Agriculture & Food Security*, **10**(1), 1-25.

Nagothu, U. S., & Chatrchyan, A. M. (2018). Agriculture development and sustainable intensification: Innovations to strengthen extension services and improve market value chains. In *Agricultural Development and Sustainable Intensification* (pp. 230-249). Routledge.

Nicholls, C.I., Altierit, M.A., & Vazquez, L. (2017). Agroecological Principles. *Agroecological practices for sustainable agriculture: Principles, applications, and making the transition*, 1.

Nicolétis, É., Caron, P., El Solh, M., Cole, M., Fresco, L. O., Godoy-Faúndez, A., ... & Zurayk, R. (2019). Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security.

Nogia, P., Sidhu, G. K., Mehrotra, R., and Mehrotra, S. (2016). Capturing atmospheric carbon: biological and nonbiological methods. *Int. J. Low-Carbon Technol.* **11**, 266–274.

Otieno, M. (2024). Ecology-Based Concepts of Sustainable Agriculture. In *Sustainable Agroecological Practices in Sub-Saharan Africa in the Face of Climate Change* (pp. 129-192). Cham: Springer Nature Switzerland.

Paramasivam, S., Henry, P., Seethapathy, P., & Rajamohan, T. (2022). A strategic model for empowering farmers by improving livelihood security through organic farming practices in Tamil Nadu, India. *Journal of Agricultural Sciences–Sri Lanka,* **17**(3).

Patel, S. K., Sharma, A., and Singh, G. S. (2020). Traditional agricultural practices in India: an approach or environmental sustainability and food security. *Energy Ecol. Environ*. **5**, 253–271.

Prajapati, C. S., Priya, N. K., Bishnoi, S., Vishwakarma, S. K., Buvaneswari, K., Shastri, S., ... & Jadhav, A. (2025). The Role of Participatory Approaches in Modern Agricultural Extension: Bridging Knowledge Gaps for Sustainable Farming Practices. *Journal of Experimental Agriculture International*, **47**(2), 204-222.

Rahman, M. A., & Rahman, S. (2015). Natural and traditional defense mechanisms to reduce climate risks in coastal zones of Bangladesh. *Weather and Climate Extremes*, **7**, 84-95.

Rai, A. K., Bana, S. R., Sachan, D. S., & Singh, B. (2023). Advancing sustainable agriculture: a comprehensive review for optimizing food production and environmental conservation. *Int. J. Plant Soil Sci*, **35**(16), 417-425.

Raynolds, L. T. (2000). Re-embedding global agriculture: The international organic and fair trade movements. *Agriculture and human values*, **17**, 297-309.

Rehman, A., Farooq, M., Lee, D. J., & Siddique, K. H. (2022). Sustainable agricultural practices for food security and ecosystem services. *Environmental Science and Pollution Research*, **29**(56), 84076-84095.

Reyes, S. R. C., Miyazaki, A., Yiu, E., and Saito, O. (2020). Enhancing sustainability in traditional agriculture: indicators for monitoring the conservation of globally important agricultural heritage systems (GIAHS) in Japan. *Sustainability* **12**:5656.

Rickards, C., Marenya, P., Chiduwa, M., Eitzinger, A., Fisher, M., & Snapp, S. (2025). Enhancing farmers' agency is a more effective extension paradigm: The case of soil health management in Africa. *Agricultural Systems,* **225**, 104267.

Röling, N., & Pretty, J. N. (1997). Extension's role in sustainable agricultural development. *Improving agricultural extension: A reference manual*, 181-192.

Saliu, F., Luqman, M., and Alkhaz'leh, H. S. (2023). A review on the impact of sustainable agriculture practices on crop yields and soil health. *Int. J. Res. Adv.Agric. Sci.* **2**, 1–13.

Santacoloma, P. (2007). Organic certification schemes: managerial skills and associated costs. *Synthesis report from case studies in the rice and vegetable sectors. AGSF Occasional paper*, *16*.

Singh, J. S., Pandey, V. C., & Singh, D. P. (2011). Efficient soil microorganisms: a new dimension for sustainable agriculture and environmental development. *Agriculture, ecosystems & environment*, **140**(3-4), 339-353.

Sivasankar, J., & Thimmaiah, A. (2021). Lunar rhythms in agriculture-review on scientific perspectives. *Int. J. Complement. Altern. Med*, **14**, 81-85.

Snapp, S. (2017). Agroecology: Principles and practice. In *Agricultural systems* (pp. 33-72). Academic Press.

Snapp, S., Kebede, Y., Wollenberg, E., Dittmer, K. M., Brickman, S., Egler, C., & Shelton, S. (2021). Agroecology and climate change rapid evidence review: Performance of agroecological approaches in low-and middle-income countries.

Stagnari, F., Ramazzotti, S., & Pisante, M. (2010). Conservation agriculture: a different approach for crop production through sustainable soil and water management: a review. *Organic Farming, Pest Control and Remediation of Soil Pollutants: Organic farming, pest control and remediation of soil pollutants*, 55-83.

Šūmane, S., Kunda, I., Knickel, K., Strauss, A., Tisenkopfs, T., des Ios Rios, I., ... & Ashkenazy, A. (2018). Local and farmers' knowledge matters! How integrating informal and formal knowledge enhances sustainable and resilient agriculture. *Journal of Rural Studies*, **59**, 232-241.

Thomas, V. G., & Kevan, P. G. (1993). Basic principles of agroecology and sustainable agriculture. *Journal of Agricultural and Environmental Ethics*, ***6***, 1-19.

Tofu, D. A., Woldeamanuel, T., and Haile, F. (2022). Smallholder farmers' vulnerability and adaptation to climate change induced shocks: the case of northern Ethiopia highlands. *J. Agric. Food Res.* **8**, 100312:100312.

Umesha, S., Manukumar, H. M., & Chandrasekhar, B. (2018). Sustainable agriculture and food security. In *Biotechnology for sustainable agriculture* (pp. 67-92). Woodhead Publishing.

van Bruggen, A. H., Gamliel, A., & Finckh, M. R. (2016). Plant disease management in organic farming systems. *Pest Management Science*, **72**(1), 30-44.

Vikas, & Ranjan, R. (2024). Agroecological approaches to sustainable development. *Frontiers in Sustainable Food Systems*, **8**, 1405409.

Westcott, P. C., & Trostle, R. (2012). Long-term prospects for agriculture reflect growing demand for food, fiber, and fuel. *Amber Waves: The Economics of Food, Farming, Natural Resources, and Rural America*, (3).

Wezel, A., Bellon, S., Doré, T., Francis, C., Vallod, D., & David, C. (2009). Agroecology as a science, a movement and a practice. A review. *Agronomy for sustainable development*, **29**, 503-515.

Wezel, A., Herren, B. G., Kerr, R. B., Barrios, E., Gonçalves, A. L. R., & Sinclair, F. (2020). Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. *Agronomy for Sustainable Development*, **40**, 1-13.

Wijeratne, M., & De Silva, W. N. (2024). The paradigm shift of agricultural extension from technology transfer towards participatory approaches. *Journal of Agricultural Sciences–Sri Lanka*, **19**(1).

Williamson, S. (2002). Challenges for farmer participation in integrated and organic production of agricultural tree crops.

Wojtkowski, P. (2006). *Introduction to agroecology: principles and practices*. CRC Press.

World Health Organization (2021). Nature, biodiversity and health: an overview of interconnections. Bonn: World Health Organization.

Yadav, S. K., Banerjee, A., Jhariya, M. K., Raj, A., Khan, N., Meena, R. S., *et al*. (2021). "Agroecology towards environmental sustainability" in Sustainable intensification for agroecosystem services and management (Cham: Springer), 323–352.