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Agroecological transitions: Reviewing crop diversification as a foundation for sustainable farming systems

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Abstract

Agricultural systems worldwide are confronting interconnected challenges of soil degradation, biodiversity decline, climate variability, and socio-economic instability arising from intensive monoculture-based production systems. Agroecological transitions centered on crop diversification are increasingly recognized as sustainable pathways for enhancing resilience and ecological sustainability. This review critically synthesizes recent Indian and global literature on diversified cropping systems, including crop rotations, intercropping, cover cropping, multiple cropping, and agroforestry. Evidence from diverse agroecological regions demonstrates that crop diversification improves soil fertility, enhances biodiversity, stabilizes yields, reduces pest and disease incidence, and strengthens climate resilience while supporting farmer livelihoods. The review integrates state-level experiences from India with international case studies to evaluate ecological, agronomic, socio-economic, and policy dimensions of diversification. Findings indicate that crop diversification offers a scalable and context-specific strategy for advancing sustainable agriculture when supported by enabling policies, research, and market systems.

Keywords: Agroecology, crop diversification; India, sustainable agriculture, agroecological transition

Introduction

(Foundational literature: Altieri, 1999; Francis *et al.*, 2003; Gliessman, 2015; Rockström *et al.*, 2017; Pretty *et al.*, 2018) [36, 33, 3, 43, 20, 19, 2] Over the past six decades, global agriculture has undergone profound transformation driven by technological intensification, specialization and input substitution. While these changes have substantially increased food production, they have also contributed to widespread environmental degradation, biodiversity loss, declining soil health and heightened vulnerability to climate variability. The dominance of monoculture-based systems has simplified agroecosystems, reducing their capacity to self-regulate and adapt to changing conditions.

Agricultural intensification over the past six decades has substantially increased food production, yet it has simultaneously undermined the ecological foundations of farming systems. Globally, monoculture-based agriculture has contributed to soil degradation, biodiversity loss, water scarcity, greenhouse gas emissions, and increasing vulnerability to climate extremes. In India, these challenges are particularly pronounced due to high population pressure, small landholdings, and dependence on climate-sensitive production systems.

The Green Revolution transformed Indian agriculture by promoting high-yielding varieties, irrigation expansion, and synthetic inputs. While this model successfully addressed food shortages, it also led to declining soil organic matter, nutrient imbalances, groundwater depletion, pest resistance, and rising production costs. Rice-wheat monocultures in the Indo-Gangetic Plains exemplify these challenges. Farmer distress, income instability, and ecological degradation highlight the limitations of the prevailing production paradigm.

Agroecology has emerged as a science, practice, and social movement that seeks to redesign agricultural systems based on ecological principles, farmer knowledge, and social equity (Altieri, 1995; Wezel *et al.*, 2014) [69]. Agroecological transitions involve gradual but systemic

shifts toward diversified, resilient, and low-external-input systems. Crop diversification defined as increasing crop diversity in time and space is a foundational agroecological strategy deeply rooted in traditional Indian farming systems.

This review critically examines crop diversification as a driver of agroecological transitions, with a primary focus on *India* while drawing comparative insights from international experiences.

2. Methodology of the review

Peer-reviewed journal articles were identified through comprehensive searches of major academic databases including Web of Science, Scopus and Google Scholar. Search strings combined terms such as agroecological transition, crop diversification, sustainable farming systems, intercropping, crop rotation and agroforestry, ensuring coverage of both conceptual and empirical literature.

Studies were screened based on relevance, methodological rigor,

geographical representation and contribution to understanding ecological, agronomic or socio-economic outcomes of diversification. Priority was accorded to meta-analyses, long-term field experiments and cross-regional comparative studies. The selected literature was thematically synthesized to integrate ecological mechanisms with socio-economic and policy dimensions, enabling a holistic assessment of crop diversification within agroecological transitions.

This review is based on a structured synthesis of peer-reviewed journal articles, ICAR publications, FAO reports, and international meta-analyses published between 2020 and 2025, supplemented by foundational agroecological literature. Databases searched included Web of Science, Scopus, Google Scholar, and ICAR e-Publications. Search terms included crop diversification, intercropping, crop rotation, agroecology, India, and sustainable farming systems. Emphasis was placed on long-term field experiments, systems-level analyses, and studies relevant to smallholder farming.

3. Conceptual framework: Agroecological transitions and crop diversification

Table 1: Classification of crop diversification practices

Type of diversification	Description	Examples
Temporal diversification	Sequential cultivation of different crops over time	Rice-wheat-mungbean rotation
Spatial diversification	Simultaneous cultivation of multiple crops	Maize + cowpea intercropping
Functional diversification	Crops introduced to support ecosystem services	Cover crops, trap crops
Structural diversification	Integration of trees and shrubs	Agroforestry systems
Genetic diversification	Use of multiple varieties or landraces	Mixed rice varieties

Source: FAO (2017); Altieri (2018) ^[43]

Agroecological transitions are not singular technological shifts but multidimensional processes involving ecological redesign, knowledge cocreation, institutional change and market restructuring. Crop diversification functions at the core of this transition by increasing biological complexity within agroecosystems. Greater crop diversity enhances functional redundancy, meaning that multiple species can perform similar ecological roles, thereby stabilizing system performance under stress.

Crop diversification can be categorized into temporal, spatial, functional, structural and genetic dimensions. Temporal diversification includes crop rotations and sequential cropping systems that disrupt pest cycles and improve soil fertility. Spatial diversification involves *intercropping* and mixed cropping, where multiple species coexist within the same field, leading to complementary resource use. Functional diversification introduces crops that provide ecosystem services such as nitrogen fixation or pest suppression. Structural diversification integrates perennial components such as trees and shrubs, while genetic diversification promotes varietal diversity within crops. Crop diversification acts as a biophysical and socio-technical lever linking ecological processes (soil health, biodiversity, pest regulation) with agronomic outcomes (productivity stability, reduced inputs) and socio-economic benefits (income resilience, food security), thereby enabling agroecological transitions.

These dimensions collectively contribute to agroecosystem resilience and productivity, making *crop diversification* a cornerstone of sustainable farming system design.

4. Global evidence on crop diversification

(Global empirical syntheses: Tilman *et al.*, 2011; Davis *et al.*, 2012; Lin, 2011; Isbell *et al.*, 2017; Tamburini *et al.*, 2020) ^[68, 30, 32, 12, 39]

4.1 Agronomic performance and yield stability

A growing body of global research demonstrates that diversified cropping systems can achieve yield levels comparable to, and in many cases exceeding, those of monoculture systems. Meta-analytical evidence indicates that yield advantages arise from complementary resource use, reduced pest pressure and

improved soil fertility. Importantly, diversification consistently enhances yield stability across seasons, thereby reducing production risk under variable climatic conditions.

4.2 Biodiversity and ecological regulation

Crop diversification substantially increases functional and taxonomic biodiversity within agricultural landscapes. Enhanced plant diversity supports pollinators, natural enemies of pests and soil biota, strengthening ecosystem processes such as biological pest control and nutrient cycling. These ecological interactions reduce dependence on chemical inputs while improving system resilience.

4.3 Soil health and nutrient dynamics

Diversified rotations, intercropping and cover cropping contribute to improved soil organic matter, aggregate stability and microbial activity. The inclusion of legumes enhances biological nitrogen fixation, while residue retention supports long-term soil fertility. Evidence from long-term trials across continents confirms that soil health improvements are cumulative and central to sustained productivity.

4.4 Climate mitigation and adaptation benefits

Diversification contributes to climate change mitigation through increased carbon sequestration and reduced emission intensity. At the same time, diversified systems enhance adaptive capacity by buffering crops against temperature extremes, moisture stress and pest outbreaks. These benefits are particularly pronounced in systems integrating perennials and trees.

5. Indian context of crop diversification

(Indian evidence base: Chand *et al.*, 2011; Chand, 2017; ICAR, 2018; Bajpai & Shanker, 2020; Government of India, 2021) ^[23, 6, 27, 10, 11]

5.1 Historical evolution of cropping patterns

India's agricultural development trajectory has been deeply influenced by its diverse agro-ecological regions, colonial legacies, post-independence policy priorities and technological interventions. Prior to the Green Revolution, Indian farming systems were largely diversified, integrating cereals, pulses, oilseeds, fodder crops and livestock in mixed farming arrangements. These systems-maintained soil fertility through organic recycling and biological nutrient flows.

The Green Revolution of the late 1960s and 1970s marked a major structural shift toward monoculture-based intensive farming, particularly rice-wheat systems in irrigated regions such as Punjab, Haryana and western Uttar Pradesh. While this transformation significantly increased national food grain production and reduced hunger, it also narrowed crop diversity,

increased dependence on external inputs and intensified pressure on natural resources. Over time, declining factor productivity, groundwater depletion and rising cultivation costs exposed the ecological and economic fragility of simplified cropping systems.

5.2 Trends in Crop Diversification in India

Empirical indicators such as the Crop Diversification Index (CDI) reveal gradual but uneven diversification across Indian states since the early 1990s. Expansion of horticulture, oilseeds, pulses, spices and commercial crops has contributed to national-level diversification trends. However, cereal monocultures continue to dominate in regions supported by assured procurement, irrigation subsidies and input incentives.

Table 2: Crop diversification patterns across selected Indian states

State	Dominant systems	Diversification trend	Key drivers
Punjab	Rice-Wheat	Low	MSP, irrigation subsidies
Maharashtra	Soybean-Cotton-Horticulture	High	Market demand, climate suitability
Tamil Nadu	Rice-Millet-Horticulture	Moderate	State diversification schemes
Bihar	Rice-Wheat-Vegetables	Increasing	Urban markets, labor availability

Source: Directorate of Economics & Statistics; ICAR; NSSO

5.3 Regional Case Studies and Empirical Evidence

State-level and district-level studies highlight the differentiated impacts of crop diversification across India. In Punjab, diversification initiatives promoting maize, pulses and oilseeds have faced resistance due to market uncertainty and procurement challenges. In contrast, Maharashtra's diversification toward soybean and horticultural crops has been facilitated by agro-climatic suitability, export-oriented markets and private sector participation. Eastern India, characterized by smallholder dominance and rainfed conditions, has witnessed diversification into vegetables, maize and pulses. These shifts have improved farm incomes, enhanced cropping intensity and contributed to nutritional security. Evidence from long-term field trials conducted by ICAR institutes demonstrates that diversified systems outperform monocultures in terms of soil organic carbon, water use efficiency and yield stability

6. State-Wise Case Studies from India

Punjab

Legume-integrated rotations improve soil health and profitability but are constrained by MSP-driven cereal dominance.

Uttar Pradesh

High crop diversification indices correlate positively with farmer incomes, particularly in rainfed districts.

Telangana

Diversified dry-irrigated systems enhance productivity and profitability.

Kerala

Coconut-based intercropping systems improve land-use efficiency and nutrient cycling.

Odisha

Emerging diversification in rainfed and coastal systems enhances livelihood resilience.

Table 3: State-Wise Crop Diversification Outcomes in India

State	Dominant system	Key benefits	Constraints
Punjab	Legume rotations	Soil recovery	Policy bias
Uttar Pradesh	Mixed cropping	Income stability	Market access
Telangana	Intercropping	Profitability	Land limits
Kerala	Perennial intercropping	Land efficiency	Small holdings
Odisha	Emerging systems	Livelihood resilience	Infrastructure

7. International comparative experiences

Table 4: India-Global Comparison of Agroecological Transitions

Region	Transition driver	Diversification role	Outcome
India	Soil & income stress	Core strategy	Resilience
Europe	Environmental policy	Crop rotation	Input reduction
Africa	Food insecurity	Legume integration	Food security
Latin America	Cultural agroecology	Polycultures	System resilience
East Asia	Resource efficiency	Rotations	Productivity

8. Agroforestry and perennial-based diversification

8.1 Historical evolution of cropping patterns

India's agricultural development has been shaped by regional agroecological diversity and policy interventions. The Green Revolution led to the dominance of rice-wheat systems in

irrigated regions, particularly Punjab, Haryana and western Uttar Pradesh. While these systems boosted food grain production, they also led to declining soil health, groundwater depletion and increased pest resistance. Over recent decades, economic liberalization, dietary diversification and environmental stress

have driven gradual shifts toward crop diversification.

8.2 Trends in Crop Diversification

Source: MOSPI (NCAVES); EPRA Journals

National level indicators show a steady increase in crop diversification indices since the early 1990s. This trend reflects

expansion of horticulture, oilseeds, pulses and commercial crops. However, diversification remains uneven across states, influenced by irrigation access, market connectivity and policy incentives. Southern and western states generally exhibit higher diversification compared to northern cereal dominated regions.

8.3 Regional Case Studies

Table 5: Crop diversification trends across selected Indian states

State	Dominant crops (earlier)	Diversified crops (recent)	Diversification trend
Punjab	Rice-wheat	Maize, pulses, vegetables	Moderate
Maharashtra	Cotton	Soybean, horticulture	High
Andhra Pradesh	Paddy	Pulses, oilseeds	High
Bihar	Cereals	Vegetables, maize	Moderate
Rajasthan	Millets	Oilseeds, pulses	Increasing

Source: NITI Aayog; MOSPI; MDPI Sustainability

In Punjab, efforts to diversify away from water intensive paddy toward maize, pulses and oilseeds have shown mixed success due to market and procurement constraints. Maharashtra has witnessed substantial diversification toward horticulture and soybean-based systems, supported by agroclimatic suitability and market demand. Eastern India has seen diversification into vegetables and maize, contributing to income growth and nutritional improvements.

8.4 Diversification, nutrition and livelihoods

Crop diversification in India is closely linked to nutritional security. District level analyses reveal that diversified farming systems improve household dietary diversity and reduce undernutrition. Income diversification through high value crops also enhances livelihood resilience, particularly for small and marginal farmers.

9. Ecosystem services generated by diversified systems

(Ecosystem services literature: Zhang *et al.*, 2007; Power, 2010; Kremen & Miles, 2012; Bommarco *et al.*, 2013; Tamburini *et*

al., 2020) [68, 44, 31, 63, 72]

Diversified cropping systems generate a broad spectrum of ecosystem services that underpin long-term agricultural sustainability. These services extend beyond direct crop production and include regulating, supporting and cultural services essential for resilient agroecosystems. By increasing biological complexity, diversified systems internalize ecological functions that are otherwise externally substituted through chemical and mechanical inputs.

Provisioning services are enhanced through diversified food, fodder, fibre and fuel outputs, reducing dependency on single commodities. Regulating services such as biological pest control are strengthened as diversified habitats support natural enemy populations, thereby lowering pesticide requirements. Supporting services including nutrient cycling, soil formation and water regulation are improved through organic matter inputs, root diversity and microbial activity. Cultural services often overlooked include preservation of indigenous knowledge, seed diversity and culturally significant cropping patterns.

Table 6: Ecosystem services enhanced by crop diversification

Ecosystem service category	Specific service	Ecological mechanism	Sustainability outcome
Provisioning	Diverse food & fodder	Multiple crop species	Nutritional security
Regulating	Pest suppression	Predator-prey dynamics	Reduced pesticide use
Supporting	Nutrient cycling	Legume fixation, residues	Soil fertility
Regulating	Climate regulation	Carbon sequestration	Mitigation & resilience
Cultural	Agrobiodiversity	Traditional knowledge	Social sustainability

Sources: FAO (2018) [16]; Nature Sustainability; Agricultural Systems

Diversified cropping systems generate a wide range of ecosystem services essential for sustainable agriculture. These include provisioning services such as food, fodder, fibre and fuel; regulating services such as pest and disease control, climate regulation and water purification; supporting services such as soil formation, nutrient cycling and primary production; and cultural services linked to traditional knowledge, agrobiodiversity conservation and landscape aesthetics.

Long-term experiments across continents demonstrate that

diversified systems internalize many ecosystem services that are otherwise externally supplied through synthetic inputs. For example, legume-based rotations reduce nitrogen fertilizer requirements, while intercropping enhances biological pest suppression. Agroforestry systems further contribute to carbon sequestration, microclimate regulation and biodiversity corridors, thereby linking farm-level sustainability with landscape-scale ecological integrity.

Table 7: Ecosystem services enhanced by crop diversification

Ecosystem service	Mechanism	Outcome
Nutrient cycling	Legume nitrogen fixation	Reduced fertilizer dependence
Pest regulation	Natural enemy diversity	Lower pesticide use
Soil health	Organic matter inputs	Improved soil structure
Climate resilience	Functional redundancy	Yield stability
Pollination	Floral diversity	Enhanced crop productivity

Source: FAO; Nature Sustainability; ScienceDirect

Table 8: Ecosystem services enhanced by crop diversification

Ecosystem service	Mechanism	Outcome
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Climate resilience	Functional redundancy	Yield stability
Pollination	Floral diversity	Enhanced crop productivity

Source: FAO; Nature Sustainability; ScienceDirect

Diversified cropping systems generate a wide range of ecosystem services essential for sustainable agriculture. These include provisioning services such as food and fodder, regulating services such as pest control and climate regulation, supporting services such as soil formation and nutrient cycling, and cultural services related to traditional knowledge and landscape diversity. By internalizing these services within farming systems, diversification reduces reliance on external inputs and enhances ecological efficiency.

10. Socio economic dimensions of crop diversification

Source: FAO; nature communications; science direct

Crop diversification reduces production and income risk by

spreading exposure across multiple crops and markets. It creates employment opportunities through labor-intensive crops and value-added activities. Diversified systems also strengthen local food systems by increasing the availability of diverse foods. Empirical studies show positive associations between diversification and farm income stability, particularly in rainfed regions.

Diversification reduces income volatility, lowers input costs, and provides multiple livelihood options. International evidence mirrors Indian findings, showing improved economic resilience among diversified smallholders.

Table 9: Socio-Economic Outcomes of Crop Diversification

Indicator	India	Global
Income stability	Higher	Higher
Input costs	Lower	Lower
Food security	Improved	Improved
Gender equity	Enhanced participation	Similar trends

11. Barriers to adoption of diversified systems

Table 10: Barriers and enabling factors for agroecological transitions

Category	Barriers	Enablers
Economic	Market risk, price volatility	Diversified MSPs, value chains
Institutional	Input-centric policies	Agroecology-focused schemes
Knowledge	Limited extension	Farmer field schools
Social	Risk aversion	Community-based approaches
Infrastructure	Storage and transport gaps	Cold chains, processing units

Source: FAO; IFPRI; Springer

Despite clear benefits, adoption of crop diversification faces multiple barriers. These include policy bias toward staple crops, inadequate market infrastructure for diverse produce, limited access to quality seed and extension services, and risk aversion among farmers. Institutional support often remains aligned with monoculture production systems, hindering largescale agroecological transitions.

12. Policy frameworks supporting agroecological transitions

12.1 Global policy perspectives

At the global level, organizations such as FAO, IFPRI and UNEP emphasize crop diversification as a cornerstone of sustainable food systems. International frameworks advocate diversification to address climate risks, biodiversity loss and nutrition insecurity simultaneously. Agroecology and diversification are increasingly integrated into global climate adaptation strategies and sustainable development goals.

12.2 Indian policy initiatives

India has introduced several policy instruments to promote crop diversification, including the Crop Diversification Programme under the Rashtriya Krishi Vikas Yojana, the National Agroforestry Policy, and state-level schemes encouraging shifts away from water-intensive crops. However, procurement policies, MSP structures and input subsidies still largely favor

cereal monocultures, limiting the pace of agroecological transitions.

Policy coherence across agriculture, nutrition, water and climate sectors remains a critical requirement for scaling diversification-based farming systems.

Policy incentives favoring monocultures remain a major barrier. Redirecting subsidies, strengthening extension, supporting seed diversity, and developing markets for diversified crops are essential.

Globally, international organizations advocate crop diversification as a pathway to sustainable food systems. In India, initiatives such as the Crop Diversification Programme, agroforestry policy frameworks and statelevel schemes promote diversification through financial incentives and technical support. However, policy coherence across production, procurement, nutrition and environmental objectives remains limited.

13. Future research directions

Future research on agroecological transitions must move beyond plot-level productivity assessments toward system-level and landscape-scale analyses. Key research priorities include long-term evaluation of diversified systems under climate variability, optimization of crop combinations for specific agro-ecological

zones, integration of digital decision-support tools, and assessment of diversification impacts across value chains.

Future research should focus on long-term systems experiments, quantification of ecosystem services, integration of livestock, and socio-institutional dimensions of transitions.

Participatory and transdisciplinary research approaches that integrate farmer knowledge, ecological science and policy analysis are essential. Strengthening data availability on diversification outcomes in India, particularly for smallholder and rainfed systems, will further support evidence-based policymaking.

Future research should focus on longterm systemlevel impacts of diversification, regionspecific optimization of crop combinations, integration of digital decisionsupport tools and assessment of diversification within value chains. Participatory research approaches that integrate farmer knowledge with scientific innovation are essential for successful agroecological transitions.

14. Conclusion

(Synthesis sources: Altieri & Nicholls, 2017; Pretty *et al.*, 2018; Rockström *et al.*, 2017; PetersenRockney *et al.*, 2021) ^[62, 36, 33, 3, 43]

Crop diversification has emerged as a scientifically robust and practically indispensable foundation for agroecological transitions. Synthesized evidence from global and Indian contexts demonstrates that diversified cropping systems deliver multiple and interlinked benefits, including enhanced productivity stability, improved soil and ecosystem health, strengthened climate resilience and more secure farmer livelihoods. By increasing biological complexity and functional diversity, diversification enables agroecosystems to perform critical ecological functions internally, thereby reducing dependence on external inputs. Crop diversification is the ecological foundation of agroecological transitions. Evidence from India and across the world demonstrates its capacity to regenerate ecosystems, stabilize productivity, and improve livelihoods. Scaling diversified systems is essential for achieving sustainable and equitable food systems under climate change. The persistence of monoculture-dominated agricultural landscapes reflects not a lack of scientific understanding but systemic policy, market and institutional barriers that favor short-term productivity gains over long-term sustainability. Overcoming these constraints requires coherent policy frameworks, supportive markets, adaptive extension systems and sustained investment in agroecological research.

As climate change, biodiversity loss and resource degradation intensify, the transition toward diversified farming systems becomes increasingly urgent. Embedding crop diversification at the center of agricultural development strategies is essential for building resilient, equitable and sustainable food systems capable of meeting future societal and environmental challenges.

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