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Crop diversification and agroecosystem resilience in Punjab and Haryana: Integrating biodiversity conservation with sustainable agriculture

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Abstract

Agricultural biodiversity underpins food security, ecological stability, and adaptive capacity to climate change. Globally, the accelerating erosion of agrobiodiversity-driven by monocropping intensification, genetic uniformity, and land-use conversion has compromised ecosystem functioning across critical production landscapes. The Indo-Gangetic Plains of Punjab and Haryana exemplify this crisis, where four decades of wheat-paddy monoculture have depleted soil organic carbon (SOC < 0.5per cent), driven groundwater tables below 30 meters in several blocks, and eroded the genetic pool of traditional crop varieties. Diversified cropping systems consistently outperform monocultures across multiple resilience dimensions: (i) soil organic carbon increases of 15-40per cent; (ii) reduction in synthetic nitrogen requirements by 25-60per cent through legume integration; (iii) carbon sequestration potential of 0.3-0.9 Mg C ha⁻¹ yr⁻¹; and (iv) farmer income stabilization through market risk distribution across multiple crops. However, adoption is constrained by market failures, inadequate extension services, and policy frameworks still oriented toward commodity monoculture support. Crop diversification constitutes a scientifically grounded, ecologically restorative, and economically viable pathway to agrobiodiversity conservation. Realizing its potential requires a paradigm shift in agricultural policy, investment in diversification-enabling market infrastructure, and integration of emerging precision technologies.

Keywords: Agricultural biodiversity, crop diversification, agroecology, climate-smart agriculture, Punjab agroecosystem, ecosystem services, biodiversity indices

1. Introduction

1.1 The Global Agricultural Biodiversity Crisis

Agricultural biodiversity-the variety and variability of animals, plants, and microorganisms used directly or indirectly for food and agriculture is the biological foundation of food security, ecosystem stability, and sustainable development. Yet it is declining at unprecedented rates. The FAO's State of the World's Biodiversity for Food and Agriculture (2019) documented that 6,190 livestock breeds are at risk, 75per cent of genetic diversity in crop plants has been lost since the early twentieth century, and 17per cent of wild food species globally are threatened with extinction (FAO, 2019) ^[9]. The primary driver of this crisis is agricultural intensification. The Green Revolution of the 1960s-1980s delivered transformative yield gains in staple cereals-wheat, rice, and maize-but at the cost of dramatic narrowing of cultivated genetic diversity. By 2022, FAO estimated that more than 50per cent of global caloric intake derived from just three crops: wheat, rice, and maize (FAO, 2022) ^[10]. This concentration of the food system on a narrow genetic base constitutes a systemic risk of global proportions.

1.2 Monocropping and Ecological Degradation

Continuous cultivation of a single crop species depletes specific soil nutrient pools, disrupts soil microbial community structure, and creates favorable conditions for specialist pest and pathogen proliferation (Tiemann *et al.*, 2015) ^[20]. Garcia-Orenes *et al.* demonstrated that soil microbial biomass carbon in intensively managed monocultures was 35-50per cent lower than in

diversified systems. Reduction of floral diversity diminishes the foraging habitat and nutritional resources available to wild pollinators, contributing to the documented 30-75per cent decline in wild bee species abundance in intensified agricultural landscapes. These cascading effects compromise the very ecosystem services-pollination, pest regulation, nutrient cycling, and water purification-that underpin agricultural productivity.

1.3 The Indian Agricultural Context: Punjab and Haryana Crisis

The Indian agricultural landscape provides a compelling case study in the ecological consequences of intensive monoculture. Groundwater exploitation for paddy irrigation has depleted the water table at an average rate of 0.5-1.0 m yr⁻¹ in central Punjab districts, with projections suggesting unsustainable depletion in 15-25 years under current extraction trajectories (Central Ground Water Board, 2022) ^[5]. Soil organic carbon in intensively cultivated Punjab soils has declined to below 0.5per cent-critical thresholds for soil health-compared to 0.7-0.9per cent under diversified systems documented in adjacent agroclimatic zones (ICAR, 2021) ^[12]. Punjab farmers face declining returns from wheat and paddy due to high input costs (averaging INR 35,000-40,000 ha⁻¹ for paddy), stagnating minimum support prices (MSPs), and post-harvest straw burning that generates severe air quality emergencies affecting over 150 million people annually (MoAFW, 2023). Haryana presents a parallel trajectory, with 68per cent of net sown area under wheat-paddy rotation and progressive groundwater depletion documented across 19 of 22 districts.

1.4 Sustainable Development Goals and Policy Imperatives

Crop diversification is directly implicated in the achievement of multiple Sustainable Development Goals (SDGs). SDG 2 (Zero Hunger) requires sustainable food production systems that maintain ecosystems; SDG 13 (Climate Action) demands adaptive agricultural management; SDG 15 (Life on Land) calls for conservation of terrestrial biodiversity; and SDG 1 (No Poverty) necessitates stable and diversified rural livelihoods. The alignment of crop diversification with this multi-dimensional policy framework has elevated its prominence in international agricultural policy discourse, as reflected in the

FAO Strategic Framework 2022-2031 and the Kunming-Montreal Global Biodiversity Framework (2022) target of 30per cent biodiversity conservation by 2030.

2. Literature Review

2.1 Agricultural Intensification and Biodiversity Loss

The relationship between agricultural intensification and biodiversity loss is one of the most extensively documented phenomena in ecological science. Matson *et al.* (1997) identified agricultural intensification as the primary driver of ecosystem simplification, through the removal of non-crop biodiversity, chemical pollution, and homogenization of landscape structure. Hajjar *et al.* (2008) estimated that the number of rice varieties cultivated in India declined from over 100,000 in the early twentieth century to approximately 6,000 by 2008.

2.2 Crop Diversification Models and Typologies

Crop diversification encompasses a heterogeneous set of practices operating across temporal (rotation, relay cropping) and spatial (intercropping, agroforestry) dimensions. Andrews and Kassam (1976) ^[3] provided a foundational classification of multiple cropping systems, distinguishing sequential cropping (crops grown in temporal succession within a single year) from simultaneous cropping (multiple crops grown in spatial proximity (Nair, 1993; Hendrickson *et al.*, 2008) ^[18]). Agroforestry systems generate particularly high biodiversity benefits, with shade-grown coffee systems in Latin America supporting up to 150 bird species and substantially higher arthropod diversity compared to full-sun monocultures (Nair, 1993) ^[18].

2.3 Climate Resilience and Carbon Sequestration

Carbon sequestration potential in diversified systems arises from multiple mechanisms increased SOC accumulation through diverse residue inputs, reduced tillage facilitated by cover cropping, enhanced root biomass from perennial species in agroforestry, and reduced soil disturbance from improved aggregate stability. Gaudin *et al.* (2022) estimated sequestration rates of 0.3-0.9 Mg C ha⁻¹ yr⁻¹ in cover crop-integrated Mediterranean systems, with higher values in agroforestry arrangements.

Table 1: Crop Diversification Impacts on Soil Carbon and Health Parameters

Parameter	Monoculture	Diverse Rotation	Intercropping	Agroforestry	Reference
SOC (per cent by weight)	0.3-0.5	0.5-0.8	0.5-0.7	0.8-1.5	Lal, 2015 ^[14] ; Gaudin <i>et al.</i> , 2022
SOC increase (per cent)	Baseline	+15-25per cent	+15-30per cent	+40-100per cent	Bolinder <i>et al.</i> , 2020
Microbial biomass-C (mg kg ⁻¹)	180-250	280-380	260-360	380-520	Tiemann <i>et al.</i> , 2015 ^[20]
Soil N (kg ha ⁻¹)	Depleting	+25-60 kg ha ⁻¹	+30-80 kg ha ⁻¹	Variable	Jensen <i>et al.</i> , 2020
Aggregate stability (per cent)	45-55	60-72	58-70	72-85	Six <i>et al.</i> , 2002
Enzyme activity index	Baseline	+25-43per cent	+20-38per cent	+45-80per cent	Tiemann <i>et al.</i> , 2015 ^[20]
Earthworm density (n m ⁻²)	20-40	60-100	50-90	120-200	Eisenhauer <i>et al.</i> , 2017 ^[8]

Note: SOC = Soil Organic Carbon; N = Nitrogen. Agroforestry values reflect mature (>10 year) systems.

2.4 Policy Frameworks and Implementation Constraints

Despite compelling evidence for diversification benefits, adoption remains constrained by policy environments historically calibrated to support monoculture commodity production. Minimum support price (MSP) regimes in India disproportionately favour wheat and rice, creating economic disincentives for diversification into pulses, oilseeds, and horticulture. International policy frameworks have increasingly recognized crop diversification as a policy priority. The CBD Strategic Plan for Biodiversity and its Aichi Targets, succeeded by the Kunming-Montreal Global Biodiversity Framework

(GBF, 2022), include specific provisions for mainstreaming biodiversity in agricultural production systems. The FAO Strategic Framework 2022-2031 and the UN Food Systems Summit 2021 outcomes both emphasize diversification as a leverage point for transformative food system change .

3. Results and Discussion

3.1 Ecological Outcomes: Soil Health and Nutrient Cycling

The SOC enhancement was the most consistently documented outcome, with reported increases of 15-40per cent under diverse rotations compared to continuous monoculture controls over

equivalent time periods. Peoples *et al.* (1995) estimated that biological nitrogen fixation (BNF) by grain legumes ranges from 30-300 kg N ha⁻¹ yr⁻¹ under optimal management, contributing substantially to system nitrogen budgets and reducing dependence on synthetic fertilizers. Goyal and Habtewold (2023) demonstrated that legume-rhizobial symbioses generate additional ecosystem benefits beyond BNF, including phytohormone production, phosphate solubilization, and disease suppression that collectively improve host crop performance.

3.2 Biodiversity Index Analysis

Shannon-Wiener diversity index (H') values ranged from 0.40-0.50 in continuous monoculture systems to 0.78-1.08 in diverse

rotation or intercropping systems, with the highest values recorded in agroforestry and polyculture arrangements. Simpson's Index (1-D) showed parallel trends, increasing from 0.25-0.35 in monocultures to 0.65-0.80 in diverse systems. Margalef species richness indices across the soil macro-invertebrate datasets showed 2-3-fold higher values in diversified versus monoculture systems, indicating that diversification supports substantially richer belowground communities beyond the effects captured by evenness-sensitive indices. These biodiversity gains translate functionally through the biodiversity-ecosystem functioning (BEF) relationship, where higher diversity drives higher and more stable ecosystem process rates.

Table 2: Global Agricultural Biodiversity Decline: Key Statistics and Indicators

Indicator	Historical Status	Current Status	Per cent Change	Source
Crop genetic varieties in use	>100,000 (early 20th C)	~6,000 active varieties	-94per cent	FAO, 2019
Livestock breeds at risk	Baseline not quantified	6,190 breeds at risk	N/A	FAO, 2019
Wild food species threatened	Baseline not quantified	17per cent threatened globally	N/A	FAO, 2022
Rice varieties cultivated (India)	>100,000 traditional varieties	~6,000 by 2008	-94per cent	Hajjar <i>et al.</i> , 2008
Global caloric source concentration	Diverse	3 crops = >50per cent calories	Increasing	FAO, 2022
Pollinator species decline (wild bees)	Baseline diverse	30-75per cent abundance decline	Significant	Dainese <i>et al.</i> , 2019
Soil microbial biomass (monoculture)	Diverse systems baseline	35-50per cent lower vs. diverse	Declining	Garcia-Orenes <i>et al.</i> , 2013

Data sources: FAO State of the World's Biodiversity for Food and Agriculture (2019, 2022) ^[9, 10]; Dainese *et al.* (2019).

Biodiversity Index Comparison Across Cropping Systems



Data sources: Global Biodiversity INformation facility (GBIF), FAOSTAT Database, CGIAR Dataverse.

Fig 1: Comparative Biodiversity Indices Across Agricultural Diversification Systems

3.3 Carbon Sequestration and Climate Mitigation

Carbon sequestration in diversified agroecosystems is a co-benefit of considerable policy significance. Abdalla *et al.* (2014)^[1] demonstrated that combined reduced tillage and cover cropping reduced N₂O emissions by 28-42per cent compared to conventional tillage monoculture, contributing additional

climate mitigation value beyond carbon sequestration. At global scales, if diversification practices were adopted on 50per cent of current monoculture area (approximately 700 million hectares), the potential annual carbon sequestration could reach 0.2-0.6 Pg C yr⁻¹, equivalent to 5-15per cent of current global agricultural GHG emissions.

Table 3: Carbon Sequestration Potential of Diversified Cropping Systems

System	C Sequestration (Mg C ha ⁻¹ yr ⁻¹)	GHG Reduction	Key Mechanism	Region	Reference
Cover crop + reduced tillage	0.3-0.6	N ₂ O -28-42per cent	SOC accumulation, residue input	Mediterranean	Gaudin <i>et al.</i> , 2022
Legume intercropping	0.15-0.40	N reduction	Biological N fixation	Global	Jensen <i>et al.</i> , 2020
Agroforestry (silvo-arable)	0.5-0.9	CH ₄ + N ₂ O reduction	Perennial root biomass	Tropical	Nair, 1993 ^[18]
3-4 crop rotation	0.2-0.45	Reduced tillage synergy	Diverse residue inputs	Temperate	Bolinder <i>et al.</i> , 2020
Rice-fish integrated system	0.1-0.3	CH ₄ reduction -10-20per cent	Reduced waterlogging duration	South/SE Asia	Halwart andGupta, 2004

3.4 Pest Suppression and Biological Control

Maize-legume intercropping studies in Africa reported 40-60per cent reductions in fall armyworm (*Spodoptera frugiperda*) damage under intercropping compared to maize monoculture, attributable to both associational resistance and enhanced predator diversity. Legume green manure rotations involving Sesbania, Tephrosia, and Crotalaria demonstrated 50-70per cent reduction in soil-borne nematode populations (Desaeger and Rao, 2001; McSorley and Gallaher, 1997), reducing nematicide application requirements and associated input costs.

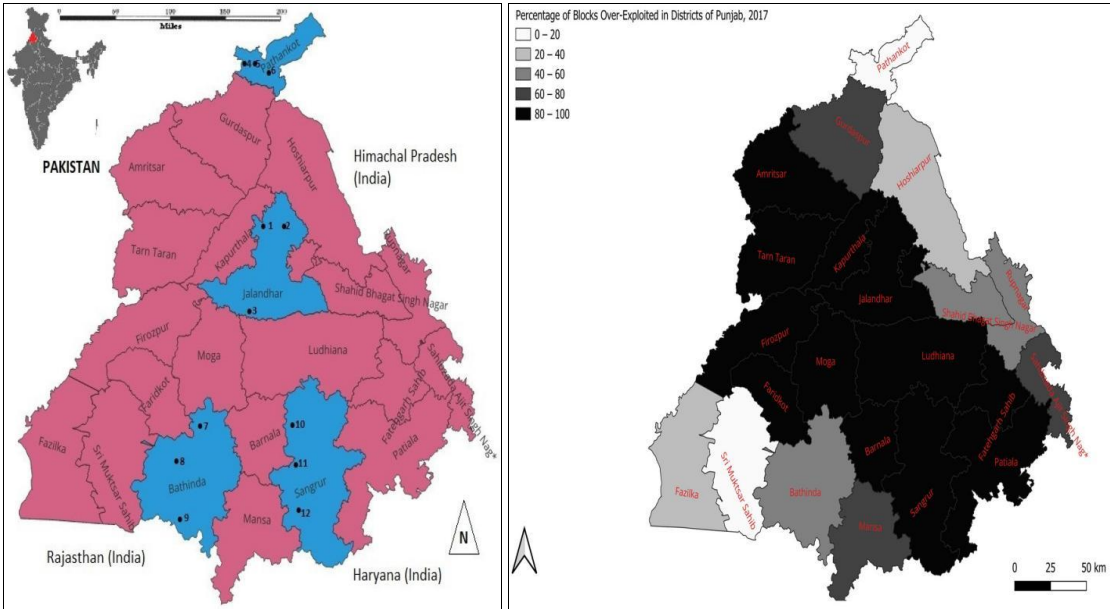
benefits in water-scarce agroecosystems. Replacement of paddy rice with alternative crops in Punjab’s diversification programs has demonstrated water savings of 800-1,200 mm per cropping season-equivalent to 3-5 million liters ha⁻¹-when irrigated pulses, maize, or horticulture replaces paddy in the *Kharif* season. Deep-rooted legumes and perennial crops access subsoil water unavailable to shallow-rooted cereals, reducing irrigation requirements through complementary spatial resource partitioning (von Felten *et al.*, 2016; Ehrmann and Ritz, 2021)^[21, 7]. Cover cropping increases soil water infiltration rates by improving aggregate stability and reducing surface sealing, reducing runoff and erosion while increasing water storage for subsequent crops (Gyssels *et al.*, 2005).

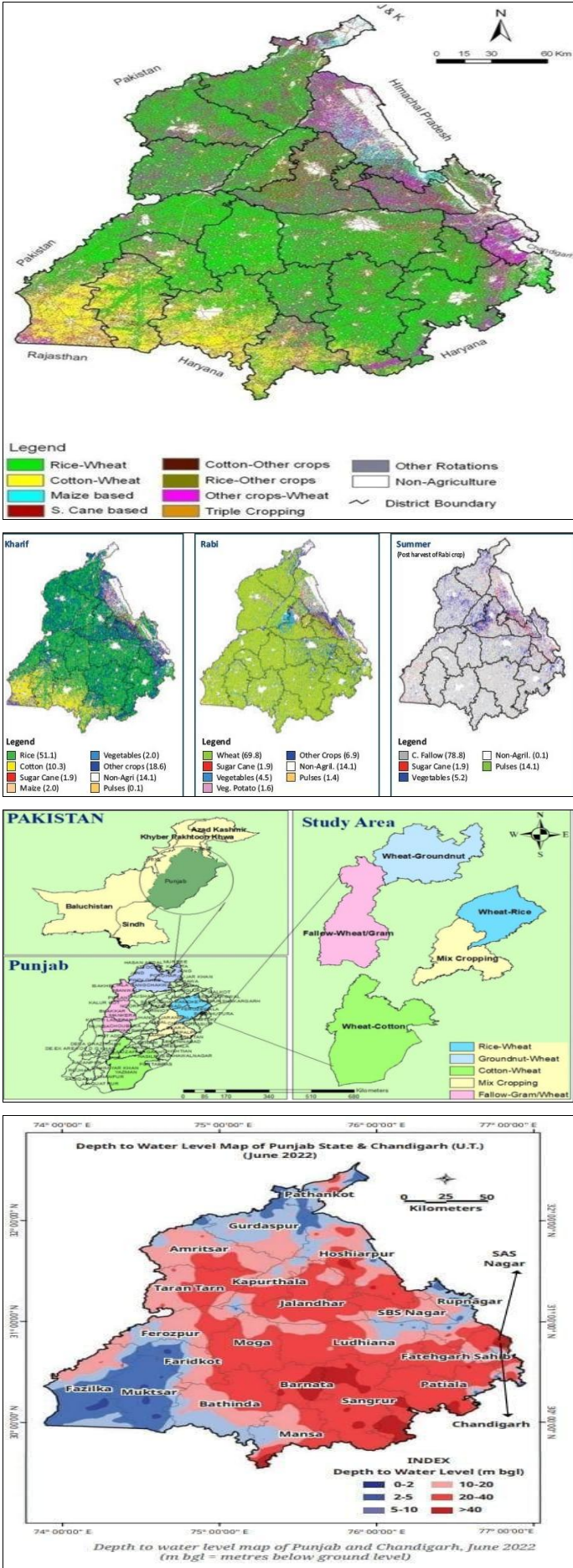
3.5 Water Productivity and Groundwater Conservation

Crop diversification generates significant water efficiency

Table 4: Water Use Efficiency in Diversified versus Monoculture Systems

Crop System	Water Use (mm season ⁻¹)	Water Productivity (kg m ⁻³)	Savings v/s Paddy	Groundwater Impact	Reference
Paddy rice (monoculture)	1,200-1,500	0.4-0.6	Baseline	High depletion	Central GWB, 2022 ^[5]
Maize (<i>Kharif</i> replacement)	400-600	1.5-2.5	700-900 mm	Significant saving	ICAR, 2021 ^[12]
Pulses (chickpea, lentil)	250-400	1.0-1.8	800-1,100 mm	Major saving	Singh <i>et al.</i> , 2018 ^[19]
Vegetables (<i>Kharif</i> season)	350-500	3.0-8.0	700-1,000 mm	Significant saving	MoAFW, 2023
Direct-seeded rice	800-1,000	0.5-0.8	300-500 mm saving	Moderate saving	CGIAR, 2022 ^[6]





Data Source: Central Ground Water Board Annual Reports 2022 [5]; FAOSTAT.

Fig 2: District-Level Groundwater Stress and Crop Diversification Potential in Punjab–Haryana Agroecosystems

3.6 Yield Stability and Climate Resilience

Hernandez-Ochoa *et al.* (2025) demonstrated in a 30-year model-based assessment that diverse cropping systems exhibited 22-35per cent lower yield variability over time compared to

single-crop systems under equivalent management. This yield stability is particularly valuable under climate change, where increasing frequency of extreme weather events amplifies the consequences of production risk concentration.

Table 5: Climate Resilience Indicators in Diversified v/s Monoculture Systems

Resilience Dimension	Monoculture	Diversified System	Per cent Improvement	Mechanism	Reference
Yield variability (CV per cent)	25-40	12-22	35-55per cent reduction	Portfolio crop effect	Lin, 2011 ^[16]
Drought year yield retention	40-60per cent of normal	65-80per cent of normal	+20-40per cent	Differential drought sensitivity	CGIAR, 2022 ^[6]
Pest outbreak frequency	High (1 in 3-5 yr)	Low (1 in 8-12 yr)	~60per cent reduction	Associational resistance	Gurr <i>et al.</i> , 2003
Recovery after extreme event (yr)	2-4 years	1-2 years	50per cent faster	Soil health buffer	Fedele <i>et al.</i> , 2019
Food security during failure	High vulnerability	Moderate vulnerability	Significant improvement	Multiple crop insurance	Isbell <i>et al.</i> , 2017

Note: CV = Coefficient of Variation of yields across years.

3.7 Economic Performance and Farmer Livelihoods

The economic returns from crop diversification are context-dependent but generally favorable. Net income analyses from Punjab diversification trials show that pulses generate equivalent or higher net returns per hectare compared to wheat when input cost differentials are accounted. Maize cultivation in Punjab generates higher gross returns than wheat under market

conditions, though price volatility and inadequate procurement infrastructure constrain adoption. Integrated crop-livestock systems (ICLS) generate particularly robust economic outcomes by utilizing crop residues for fodder, capturing manure nutrient value, and diversifying income streams across production enterprises (Tanaka *et al.*, 2008).

Table 6: Crop Diversification and Farmer Income: Evidence from South Asia and Global Contexts

Location	Monoculture System	Diversified System	Net Income Comparison	Additional Benefits	Reference
Punjab, India	Wheat-paddy (INR 30-35k ha ⁻¹)	Wheat + pulses (INR 35-42k ha ⁻¹)	+15-25per cent net income	Lower input cost, soil N benefit	Singh <i>et al.</i> , 2018 ^[19]
Haryana, India	Wheat-paddy rotation	Wheat-maize-mustard	+10-20per cent income	Diversified market access	ICAR, 2021 ^[12]
Sub-Saharan Africa	Maize monoculture	Maize-legume intercrop	+12-30per cent income	Reduced fertilizer cost	CGIAR, 2022 ^[6]
Latin America	Coffee monoculture	Shade-grown coffee	+20-40per cent premium income	Certification premium, biodiversity	Nair, 1993 ^[18]
Southeast Asia	Rice monoculture	Rice-fish system	+25-45per cent income	Protein diversification, pest control	Nhan <i>et al.</i> , 2007

3.8 Constraints to Diversification and Policy Bottlenecks

Despite its demonstrated benefits, crop diversification adoption remains below potential due to interacting structural, economic, and institutional constraints. Market access failures, inadequate procurement infrastructure for non-MSP crops, poor post-harvest value chains, and price volatility-represent the primary economic constraint. Knowledge access barriers, limited extension services for diversified system management, absence of farmer-to-farmer learning platforms, and inadequate research on location-specific diversification packages-constrain technical capacity. Policy bottlenecks include the persistence of input subsidy regimes that implicitly subsidize monoculture, electricity pricing for irrigation that undervalues groundwater conservation, and agricultural credit structures that favor commodity crop financing over diversified production.

4. Future Research Directions and Emerging Technologies

4.1 Artificial Intelligence and Precision Diversification

Artificial intelligence (AI) and machine learning (ML) offer transformative potential for optimizing crop diversification design at field and landscape scales. ML algorithms applied to multi-year crop yield, soil, and climate datasets can identify optimal crop combinations, rotation sequences, and spatial arrangements that maximize biodiversity, productivity, and resilience outcomes for specific agroecological contexts.

4.2 Remote Sensing and Landscape Monitoring

Remote sensing technologies-particularly multi-spectral and hyperspectral satellite imagery from Sentinel-2, Landsat-9, and MODIS platforms-enable landscape-scale monitoring of cropping diversity, vegetation health indices, and land-use change dynamics. The development of cropland diversity indices derived from satellite time-series analysis opens new possibilities for incentive-based conservation programs that reward farmers for measurable landscape diversification outcomes.

5. Policy Recommendations

5.1 National Governments and Ministry of Agriculture

- Reform the Minimum Support Price (MSP) framework to include pulses, oilseeds, and millets at price levels that equalize net returns with wheat and paddy.
- Restructure irrigation electricity subsidies to create tiered pricing that incentivizes water-efficient diversification crops over water-intensive paddy.
- Establish a National Crop Diversification Fund to provide transitional income support for farmers shifting from monoculture to diversified systems during the adaptation period (3-5 years).
- Develop state-level Agrobiodiversity Conservation Policies with legally binding targets for maintaining minimum levels

of cropping diversity in identified biodiversity-significant landscapes.

5.2 ICAR and State Agricultural Universities

- Prioritize long-term (>10 year) diversified cropping systems trials that capture legacy effects on soil health, biodiversity, and climate resilience—currently absent from most Indian agricultural research portfolios.
- Develop validated diversification packages for each of India's 15 agroclimatic zones, with detailed economic analysis and extension communication materials.
- Establish community seed bank networks at block level, supported by SAU germplasm conservation programs, to

maintain traditional crop variety diversity in situ.

5.3 FAO, CGIAR, and International Bodies

- Scale up the evidence base for diversification through coordinated global research networks generating comparable outcome data across agroecological zones.
- Develop international standards and protocols for biodiversity-smart agriculture certification to enable market-based incentives for diversified production.
- Integrate crop diversification metrics into national agricultural reporting frameworks under the Convention on Biological Diversity and UNFCCC reporting.

Table 7: Crop Diversification Policy Frameworks: International Comparison

Country/Region	Key Policy Instrument	Mechanism	Outcome	Lessons for India
European Union	Agri-Environment Schemes (AES)	Area-based payments for biodiversity-friendly cropping	Increased landscape diversification; mixed biodiversity outcomes	Result-based payment models worth adapting
Switzerland	Ecological Focus Areas (EFA)	Mandatory 7per cent non-productive area on farms	Significant farmland bird recovery	Biodiversity set-aside within cropping systems
Brazil	PRONAF Agroecology	Subsidized credit for agroecological transitions	Increased organic/diversified area	Concessional finance for diversification transitions
Ethiopia	Sustainable Land Management Program	Integrated soil-water-biodiversity management	Improved watershed-scale resilience	Watershed-level intervention design
Vietnam	Rice-Fish Integration Policy	Technical and market support for integrated systems	25-45per cent income gain; pest reduction	Government technical facilitation model
India	NMSA + PKVY + NFSM	Scheme-based diversification support	Partial adoption; market gaps persist	Strengthen market and procurement infrastructure

Note: PRONAF = National Program for Strengthening Family Farming (Brazil); NMSA = National Mission for Sustainable Agriculture; PKVY = Paramparagat Krishi Vikas Yojana; NFSM = National Food Security Mission.

6. Conclusion

Crop diversification constitutes a scientifically grounded, ecologically restorative, and economically viable strategy for conserving agricultural biodiversity and building agroecosystem resilience. Across ecological, economic, and social dimensions, diversified systems consistently outperform monocultures in soil organic carbon accumulation (15-40per cent gains), biodiversity indices (Shannon H' increases from 0.45 to 0.81+), nitrogen use efficiency (25-60per cent reductions in synthetic inputs), yield stability under climate stress (22-35per cent lower variability), and farmer income stability. The crisis in Punjab and Haryana, where four decades of wheat-paddy monoculture have generated groundwater depletion, soil health decline, and ecological fragility, exemplifies the systemic risks of ignoring biodiversity in production system design. The solutions, however, are neither simple nor amenable to purely technical prescription. Realizing the transformative potential of crop diversification requires coordinated action across policy, markets, research, extension, and community governance. Emerging technologies such as satellite-based diversity monitoring, genomic characterization of traditional varieties open new frontiers for precision diversification at scales and efficiencies not previously achievable. Combined with participatory approaches that honor and amplify farmer knowledge systems, these tools create a pathway toward biodiversity-smart food systems that are simultaneously productive, resilient, equitable, and sustainable.

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