Indexed in UGC CARE List
ISSN : 0970-3349 (Print) I ISSN : 0976-1721 (Online)

INDIAN JOURNAL OF SOIL CONSERVATION

Special issue on Hill and Mountain Agriculture

Indian J. Soil Cons.
Vol 53 No. 3
December 2025
pp 195-301

INDIAN ASSOCIATION OF SOIL AND WATER CONSERVATIONISTS
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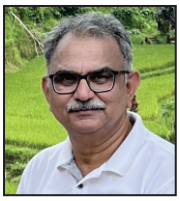
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Received: 01 March 2026 | Accepted: 30 March 2026 | Published online: 06 April 2026

DOI: 10.53550/ijsc.v53.i3.203

ORIGINAL ARTICLE

Indian Journal of Soil Conservation

Mapping Hill and Mountain Ecosystem in India: A Review and Framework for Ecological Production Units (EPUs)

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Handling Editor:
Dr A.K. Srivastva

Key words:
Ecological production units
Hill ecosystems
Land mapping
Spatial classification
Watershed planning

ABSTRACT

Mountain and hill ecosystems (the Himalaya-Northwest hills and Northeast hills, Aravalli, Western Ghats, and Eastern Ghats) in India provide critical ecosystem services, including biodiversity conservation, water regulation, and livelihood support, yet their spatial heterogeneity is poorly captured by existing classification frameworks. This paper presents a narrative synthesis of global and Indian approaches to mapping mountain ecosystems and evaluates their suitability for land-use planning in complex upland regions. We review major frameworks, including biogeographic zones, agro-ecological regions, watershed divisions, WWF ecoregions, and global mountain classifications, highlighting their strengths and limitations in representing ecological and production variability. A key gap identified is the absence of an integrated, operational unit that combines ecological, climatic, and socio-economic dimensions for planning purposes. To address this, we propose a conceptual multi-criteria GIS-based framework for delineating Ecological Production Units (EPUs) in Indian hill regions. The framework integrates topography, climate, soils, land cover, and human factors to define homogeneous units of ecological productivity and management relevance. The study demonstrates that EPUs can serve as a bridge between ecological classification and decision-making, with applications in watershed management, agroforestry, conservation planning, and climate adaptation. However, implementation is constrained by data gaps, scale mismatches, and institutional fragmentation. The paper contributes a structured synthesis of classification systems and provides a conceptual pathway toward operationalizing spatially explicit, ecosystem-based planning in India's hill and mountain regions.

1 | INTRODUCTION

Mountain and hill regions are globally recognized as ecological hotspots that sustain biodiversity and provide critical ecosystem services. Approximately 27% of Earth's land surface is mountainous, and these areas contain 25 of the world's 34 biodiversity hotspots (Kapos *et al*., 2000). They support water resources by intercepting monsoon rainfall and have high carbon storage and agro-diversity. In India, major mountain and hill systems, such as the Himalaya in the north, the Western and Eastern Ghats in the south, and the northeastern hill chains, are rich in endemic species. The Western Ghats, a UNESCO World Heritage site, are home to at least 325 globally threatened species and are one of only eight "hottest" biodiversity hotspots (Myers *et al*., 2000). Hill ecosystems also support millions of rural livelihoods through terrace agriculture, forestry, and pasture. The Indian Himalayas are especially significant. They encompass the highest and youngest mountain systems globally and represent a critical agroecosystem that supports approximately 75% of India's workforce. These regions are essential for both livelihood security and environmental stability, significantly influencing the sub-continent's climate by regulating monsoon patterns and preventing cold continental air from moving southward. The Himalayan region also provides approximately 1,204 km³ of perennial water flow annually to the Indo-Gangetic plains through snowmelt and glacial systems (Singh *et al*., 2011).

However, these landscapes are highly heterogeneous, with steep slopes, varied soils, and microclimates, and are increasingly vulnerable to deforestation, erosion, and climate change. Integrated planning (e.g., watershed management, agroforestry, integrated farming system) requires mapping upland ecosystems into homogeneous units that reflect natural productivity patterns and constraints. In this context, the concept of Ecological Production Units (EPUs) has gained attention. Adapted from marine ecology, EPUs are spatial units defined by consistent environmental and biological attributes, essentially homogeneous in ecological productivity. For terrestrial systems, EPUs can be seen as contiguous areas of land with similar topography, climate, soils, and land use, yielding uniform potentials for agriculture, forestry, and

conservation.

This review synthesizes how hill and mountain ecosystems are characterized and mapped globally and within India, emphasizing zonation frameworks and data sources. We examine Indian mapping efforts such as NRSC land-use/cover maps, NBSS&LUP agroecological zones, biogeographic zones, and watershed hierarchies, along with international schemes like WWF ecoregions, FAO agroecological zones, EPA ecoregions, Kapos mountain classes, and GMBA inventory. A practical multi-criteria EPU mapping framework is proposed for India's hill regions, including discussions on applications to watershed planning, agroforestry, conservation, and climate resilience. Despite multiple classification frameworks, existing approaches remain fragmented and sector-specific. There is a lack of spatial units that simultaneously capture ecological processes, production potential, and management relevance. This paper addresses the following questions: (i) How are hill and mountain ecosystems currently classified? (ii) What are the strengths and limitations of existing frameworks? (iii) How can EPUs provide an integrative operational framework? The study aims to synthesise classification approaches and propose a conceptual EPU framework tailored to Indian conditions.

2 | METHODS

This review conducted a systematic literature survey of peer-reviewed articles, technical reports, and agency documents on the classification of hill and mountain ecosystems in India and globally. We searched databases (Web of Science, Google Scholar) and agency websites using keywords such as "mountain ecosystem India," "hill agroecological mapping," "ecoregion classification India," "watershed zonation," and "ecological production units." Government and institutional sources (ISRO/NRSC, ICAR–NBSSLUP, UNESCO, FAO, etc.) were included. We analysed definitions (e.g., FAO/UNEP mountain classes), data sources (DEM, climate, soil maps, LULC), and classification schemes. Comparative international examples (WWF ecoregions, NOAA EPUs, GMBA inventory) were reviewed to identify relevant criteria. Based on the synthesis, we drafted a multi-criteria framework tailored to Indian hill zones, outlining data inputs, processing steps, major gaps, and policy linkage issues.

2.1 | Definitions and Characteristics

There is no single universal definition of "hills" versus "mountains." Mountain areas are most commonly defined by elevation and slope criteria. FAO and UNEP's global definition (used in SDG 15.4.2) classifies mountains into seven altitude–slope "Kapos classes" (Kapos *et al*., 2000): for example, terrain ≥4,500 m (Class 1), ≥3,500 m (Class 2), ≥2,500 m (Class 3), or lower altitudes with minimum slopes (e.g., ≥1,000 m with slope ≥5°, Class 5). By these rules, many of India's foothills qualify as mountain areas if they have steep relief. In some legal contexts, arbitrary criteria have also been applied; for example, the Indian Supreme Court recently defined "Aravalli Hill ranges" as any landform ≥100 m high with ≥500 m gap between hills. In ecosystem terms, hill and mountain ecosystems are typically rugged terrain with altitude-driven climate gradients, featuring montane forests, grasslands, and alpine zones that contrast with adjacent lowland plains (Fig. 1).

HIGHLIGHTS

- The complex hill ecosystems require integration of multiple classification systems (biogeographic, agro-ecological, hydrological, and global) as each capture only one dimension of a complex landscape.
- A GIS-based, multi-criteria Ecological Production Unit framework integrating topography, climate, soils, and land cover can enable more targeted conservation, agroforestry, and climate adaptation than coarse administrative zones.
- Supporting 75% of India's agricultural workforce and supplying 1,204 km³ of annual water flow, the Himalayas face accelerating threats from population pressure, mining, and glacial retreat.
- Outdated soil maps, infrequent land-cover surveys, and inter-agency silos hinder EPU adoption; progress requires updated geospatial data, participatory mapping, and stronger policy mandates.



FIGURE 1 Hill and Mountain Ecosystems of India

2.2 | Ecological Production Units (EPUs)

A central goal of mapping is to partition the landscape into homogeneous ecological units — areas relatively uniform in abiotic conditions and ecological response. In landscape ecology, analogous terms like *ecotope* or *habitat unit* have been used (Forman & Godron, 1986; Turner *et al*., 2001): they are spatially explicit, homogeneous landscape units useful for stratification. The EPU concept stresses functional productivity: an EPU should represent a zone with consistent potential for biomass production or ecosystem services given its environment. NOAA's EPUs on the US continental shelf are defined using "physiographic, oceanographic, and biological variables." Similarly, terrestrial EPUs would integrate topography, climate, soils, vegetation, and land use. By mapping EPUs in hilly regions, planners can identify areas sharing similar constraints (e.g., erosion risk) and potentials (e.g., suitable cropping systems).

2.3 | Scale and Hierarchy

Homogeneous units can be defined at multiple scales, from macro ecoregions to micro-watersheds. For instance, Rodgers and Panwar's (1988) biogeographic zones partition India into 10 major zones (e.g., Trans-Himalaya, Himalaya, Western Ghats), each containing several provinces. Within these, agroecological subregions (NBSS&LUP, 1999) further refine areas based on soil and climate. Watershed hierarchies form another nested scheme. An effective EPU mapping thus employs a hierarchical approach — broad zones divided into finer units — reflecting ecological theory that processes (climate patterns, species communities) operate differently at different scales.

3 | GLOBAL AND INDIAN CLASSIFICATION FRAMEWORKS

3.1 | Global Frameworks

3.1.1 | Kapos Mountain Classes (UNEP-WCMC/FAO)

Developed by UNEP's World Conservation Monitoring Centre in 2000, the Kapos classification assigns 6–7 global mountain classes based on elevation, slope, and local relief (Kapos *et al*., 2000). For example, Class 1 is ≥4,500 m, Class 4 is 1,500–2,499 m with slope >3.5°, and Class 6 is 300–999 m with local elevation >300 m. Using global DEMs such as GMTED2010 or GTOPO30, it identifies about 24–26% of the land as mountainous. It aims to create a simple, reproducible global mountain map widely used for SDG 15.4 monitoring, relying solely on topography (Table 1). However, fixed thresholds can misclassify terrain, and they overlook climate and ecological zones. While useful as a baseline, it needs additional biological or climatic data for biodiversity or local planning purposes (Snethlage *et al*., 2022).

3.1.2 | WWF Terrestrail Ecoregions

Olson *et al.* (2001) define about 867 terrestrial ecoregions worldwide, grouped into 8 biogeographic realms and 14 major biomes. Each ecoregion is a large area with relatively uniform climate, vegetation, and distinct species communities. India has roughly 45–46 terrestrial ecoregions (Olson & Dinerstein, 2002), including "Himalayan Subtropical Pine Forests," "South Western Ghats Montane Rain Forests," and "Eastern Himalayan Broadleaf Forests." These ecoregions implicitly represent mountains through categories like "Montane Grasslands," "Tropical Montane Forests," and others. They provide a biologically meaningful, integrated framework of flora and fauna data that is consistent on a global scale for conservation. However, their limitations include being coarse for local use, having subjective boundaries, not directly incorporating physical terrain data, potentially lumping or splitting mountain systems, and being a static map not suited for land use or agriculture planning. WWF ecoregions connect mountains to ecological communities, highlighting biodiversity patterns and endemism (e.g., unique assemblages in Eastern Himalaya vs. Western Ghats), but they lack detailed topographic criteria and are primarily intended for conservation rather than agricultural or hydrological planning (Dinerstein *et al*., 2017).

3.1.3 | GMBA Mountain Inventory

The GMBA inventory (Körner *et al.*, 2017; Snethlage *et al*., 2022) offers a hierarchical, GIS-based global delineation of mountains. Version 2 (2022) includes about 8,616 named mountain ranges across multiple levels, with two spatial extents: Standard (core mountainous areas) and Broad (transitional slopes). For example, the Himalayas are divided into numerous ranges, such as the Great Himalayas, Kumaon Himalayas, and Karakoram. Strengths of the inventory include its detailed, updated, hierarchical, and scale-flexible data that is freely accessible, capturing known ranges and subranges, and being widely used in research. Its limitations include complexity, the need for GIS skills, overlapping polygons that complicate simple area calculations, and a focus on mountainous areas rather than non-mountainous hills. The inventory provides the most detailed global mountain map, linking terrain and biodiversity, and supports cross-scale comparisons. However, it may be excessive for general planning and still requires alignment with other frameworks, such as ecoregions or climate belts.

3.2 | Indian Frameworks

3.2.1 | Biographic Zones

Rodgers and Panwar (1988) classified India into 10 biogeographic zones based on overall biota and broad environmental differences, further dividing these into 27 provinces. Mountain-specific zones include the Trans-Himalaya (Zone 1), Himalaya (Zone 2), Northeast (Zone 9), and Western Ghats (Zone 5). These zones were created primarily for wildlife conservation, focusing on flora and fauna distributions. Strengths include an ecology-centered approach, reflection of historical biogeography (such as Gondwanan versus Laurasian affinities), and their simplicity and influence in protected area planning. However, they have limitations: being broad-brush, they overlook sub-national elevation variations, have coarse,

somewhat subjective boundaries, are outdated (from 1988), were not initially GIS-based, and are less applicable to agriculture or watershed management. A key insight is that the zonation emphasizes India's main mountain and hill regions but combines diverse habitats — such as dry Ladakh and the lush Eastern Himalayas into a single "Himalaya" zone. While useful for summarizing biogeography, it offers limited detail on elevational gradients or local heterogeneity.

3.2.2 | Agro-ecological Zones (ICAR-NBSS&LUP)

In 1999, the NBSS division of ICAR identified 20 agroecological regions (AERs) by combining data on physiography, climate (growing period), and soils (NBSS&LUP, 1999). These regions represent broad production zones, such as AER-1 "Western Himalayas (cold arid)" and AER-17 "Northeastern Hills (warm perhumid)", and were intended to guide agricultural research and technology transfer. About 60 smaller agroecological sub-regions provide more detailed stratification. Strengths include focusing on key factors such as rainfall, soils, and season length, which are crucial for farming; making them more relevant for crop planning; and considering the interaction between climate and soils. Limitations include their design for agriculture rather than ecology, the possibility that a single region might encompass both lowland and highland areas if their growing periods (LGP) are similar, and their age, last formally updated in 1996. These zones are relatively large with limited ecological context. A key insight is that AEZs emphasize agro-climatic continuity but may divide mountain systems by cropping conditions rather than ecological coherence—for example, grouping the entire Western Ghats and nearby coastal plains into a single region based on similar rainfall and soil characteristics.

3.2.3 | Watershed/River-Basin Framework CWC/India-WRIS

India's river systems are organized hierarchically into basins, sub-basins, watersheds, and micro-watersheds (Central Water Commission [CWC], 2012 & 2014). The India-WRIS divides the country into 6 river regions, 35 basins, 112 catchments, 550 sub-catchments, and 3,257 watersheds ranging from 50 to 200 km². These river basins are categorized as Himalayan, Peninsular/Deccan, Coastal, and Inland Drainage rivers. Strengths include a terrain-based approach that is useful for water and flood planning, along with a detailed atlas and digital GIS data. Watershed boundaries naturally follow topographic divides in mountainous areas. However, the major concern is that the focus isn't on ecology or agriculture; mountain systems are divided by drainage patterns rather than continuous ecological zones, and boundaries can vary across watershed scales, potentially overlooking non-hydrological connections. Nevertheless, watershed mapping offers a hydrologic perspective on mountain regions—ideal for water resource management but less so for biodiversity or agricultural zones. For example, a single mountain ridge in the Western Ghats might drain to two different seas, resulting in separate basin classifications.

TABLE 1 Comparison of major classification frameworks relevant to hill and mountain ecosystems of India

Framework (Institutions)	Criteria/Data Used	Mountain Relevance	Application/Sector	Spatial Scale	Strengths/ Limitations
Kapos Mountain Classes (UNEP–WCMC/FAO)	Elevation, slope, local relief	Explicitly delineates mountain terrain globally	Biodiversity, SDG monitoring	Global; ~1 km DEM	Objective, reproducible; ignores climate/ecology
WWF Terrestrial Ecoregions (Olson et al., 2001)	Climate, vegetation, species endemism	Montane forests/grasslands (e.g., Himalayan broadleaf, WG evergreen)	Biodiversity conservation	Global (~867 ecoregions)	Biologically meaningful; coarse for local planning
GMBA Mountain Inventory (Körner et al., 2017)	DEM ruggedness + expert mapping	Full extent of mountain terrain; 8,616 named ranges	Mountain ecology, biodiversity research	Global, hierarchical	Highly detailed, complex, focused on ranges only
Biogeographic Zones (Rodgers & Panwar, 1988)	Flora/fauna, physiography	10 zones including Himalaya, WG, NE Hills	Conservation/wildlife planning	National (10 zones, 27 provinces)	Ecology-focused; dated; too broad for site-level use
Agro-ecological Regions (NBSSLUP, 1999)	Topography, soil, climate, LGP	AER-1 (W. Himalaya), AER-17 (NE Hills), AER-19 (WG)	Agriculture and land-use planning	National (20 regions, 60 subregions)	Agriculture-relevant; ignores biodiversity/forestry

Continued on next page

Table 1 continued

Framework (Institutions)	Criteria/Data Used	Mountain Relevance	Application/Sector	Spatial Scale	Strengths/ Limitations
Watershed Atlas (CWC, 2012)	Hydrology (drainage divides)	Himalayan/Peninsular river basins	Water resources and development	National (6 regions to micro-watersheds)	Physically rigorous; splits ecological continuity
LULC Maps (NRSC/ISRO)	Remote sensing imagery	Alpine grassland, Snow/Glacier, Ravines classes	Land-use planning baseline	National (1:50k)	Detailed; infrequently updated
Forest Type Maps (FSI, 1987)	Forest community/structure	Himalayan moist temperate, Sub-tropical pine, etc.	Forestry planning	National (4 groups × 32 types)	Illustrative; dated
FAO Global AEZ	Climate, soils, land suitability	Aligns with national AERs	Agriculture, food security	Global	Mirrors NBSS AERs for India

3.2.4 | Land-Use/Land-Cover Maps (NRSC, ISRO)

The national LULC mapping (e.g., 2016–2020) uses satellite imagery to classify land at 1:50k scale (NRSC, ISRO). Hill-specific categories include *"Alpine/Sub-Alpine Grassland," "Snow and Glaciers,"* and *"Gullied/Ravinous Land."* Together, these classes capture both natural cover (forest, grassland) and anthropogenic use (cropland terraces, settlements) and serve as a primary input for any land-use planning.

3.3 | Integrated Discussion: Global vs. Indian Frameworks

The global schemes and Indian schemes each emphasize different aspects of mountain lands. The Kapos/UNEP classes and GMBA inventory use physical criteria (elevation, slope, relief) to objectively identify mountain terrain, whereas the WWF ecoregions use ecological-historic criteria (species assemblages and climate). Indian frameworks are context-specific: Rodgers–Panwar biogeographic zones emphasize India's distinct biogeographic histories; agro-ecological zones emphasize agriculture-related climate-soil factors; and watershed basins emphasize hydrology. For example, the Himalayan region is treated in multiple ways: Rodgers–Panwar designate it as a single "Himalaya" zone; WWF identifies at least six Indian ecoregions from alpine shrublands to subtropical forests; GMBA lists dozens of named ranges; AEZ splits the region by growing season; and the Watershed Atlas splits it by river basins (Indus vs. Ganga vs. Brahmaputra). Each framework offers a different but equally valid "lens." A critical insight from a synthesis is that no single map suffices for Himalayan or broader hill issues. Conservationists may overlay WWF ecoregions and GMBA ranges to identify biodiversity hotspots, while agricultural planners rely on AEZs and watershed units to design interventions. Effective conservation or planning will overlay and cross-reference these maps. The choice of framework depends on purpose: WWF ecoregions emphasise biodiversity patterns; AEZs emphasise crop-climate suitability; and watersheds emphasise drainage connectivity.

4 | THE INDIAN HIMALAYAS: CLASSIFICATION, ECOLOGY, AND PRODUCTION SYSTEMS

The Indian Himalayas are geographically divided into two primary flanks: The Western Himalayas and the North-Eastern Himalayas (NEH), collectively covering 14 states and 90 districts.

- **Western Himalayas:** This region constitutes 62.4% of the total Himalayan area, characterized by steep slopes, severe winters, and predominantly coniferous forests. It includes Jammu & Kashmir, Ladakh, Himachal Pradesh, and the hill regions of Uttarakhand.
- **North-Eastern Himalayas:** Defined by relatively gentler slopes, high rainfall, and a humid climate, this region includes Arunachal Pradesh, Sikkim, and Meghalaya.

The divergence between classification frameworks is especially instructive in the Himalayan context. Rodgers and Panwar (1988) assign the entire range to one or two zones (Trans-Himalaya, Himalaya), so policy documents often treat "Himalaya" as a single unit. WWF (Olson *et al*., 2001) identifies at least six Indian ecoregions across the range — from alpine shrublands to subtropical forests — underscoring its ecological complexity. The GMBA inventory (Snethlage *et al*., 2022) further delineates dozens of named sub-ranges (e.g., Great Himalaya, Kumaon Himalaya, Karakoram). AEZs (NBSS&LUP, 1999) break the range into regions by climate: far-north Ladakh is "cold dry" (Region I) while eastern slopes fall under "Eastern Himalayas" (Region XVI). The Watershed Atlas (CWC, 2012) splits the range by drainage — Indus for Ladakh/Karakoram, Ganges for Garhwal and Kumaon, and Brahmaputra for Arunachal/Assam. Each scheme is valid for its goal: WWF/GMBA emphasises high levels of endemism between the Eastern and Western Himalayas, AEZ emphasises crop-growing challenges at altitude, and watershed maps serve hydropower and flood-control planning.

Himalayan ecosystems are defined by fragility, marginality, and poor accessibility (Singh *et al*., 2011). The

wide variation in altitude and latitude generates a vast diversity of microclimates, habitats, and vegetation. Approximately 15% of the area is under permanent snow, providing a perennial flow of roughly 1,204 km³ annually to the Indo-Gangetic plains (Singh *et al*., 2011). Despite this abundance, the western region faces acute water scarcity during summer (Table 2). The ecosystem is under severe threat from excessive exploitation due to increasing human and livestock populations; activities such as mining and road construction in fragile areas lead to mass soil erosion and heavy sedimentation of downstream reservoirs (Negi & Joshi, 2002; Xu *et al.*, 2009). Livelihood systems vary spatially based on altitudinal zones:

- **Sub-montane/Low-hill Zone:** Focuses on rice, maize, wheat, citrus, mango, and livestock such as buffaloes.
- **Mid-hill Zone:** Predominantly an agri-horti-livestock system involving maize, wheat, citrus, pineapple, and banana.
- **Dry Temperate Zone (>2,200 m):** Dominated by sheep, goats, and yak. Migratory or nomadic pastoralism is a traditional practice to maintain ecosystem integrity.
- **Western Region Specialisation:** Apples are the major horticultural crop; off-season vegetables (peas, tomato) are widely cultivated.
- **NEH Region Specialisation:** Shifting cultivation (Jhum) is still practiced; high-value crops include spices, condiments, pineapple, and banana (Tripathi & Barik, 2003; Tiwari *et al.*, 2010).

TABLE 2 Synthesis of Strengths, Weaknesses, Opportunities, and Threats (SWOT) for Indian Himalayan hill ecosystems.

Category	Key Findings
Strengths	Enormous wealth of natural resources (land, water, vegetation) and rich indigenous knowledge systems.
Weaknesses	Poor infrastructure, subsistence-oriented economy, and lack of situation-specific modern technologies.
Opportunities	Potential for high-density orcharding, cold-water aquaculture (Mahaseer), and value-added agroforestry interventions.
Threats	Resource degradation, unauthorised migration, loss of genetic diversity in local crops, and increasing highland–lowland conflicts.

TABLE 3 Major geospatial data sources for hill and mountain ecosystem mapping in India

Data Type	Source/Resolution	Coverage & Use	Indian Example/ Agency
Digital Elevation Model	SRTM (~30 m); ASTER (~30 m); Cartosat-1 DEM (30 m)	Elevation, slope, aspect, ruggedness — delineating altitude zones and hillslopes	ISRO Cartosat DEM
Climate	IMD (rainfall grids, ~25 km); WorldClim/CHELSA (~1 km)	Rainfall, temperature, season length — defining climate belts	IMD State Centre; ICAR climate zones
Soils	NBSS&LUP soil map (1:250k); SoilGrids (250 m)	Soil orders, texture, depth — affecting fertility and erosion risk	NBSS&LUP soil maps and AER charts
Land Cover	NRSC LULC maps (1:50k); MODIS (500 m); ESA-CCI (300 m)	Vegetation and land-use classes (forests, grasslands, agriculture, built-up)	NRSC Bhuvan portal
Vegetation/Ecoregions	FSI forest type map; UNEP ecoregions dataset	Broad vegetation zones (montane forest, dry forest, etc.)	FSI Report (1987) forest atlas
Hydrology/Watersheds	River network GIS; Watershed Atlas polygons	Drainage divides — organising units by catchment	India-WRIS GIS (CWC, 2012)
Socio-economic	Census 2011 (district/tehsil); Tribal map; Road network	Population density, land-use pressure, infrastructure	Census of India; Ministry of Tribal Affairs
Remote Sensing	Landsat, Sentinel imagery; Google Earth; field surveys	Satellite imagery for validation; local data (crop, micro-topography)	NRSC ground truth programmes

5 | PROPOSED MULTI-CRITERION FRAMEWORK FOR HILL AND MOUNTAIN EPUS

To define **Ecological Production Units (EPUs)** in Indian hill regions, we propose a GIS-based, hierarchical multi-criteria framework (Table 3). The key steps are as follows.

Step 1 — Initial Stratification: Use existing broad divisions to define the analysis extent, separating the country into major mountain complexes: Western Himalaya, Eastern Himalaya, Central Indian Highlands, Western Ghats, Eastern Ghats, and NE Hills (Fig. 2). These align broadly with WWF ecoregions or biogeographic provinces (Rodgers & Panwar, 1988; Olson *et al*., 2001).

Step 2 — Variable Selection: Compile layer data including DEM (elevation, slope), climate (rainfall, temperature, growing period), soils (texture, depth), land cover, and socio-economics (population, livelihoods). Where available, include disturbance and hazard layers (landslide susceptibility, fire risk).

Step 3 — Criteria Derivation: For each pixel or watershed unit, compute derived indicators:

- Elevation band (e.g., 0–500 m, 500–1,500 m, >1,500 m)
- Slope category (e.g., <15°, 15–30°, >30°)
- Rainfall regime (e.g., >2,000 mm/yr, 1,000–2,000 mm/yr, <1,000 mm/yr)
- Length of Growing Period (LGP in days)
- Soil depth class (deep vs. shallow)
- Land cover type (dense forest, open forest, grassland, agriculture)
- Population pressure (e.g., low <50/km², medium, high)
- Accessibility (distance to roads or towns)

Step 4 — Homogeneity Analysis: Group areas similar across these indicators using:

- *Clustering algorithms:* K-means or hierarchical clustering on a multi-dimensional normalised feature space;
- *Overlay and rule-based grouping:* Pre-define classes (e.g., all pixels with >2,000 m, >30° slope, and <800 mm rain as "high alpine zone");
- *Principal Component Analysis (PCA):* Reduce dimensionality, then classify principal components.

Step 5 — Refinement and Expert Review: Check candidate EPU maps for ecological coherence; merge small fragments with adjacent units where conditions are similar; adjust boundaries to align with natural features (ridges, rivers) or administrative units for practicality.

Step 6 — Validation: Compare EPUs with independent data (e.g., vegetation maps, known farming practices). Each EPU should ideally correspond to a consistent set of dominant tree species or crop systems. Field surveys and local expert input — including participatory GIS with tribal and rural communities — can refine the units (Tiwari *et al.*, 2010).



FIGURE 2 Different mountain regions of India

Step 7 — Scale Tiers: Produce EPUs at multiple scales — coarse units of 100–1,000 km² for landscape planning, and finer subunits of 10–50 km² for local watersheds — nested so that coarse units aggregate to ecoregions and fine units align with micro-watersheds.

High-altitude catchments (>3,500 m) with glaciers form a *"Glacial Alpine"* EPU, characterised by permanent snow cover, sparse vegetation, and meltwater provisioning. Mid-montane forests (2,000–3,500 m, high rainfall, brown forest soils) form a *"Subalpine Broadleaf"* EPU. Lower rain-shadow slopes (<1,500 m, <800 mm) form a *"Dry Temperate"* EPU. Each has distinct production potential: alpine pastures, oak forests, and chestnut forest, respectively. Across the country, analogous sets of EPUs would be delineated for each mountain system.

5.1 | Application to Planning and Climatic Adaptation

Once EPUs are mapped, they can inform multiple planning domains. In watershed management, EPUs identify zones with similar erosion risk and land use; for example, an EPU designated "steep degraded mid-hills" might be prioritised for terracing, afforestation, and rainwater harvesting. In

agroforestry, EPUs match species to ecological suitability: Shisham (*Dalbergia sissoo*) might suit lower humid EPUs, while pine or fir suits cooler, higher EPUs. In conservation zoning, EPUs can target high-endemism areas — for example, an EPU corresponding to the "Shola-grassland mosaic" in the Nilgiris. For climate adaptation, EPUs with limited moisture or short growing seasons can be prioritised for drought-resistant cropping trials. In policy, EPUs could integrate multiple schemes. MGNREGA (Mahatma Gandhi National Rural Employment Guarantee Act) could allocate soil conservation funds based on EPU vulnerability. State horticultural boards could use EPU maps to diversify hill agriculture. The National Mission for Himalayan Studies (NMHS) and "Sub-Mission on Himalayan Ecosystems" under India's National Action Plan on Climate Change could adopt EPU mapping as a decision-support tool.

6 | GAPS AND RECOMMENDATIONS

Despite these opportunities, significant gaps remain. NBSS soil maps are at 1:50,000, and some regions lack detailed surveys. LULC maps are updated infrequently. Climate change impacts — shifting rainfall patterns, glacial retreat (Xu *et al*., 2009) — are seldom integrated into static zonations. Socio-economic mapping (livelihood zones, land ownership) is weakly linked to ecological units. Many existing classifications were designed pre-GIS and are not easily digitised. Institutional silos (agriculture vs. forestry vs. water) mean no single agency owns the EPU concept. Methodologically, automated classification can be challenged by subjectivity in variable weighting or cluster number selection, and local variability (microclimates, ethnic land practices) may not be captured.

We propose the following priority actions:

1. **Update and integrate geospatial data**: Release high-resolution DEM (IIRS Cartosat SRTM); expand soil and forest inventories with new field sampling and remote sensing (e.g., LiDAR for canopy).
2. **Develop standardised EPU guidelines**: Pilot EPU mapping in one Himalayan state (MoEF/NBSS&LUP leadership) to refine criteria.
3. **Link EPUs to monitoring**: Tie forest cover change or groundwater depletion indicators to each EPU.
4. **Encourage interdisciplinary research**: Combine geography, ecology, and social science — for example, incorporating community land tenure (Tiwari *et al*., 2010).
5. **Use participatory GIS**: Involve local stakeholders, including tribal communities, in validating EPU maps.
6. **Policy mainstreaming**: Mandate use of EPU-level analysis in watershed management plans, hill area development programmes, and adaptation planning.
7. **Human Resource Development**: Empower women, who constitute the primary agricultural workforce in Himalayan regions (Planning Commission, Government of India, 1989).
8. **Technology Refinement:** Develop stress-resistant crop varieties and localised water harvesting systems appropriate to specific EPU conditions.

7 | CONCLUSIONS

Hill and mountain ecosystems in India are complex mosaics of soils, climates, and communities. Traditional maps — states, districts, broad agro-climatic zones — do not capture this heterogeneity. As demonstrated in this review, multiple Indian and international frameworks exist that stratify landscapes by ecological factors. The Himalayan region, for example, is simultaneously a single biogeographic zone (Rodgers & Panwar, 1988), six or more ecoregions (Olson *et al*., 2001), dozens of named mountain ranges (Snethlage *et al.*, 2022), two agro-ecological regions (NBSS&LUP, 1999), and three major river basins (CWC, 2012) -each perspective revealing distinct but complementary information.

A gap remains in *integrating* these approaches into a single, operational mapping of homogeneous Ecological Production Units. The multi-criteria GIS framework proposed here — combining topography, climate, soils, cover, and human data — can sharpen the focus of conservation and development: directing soil conservation to the most erosion-prone units, matching crop and forest types to suitable zones, and targeting climate adaptation to vulnerable hill strata. The approach aligns with global ecosystem-based management practices (FAO, 2007) while being tailored to Indian data and policy contexts.

For next steps, pilot studies are needed (e.g., mapping EPUs in a Himalayan state or the Western Ghats). The scientific community should work with government agencies (forest, agriculture, environment ministries) to harmonise terminology and data standards, perhaps through a national "Hills GIS" database. Given accelerating pressures on upland ecosystems, there is an urgency to refine and apply these mapping frameworks. Ultimately, delineating homogeneous ecological production units can make land management in India's hills more targeted, efficient, and resilient.

ACKNOWLEDGEMENTS

Authors sincerely thank editor and reviewers of the manuscript for much help in improving this manuscript.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

Data will be made available on the request.

AUTHOR'S CONTRIBUTION

Rajive K. Singh: Conceptualization, Investigation, Formal analysis, Writing - original draft, Review & editing. Raman Jeet Singh: Review & editing, Formal analysis, Writing - original draft.

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How to cite this article: Singh, R.K., and Singh, R.J., 2025. Mapping Hill and Mountain Ecosystems in India: A Review and Framework for Ecological Production Units (EPUs). *Indian J. Soil Cons*., **53(3) (***Hill & Mountain Agriculture S*pecial Issue**): 195-203**

Received: 09 September 2025 | Accepted: 19 December 2025 | Published online: 06 April 2026

DOI: 10.53550/ijsc.v53.i3.204

ORIGINAL ARTICLE

Indian Journal of Soil Conservation

Water Management Technologies in Ladakh's Cold Arid Region: Climate Impacts and Adaptive Strategies - A Field Documentation Study

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Handling Editor:
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Key words:
Artificial glaciers
Climate change
Ladakh
Sustainable agriculture
Water management

ABSTRACT

Ladakh, a high-altitude cold arid region in the trans-Himalayan zone, faces escalating water scarcity due to climate change, marked by glacial retreat, reduced snowfall, and warming trends. This field documentation study synthesizes traditional and modern water management technologies—zings, kuhls, artificial glaciers, ice stupas, and polyhouses—to address these challenges in Leh and surrounding areas. Drawing on field observations (2022-2024), statistical climate analysis (1901-2023), and community insights, it evaluates technology performance and socio-economic impacts. Statistical analysis using Mann-Kendall tests (τ=0.18-0.32, $p < 0.05$) confirms significant warming trends (0.02-0.21°C year^{-1}), while precipitation shows pronounced decline (-7.9 mm/year, 1990-2020) with increased drought frequency (SPI <-1 every 5-7 years). Field surveys demonstrate that traditional technologies (zings, kuhls) increase irrigation coverage by 20-30%, while modern innovations (artificial glaciers, ice stupas, polyhouses) extend growing seasons and boost yields by 20-40%. However, challenges include groundwater depletion (1-2 m annually), contamination (70% of aquifers), high technology costs (₹13.5-75 lakh), and tourism-driven demand surges (10-15% in 2023). Sustainable strategies, including wastewater recycling, kuhl lining, technology subsidies, and policy reforms like water pricing, are proposed to enhance resilience. Comparisons with global arid regions underscore Ladakh's unique community-driven approach. This synthesis advocates integrating traditional practices with modern innovations to ensure water security in Ladakh's fragile ecosystem.

1 | INTRODUCTION

Ladakh, a trans-Himalayan cold desert in northern India, epitomizes the challenges of water management in arid, high-altitude ecosystems (Fig. 1). Spanning 59,146 km² across Leh and Kargil districts, the region relies heavily on glacial and snowmelt for its water supply, which supports agriculture (80% of livelihoods), tourism (4.5 lakh visitors in 2023), and hydropower (Gaur, 2025). With annual precipitation below 100 mm and evaporation rates reaching 2,000 mm, Ladakh's water resources are under severe strain from climate change, characterized by a 15-20% glacial retreat since the 1980s, a 30% reduction in winter snowfall, and temperature increases of 0.02-0.21°C per year (Chevuturi *et al.*, 2018; Immerzeel et al., 2020).

These changes disrupt traditional agricultural cycles, delay sowing from April to May, and exacerbate water shortages, particularly in Leh, where inefficiencies in supply systems, groundwater depletion (1-2 m annually), and contamination (70% of aquifers) create a management crisis rather than a scarcity issue (Gohel *et al*., 2019; LAHDC, 2023). Tourism, while economically vital, amplifies water demand by 10-15% and generates 1.2 million plastic bottles annually, compounding environmental stress (Gaur, 2025). The region's economy relies on agriculture, tourism, and hydropower, with glaciers such as Siachen and Drang-Drung playing a pivotal role in water supply.

While previous studies have documented climate trends (Chevuturi *et al.*, 2018; Shafiq *et al.*, 2016) and individual water management practices (Namtak & Sharma, 2018; Nüsser *et al.*, 2019) in Ladakh, a comprehensive synthesis integrating statistical climate analysis, technology performance assessment, and policy recommendations is lacking. This study bridges this gap through systematic field documentation and quantitative evaluation of adaptation strategies. This field documentation study aims to analyze climate change impacts on water resources (1901-2023), and evaluate the performance and scalability of traditional (zings, kuhls) and modern (artificial glaciers, ice stupas, polyhouses) water conservation technologies through field surveys and farmer assessments. This documentation study provides a comprehensive overview of sustainable water management technologies in Ladakh, blending traditional practices like zings and kuhls with modern innovations such as artificial glaciers, ice stupas, and polyhouses. Drawing

on field observations (2022-2024), statistical climate analysis (1901-2023), interviews with farmers and officials, and secondary data from meteorological records and government reports, it evaluates their efficacy, challenges, and socio-economic implications.

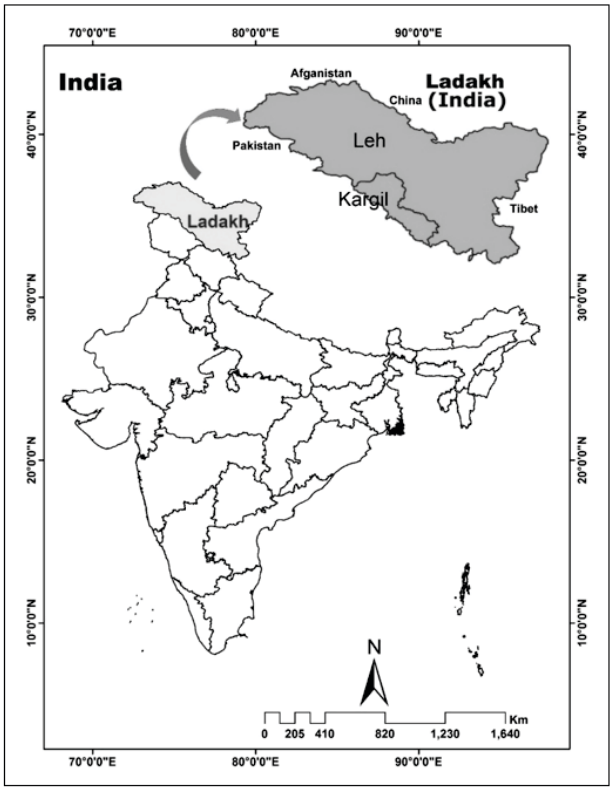


FIGURE 1 Location map of Ladakh (India)

2 | MATERIALS AND METHODS

This study employs a mixed-methods approach that combines quantitative climate data analysis spanning from 1901 to 2023, field-based technology assessment conducted between 2022 and 2024, qualitative stakeholder consultations, and secondary data synthesis from government and research sources. The research framework integrates observational documentation with statistical validation to assess the linkages between climate, water resources, and agriculture in Ladakh's cold arid ecosystem. Fieldwork concentrated on Leh city to examine urban water management challenges, while rural villages such as Stakmo, Phyang, Sabu, Choglamsar, Nang, and Gangles served as sites for technology implementation, with the study area's altitude ranging from 3,350 to 4,267 meters above sea level.

Primary data collection involved field surveys carried out from June to September during the years 2022 to 2024, aligning with the summer months for agricultural and tourism seasons. A total of six villages across Leh district were surveyed using a purposive sampling strategy based on technology adoption and accessibility. The interview protocol consisted of semi-structured interviews with farmers, local authorities, and water management officials to gather insights on technology performance, challenges, and socio-economic impacts. Technology assessment was evaluated through yield comparisons, irrigation coverage measurements, qualitative farmer feedback, and on-site observations of water conservation efficiency.

HIGHLIGHTS

- In Cold Arid regions of Leh -Ladakh, traditional water systems like *zings* and *kuhls* improved irrigation coverage by 20–30% through community-managed practices.
- Artificial glaciers and ice stupas extend early-season water availability by 20–40 days, boosting crop yields by 20–40%.
- Polyhouses enable 4–8 times higher yields and extend growing seasons by 2–3 months.
- Key challenges: groundwater depletion (1–2 m/year), 70% aquifer contamination, tourism-driven demand surge (10–15%) intensify water stress.
- Integrating traditional knowledge with modern technologies is essential for climate-resilient water management in Ladakh.

Secondary data sources included climate data and hydrological information, such as groundwater assessments from the LAHDC 3rd Groundwater Assessment in 2023, water quality analyses and water supply statistics from the PHE Department and Leh Municipal Corporation, and glacial retreat data from peer-reviewed studies like those by Immerzeel et al. (2020) and Soheb et al. (2022). Socio-economic data encompassed tourism statistics on visitor numbers and waste generation from the Leh tourism department, agricultural data on cropping patterns and yields from the Department of Agriculture in Ladakh, and demographics from the Census of India and LAHDC reports. The literature search protocol utilized a systematic search on platforms including Google Scholar, Web of Science, and Scopus.

Data analysis methods for climate data involved the Mann-Kendall (MK) test for monotonic trend identification, with the null hypothesis assuming no trend in the time series at a significance level of $\alpha = 0.05$, using the test statistic τ (tau) along with its corresponding p-value (Reddy *et al*,. 2020; Jeet *et al.*, 2024). Sen's slope estimator was applied to determine trend magnitude, while the modified Mann-Kendall test was used for precipitation analysis. Additional techniques included the Standardized Precipitation Index (SPI) for drought assessment, return period estimation for drought frequency analysis. R statistical software was employed for trend analysis and variability indices. Water management assessment was quantified using data on supply-demand balance, and technology efficacy via yield comparisons and farmer feedback. Groundwater analysis evaluated depletion rates and contamination levels from LAHDC reports, while economic evaluation involved cost-benefit analysis of technologies, incorporating installation costs and yield boosts.

3 | RESULTS AND ANALYSIS

3.1 | Climate Data Analysis And Hydrological Impacts

This section provides a detailed statistical analysis of climate data for the Ladakh region, focusing on long-term trends, interannual variability, and shifts in baseline climate behavior. Analyses incorporate time-series trend detection using the Mann-Kendall (MK) test and Sen's slope estimator, anomaly detection, change point analysis, and climate variability indices such as the Standardized Precipitation Index (SPI) and coefficient of variation (CV). Data are drawn from historical records (1901–2023) and peer-reviewed studies.

3.1.1 | Climate Data Analysis

The impacts of climate change on Ladakh's water resources have been evaluated along with an analysis of water management challenges in Leh, as well as assessment of the effectiveness of traditional and modern water conservation technologies. The discussion is supported by quantitative data, visual representations, and qualitative insights from field surveys conducted between 2022 and 2024. The analysis addresses the region's vulnerability to climate variability, socio-economic pressures, and the potential of adaptive strategies to ensure water security.

3.1.1.1 | Temperature Trends And Variability

Historical data indicate significant warming in Leh. Mean annual temperature increased at 0.02°C per year from 1901–2019 (Romshoo *et al.,* 2022) (Fig. 2). More recent periods show accelerated rates: annual temperature rose by 0.21°C per decade from 1979–2009 (Chevuturi *et al*., 2018), with mean monthly maximum temperatures increasing at 0.2°C per year and minimum at 0.07°C per year from 2000–2013 (Tundup *et al*., 2016). Seasonal analysis reveals summers warming at 0.006°C per year and winters at 0.08°C per year (Lone *et al*., 2019).

The Mann-Kendall test applied to temperature series (1901–2013) confirms a significant positive trend ($\tau = 0.25$, $p < 0.05$) for annual mean temperatures (Chevuturi et al., 2018). Sen's slope estimator indicates a rise of 0.015°C per year overall, with higher slopes in winter (0.08°C/year). Interannual variability, measured by CV, is higher for minimum temperatures (CV = 15–20%) than maximum (CV = 10–12%), suggesting greater fluctuations in cold extremes.

Anomaly detection relative to the 1901–1950 baseline shows positive anomalies post-1980, with a change point around 1975 identified via Pettitt's test, marking a shift to warmer conditions (Shafiq *et al*., 2016).

Table 1 Temperature Trends in Leh, Ladakh

Period	Variable	Trend (MK τ)	Sen's Slope (°C/year)	Source
1901-2019	Mean Annual Temperature	0.18*	0.02	Romshoo *et al.* (2022)
1979-2009	Annual Temperature	0.25*	0.021	Chevuturi *et al.* (2018)
2000-2013	Mean Monthly Maximum	0.32*	0.2	Tundup *et al.* (2016)
2000-2013	Mean Monthly Maximum	0.28*	0.07	Tundup *et al.* (2016)

*Significant at $p < 0.05$.

Table 1 presents temperature trends in Leh, Ladakh, based on data from various studies, highlighting changes over different time periods. It includes four key metrics: the period of study, the temperature variable analyzed, the trend (expressed as the Mann-Kendall tau, or MK τ), and the Sen's Slope (indicating the rate of temperature change in °C per year).

1901–2019: Mean Annual Temperature: Over the 118-year period from 1901 to 2019, the mean annual temperature in Leh, Ladakh, showed a statistically significant upward trend, with an MK τ value of 0.18. The Sen's Slope indicates a warming rate of 0.02°C per year. This suggests a gradual but consistent increase in average temperatures over the long term. The data comes from Romshoo *et al.* (2022).

1979–2009: Annual Temperature: Over the 30-year period from 1979 to 2009, the annual temperature also exhibited a statistically significant rising trend, with an MK τ of 0.25. The Sen's Slope shows a warming rate of 0.021°C per year, slightly higher than the long-term trend observed over 1901–2019. This indicates a more pronounced warming in recent decades. The source for this data is Chevuturi *et al*., (2018).

2000–2013: Mean Monthly Maximum Temperature: Over the 13-year period from 2000 to 2013, the mean monthly maximum temperature (the average of daily high temperatures) increased significantly, with an MK τ of 0.32. The Sen's Slope reveals a steep warming rate of 0.2°C per year, much higher than the annual averages in the longer-term studies. This suggests that daytime temperatures in Leh were rising rapidly during this period. The data is sourced from Tundup *et al*., (2016).

2000–2013: Mean Monthly Minimum Temperature: During the same 2000–2013 period, the mean monthly minimum temperature (the average of daily low temperatures) also showed a statistically significant upward trend, with an MK τ of 0.28. The Sen's Slope indicates a warming rate of 0.07°C per year. While this rate is lower

than that for maximum temperatures, it still reflects a notable increase in nighttime or early-morning temperatures. This data is also from Tundup *et al.*, (2016).

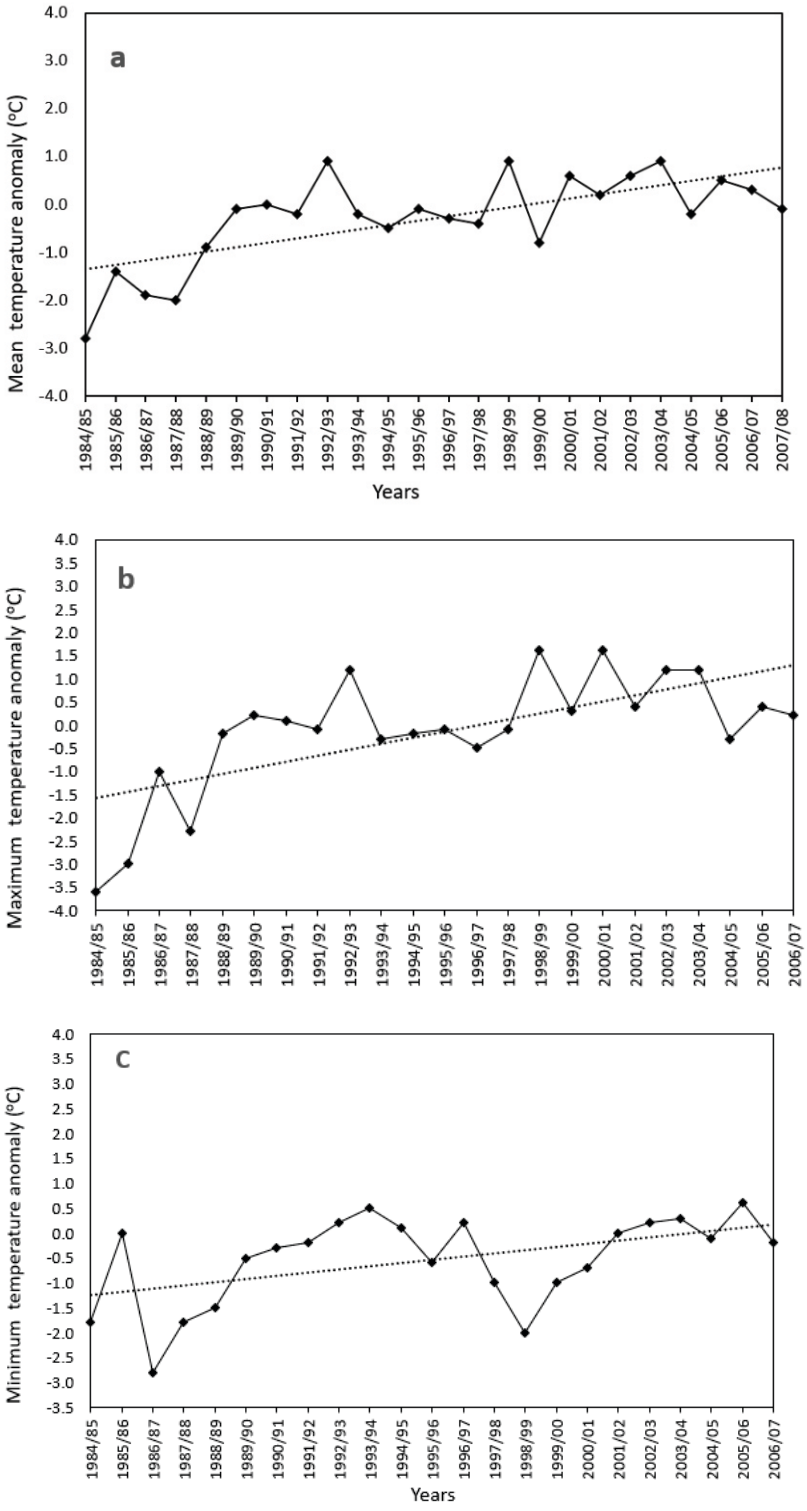


FIGURE 2 (a) mean, (b) maximum, and (c) minimum temperature anomalies for November–April over the western Himalaya. The dotted lines in this and subsequent figures are simple trends of the time series of the parameters (Adapted and modified after Chevuturi *et al*., 2018; Shekhar *et al*., 2017, and Romshoo *et al*., 2022).

Thus the Table 1 indicates a clear warming trend in Leh, Ladakh, across different time scales and temperature metrics. The long-term data (1901–2019) shows a steady but slow increase in mean annual temperatures, while the more recent periods (1979–2009 and 2000–2013) suggest accelerated warming, particularly in maximum temperatures during 2000–2013. The higher Sen's Slope for maximum temperatures (0.2°C/year) compared to minimum temperatures (0.07°C/year) in the 2000–2013 period points to more rapid increases in daytime highs than nighttime lows. All trends are statistically significant, reinforcing the reliability of these findings. The data collectively underscores the impact of climate change in this high-altitude region, with implications for local ecosystems, water resources, and livelihoods.

Chevuturi *et al.,* (2018) has reported a 30% reduction in winter precipitation (primarily snowfall) from 1901 to 2018, with reduced precipitation in recent decades. Mean annual temperature at Leh is 7.3°C, with extremes of 34.8°C (summer) and -27.9°C (winter). Shafiq *et al* (2016) has indicated that winter precipitation (November–February) at Leh showed a positive trend from 1941–1950 (95.8 mm) but decreased thereafter until 1970, with an overall negative trend from 1901–2000. Winter precipitation increased at 0.42 mm/yr from 1991–2000. Meteorological Centre, Ladakh has reported a maximum temperature of 33.5°C on July 28, 2024, and noted temperatures frequently reaching 33°C in recent years, with 36.6°C in 2013 as the highest in 52 years (Fig. 3).

3.1.1.2 | Precipitation Trends And Variability

Precipitation in Leh averages <100 mm annually, with winter snowfall dominating. From 1901–2000, winter precipitation (November–February) averaged 68.09 mm (liquid equivalent), showing a negative trend (MK $\tau = -0.15$, $p < 0.05$) and Sen's slope of -0.127 mm/year for summer rainfall (Shafiq *et al.*, 2016). Recent data (1990–2020) indicate an annual decline of -7.9 mm/year, with seasonal decreases: winter (-4.09 mm), spring (-3.48 mm), autumn (-1.90 mm), and summer (-0.66 mm) (Kumar et al., 2023). Modified MK test confirms these negative trends ($z = -2.1$ to -3.5, $p < 0.05$).

SPI analysis reveals increased drought frequency post-1970, with moderate droughts (SPI < -1) occurring every 5–7 years. CV for annual precipitation is high (35–45%), indicating substantial interannual variability. Change point analysis detects a shift around 1970 toward reduced snowfall (Shafiq *et al.*, 2016). Summer rainfall increased slightly at 0.11 mm/year, while winter snowfall decreased at -0.18 mm/year (Chevuturi *et al*., 2018). Figure 5 shows precipitation trends. An in-depth analysis of annual precipitation trends in Leh, Ladakh, reveals a consistent and statistically significant decreasing monotonic trend in annual precipitation over the studied period. The majority of data points in the trend analysis fall below the 45° line, indicating a clear departure from a stable or constant precipitation pattern. Furthermore, a significant portion of these data points lies outside the 5% confidence interval, providing robust evidence of the trend's statistical significance. The innovative trend analysis method confirms a pronounced monotonic decline in annual precipitation, characterized by a negative slope. Specifically, the calculated slope indicates an average decrease of approximately -2.45 mm in annual precipitation per year. Additionally, the percent bias analysis highlights a substantial reduction, with annual precipitation decreasing by approximately 49% compared to the baseline. This significant decline in precipitation could have critical implications for water availability, agriculture, and ecosystem stability in the region, underscoring the need for further monitoring and adaptive measures to address the impacts of this trend (Fig. 4).

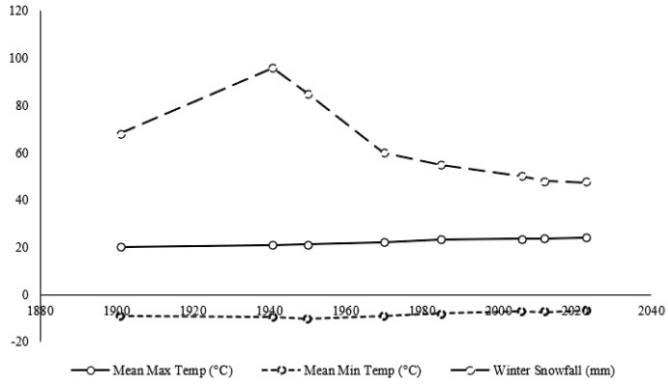


FIGURE 3 Temperature and Precipitation Trends in Leh (1901-2023) (Source: Adapted and modified after Shafiq *et al.*, 2016 and Chevuturi *et al*., 2018*)*

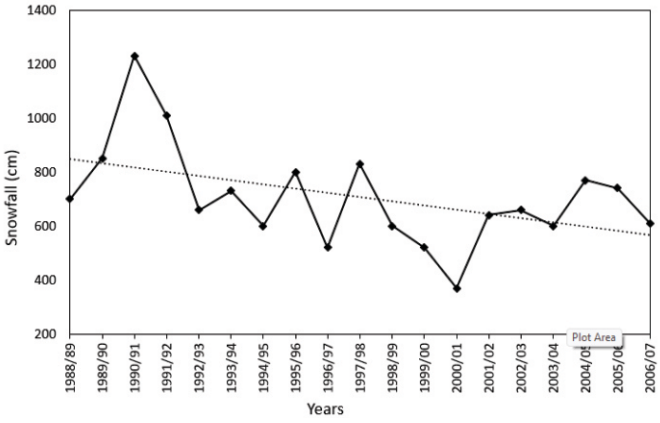


FIGURE 4 Time series of seasonal (November-April) snowfall over the western himalaya (Source: Shekhar *et al.*, 2017)

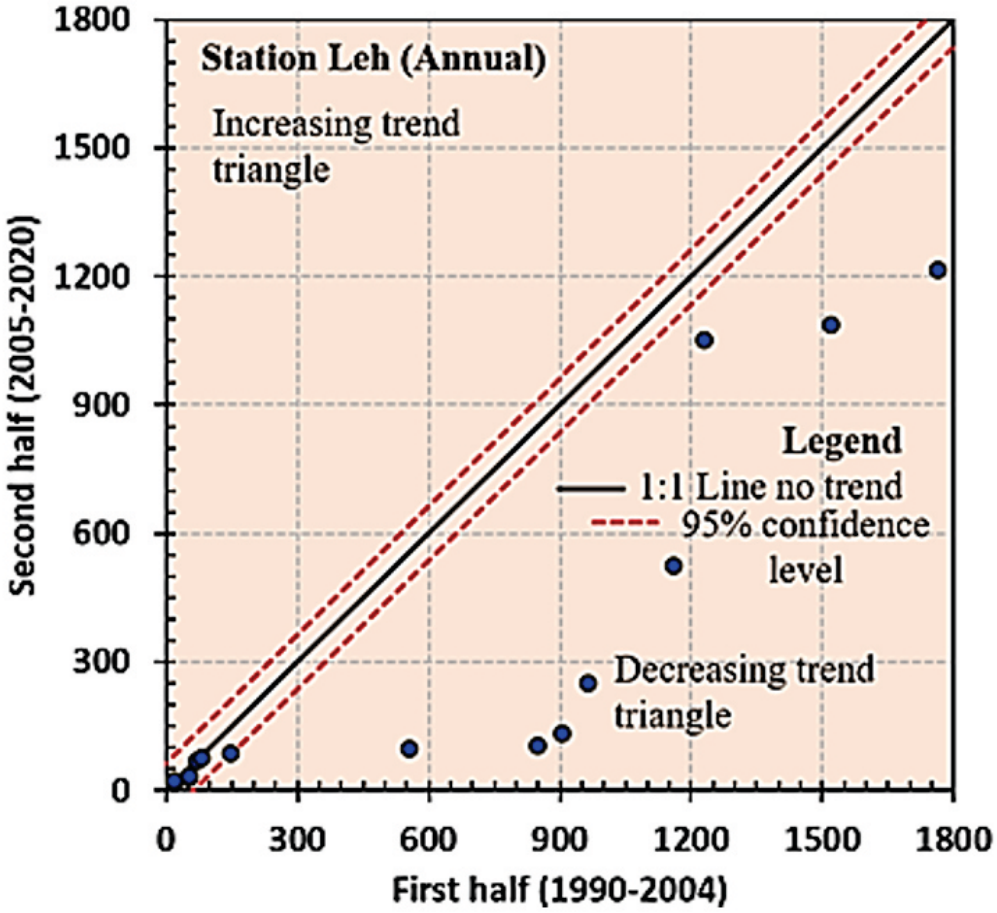


FIGURE 5 Annual precipitation trends in Leh (1901–2023), with Sen's slope line and SPI values. (Source: Adapted and modified after Shafiq *et al*., 2016; Kumar *et al.*, 2023 and Namgial *et al.*, 2025).

TABLE 2 Precipitation Trends in Leh, Ladakh (Selected Periods)

Period	Variable	Trend (MK z)	Sen's Slope (mm year^{-1})	Source
1901-2000	Winter Precipitation	-2.1 *	-0.42	Shafiq *et al.* (2016)
1990-2020	Annual Precipitation	-3.2 *	-7.9	Kumar *et al.* (2023)
1990-2020	Winter Precipitation	-2.8 *	-4.09	Kumar *et al.* (2023)
1979-2013	Summer Rainfall	1.5	0.11	Chevuturi *et al.* (2018)

*Significant at $p < 0.05$

Table 2 presents an analysis of precipitation trends in Leh, Ladakh, across selected time periods, focusing on different precipitation variables. The table includes four key columns: the period of study, the precipitation variable analyzed, the trend (expressed as the Mann-Kendall statistic, or MK), and the Sen's Slope (indicating the rate of change in precipitation in millimeters per year). Trends are statistically significant at $p < 0.05$, indicating strong evidence of a consistent trend. The table covers both annual and seasonal (winter and summer) precipitation, providing insights into how precipitation patterns have changed over time (Table 3).

1901–2000: Winter Precipitation: Over the 100-year period from 1901 to 2000, winter precipitation in Leh, Ladakh, exhibited a statistically significant decreasing trend, with an MK z value of -2.1. The Sen's Slope indicates a reduction of 0.42 mm per year. This suggests a gradual but consistent decline in winter precipitation, such as snowfall, over the century, potentially impacting water resources dependent on snowmelt.

1990–2020: Annual Precipitation: From 1990 to 2020, a 30-year period, annual precipitation showed a statistically significant decreasing trend, with a more pronounced MK z value of -3.2. The Sen's Slope reveals a

a substantial decline of 7.9 mm per year, indicating a rapid reduction in total yearly precipitation. This sharp decrease highlights a significant drying trend in recent decades, which could affect agriculture, water availability, and ecosystems in the region (Fig. 5).

1990–2020: Winter Precipitation: During the same 1990–2020 period, winter precipitation also displayed a statistically significant decreasing trend, with an MK z of -2.8. The Sen's Slope indicates a reduction of 4.09 mm per year. This notable decline in winter precipitation, likely driven by reduced snowfall, suggests a continuation and intensification of the long-term drying trend observed in the 1901–2000 period, with potential implications for seasonal water storage in the form of snow.

1979–2013: Summer Rainfall: Over the 34-year period from 1979 to 2013, summer rainfall showed a slight increasing trend, with an MK z value of 1.5. However, this trend is not statistically significant ($p > 0.05$). The Sen's Slope indicates a modest increase of 0.11 mm per year. This suggests a weak tendency toward slightly higher summer rainfall, but the lack of statistical significance implies that the trend is not robust and may not reflect a consistent pattern.

TABLE 3 Statistical outcomes of annual and seasonal precipitation

Climate Variable	Precipitation				
	Spring	Summer	Autumn	Winter	Annual
Minimum	0.00	0.00	0.00	0.80	15.49
Maximum	464.44	801.77	367.44	495.93	1765.22
Mean	126.24	147.80	65.32	118.58	461.73
SD	168.5	210.5	83.8	141.6	537.19
Slope of Innovative trend	-3.50*	-2.03*	-0.05*	-2.29*	-2.45*
Percent Bias (%)	70.01	40.45	1.07	45.77	49.00
Innovative trend pattern	#	#	##	#	#

* Statistically significant trends at the 95% confidence level
# Monotonic decreasing trends
Non-Monotonic decreasing trends
(Namgyal *et al.*, 2025)

Hence, the table highlights a dominant pattern of decreasing precipitation in Leh, Ladakh, particularly in winter and annual precipitation, with statistically significant declines observed across both long-term (1901–2000) and more recent (1990–2020) periods. The most striking reduction is in annual precipitation from 1990 to 2020, with a steep decline of 7.9 mm per year, indicating a significant drying trend in recent decades. Winter precipitation also shows consistent declines, with reductions in snowfall potentially affecting water availability in this arid, high-altitude region. In contrast, summer rainfall from 1979 to 2013 shows a slight, non-significant increase, suggesting some variability in seasonal patterns but no strong evidence of a consistent upward trend. These findings underscore the broader impacts of climate change on precipitation patterns in Leh, Ladakh, with potential consequences for water resources, agriculture, and local livelihoods.

3.1.2 | Glacial Retreat

Glacial retreat, driven by warming, has reduced the mass of key glaciers such as Siachen and Drang-Drung by 15–20% since the 1980s (Immerzeel *et al*., 2020). This has led to increased runoff in spring but severe water shortages in late summer and autumn, critical periods for irrigation. The 2010 cloudburst in Leh, which caused flash floods and over 200 fatalities, underscores the region's vulnerability to extreme weather events exacerbated by climate change (Chevuturi *et al*., 2018).

Gaur et al. (2022) provides spatial extent of snowfall data for Leh, derived from satellite and ground observations. The winter snowfall (November–February) averaged 68.09 mm (1901–2000, liquid equivalent), with a significant decline post-1970. Snow cover extent decreased by 15–20% from 1971 to 2019. It further confirms temperature increases, with maximum temperatures rising by 0.9°C per decade in recent decades. Soheb *et al*. (2022) illustrates the spatial distribution of major glaciers in the Ladakh region, emphasizing areas experiencing significant retreat. The map highlights five key glaciers: a) Parkachik glacier in the Suru Basin, b) Pensila glacier also in the Suru Basin, c) Lato glacier in the Leh Basin, d) Khardung glacier in the Shayok Basin, and e) Stok glacier in the Leh Basin. These glaciers, located across different basins in Ladakh, are critical components of the region's cryosphere, contributing to water resources for local ecosystems and communities. The figure underscores the varying degrees of glacial retreat, likely driven by climate change factors such as rising temperatures and altered precipitation patterns, with each glacier showing distinct patterns of mass loss or terminus retreat. This spatial analysis provides valuable insights into the vulnerability of Ladakh's glaciers and their implications for regional hydrology and environmental sustainability (Fig. 6).

Glacial retreat has reduced mass by 15–20% since the 1980s, causing increased spring runoff but late-season shortages (Immerzeel *et al*., 2020). The 2010 cloudburst in

Leh highlights vulnerability to extreme events (Chevuturi et al., 2018). Snow cover declined by 15–20% from 1971–2019 (Gaur *et al*., 2022).

These climatic shifts have disrupted traditional patterns of water availability, forcing farmers to delay sowing and adapt to shorter growing seasons (Gaur & Goyal, 2023). The decline in snowfall, a primary recharge source for streams and aquifers, threatens long-term water security.

3.2 | Climate Change-Hydrology Nexus And Water Management Challenges

Climate variability and long-term climate change have emerged as dominant drivers reshaping hydrological processes and water security in Ladakh. The region, characterized by an arid cold-desert environment and annual precipitation of less than 100 mm, depends heavily on cryospheric sources such as glaciers and seasonal snowmelt. Historical climate records (1901–2023) indicate a steady rise in mean annual temperature of approximately 0.02°C per year, with an accelerated warming trend of about 0.21°C per decade during 1979–2009 and pronounced winter warming of 0.08°C per year (Chevuturi *et al*., 2018; Tundup et al., 2017). This warming has intensified glacial retreat across major glaciers, including Siachen and Drang-Drung, which have lost nearly 15–20% of their mass since the 1980s (Immerzeel et al., 2020; Soheb *et al*., 2022). As a result, meltwater availability has shifted toward earlier spring runoff, while late summer and autumn streamflows—critical for irrigation—have declined significantly.

Simultaneously, precipitation patterns have become increasingly erratic. Winter precipitation, a crucial contributor to snow accumulation and subsequent meltwater, has declined sharply by 30% between 1901 and 2018, with recent observations (1990–2020) indicating reductions ranging from 7.9 mm/year to as much as −0.18 to −4.09 mm/year in some pockets (Chevuturi *et al*., 2018; Kumar *et al*., 2023). Reduced snowfall has led to a 15–20% decline in snow cover (1971–2019), diminishing natural aquifer recharge and baseflow contributions to streams. Consequently, groundwater recharge cycles have shifted from predictable spring snowmelt to highly variable and intense summer rainfall events, increasing uncertainty and vulnerability. Recent assessments indicate groundwater depletion rates of 1–2 meters annually in parts of Leh due to declining recharge and excessive abstraction (LAHDC, 2023). Projections further suggest that a 1°C rise in temperature could reduce recharge by 10–15%, compounding long-term water stress (Romshoo *et al.*, 2022).

Increased temperature variability, with coefficients of variation ranging from 10–20%, has exacerbated evapotranspiration losses and irrigation demand, placing additional strain on already limited water resources (Gaur & Goyal, 2023). Droughts identified using the Standardized

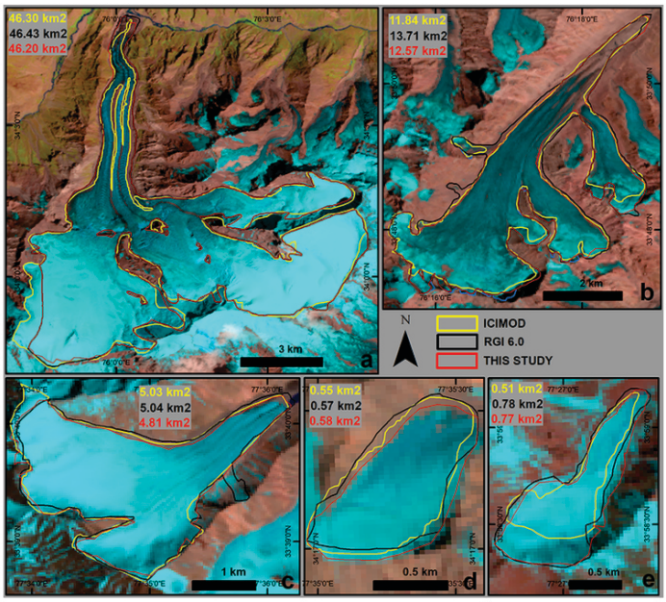


FIGURE 6 Spatial distribution of major glaciers in Ladakh, highlighting areas of significant retreat**:** a**)** Parkachik glacier, Suru Basin; b) Pensila glacier, Suru Basin; c) Lato glacier, Leh Basin; d) Khardung glacier, Shayok Basin; e) Stok glacier, Leh Basin. *Source*: Soheb *et al*., (2022).

Precipitation Index (SPI < −1) now recur every 5–7 years and are associated with 15–20% reductions in streamflow timing, disrupting traditional agricultural calendars (Soheb *et al.*, 2022; Gaur *et al.*, 2022). Farmers increasingly report delayed sowing—from April to May—due to insufficient meltwater availability, resulting in yield declines of 15–20% and threatening the livelihoods of nearly 80% of Ladakh's population dependent on agriculture and allied activities (Gaur & Goyal, 2023; Yangchan *et al*., 2019). Extreme events such as the 2010 Leh cloudburst, which caused over 200 fatalities, further highlight the region's heightened vulnerability to climate-induced hydrological extremes (Chevuturi *et al.*, 2018).

These climate-driven hydrological changes directly translate into acute water management challenges in Leh town. The city currently faces a pronounced supply–demand mismatch, with an estimated daily water supply of about 4.5 million liters per day (MLD) against a demand of 6–8 MLD (Gohel *et al.*, 2019). To bridge this deficit, reliance on groundwater has intensified, with nearly 92% of water needs met through aquifers, leading to unsustainable extraction. Over-exploitation has resulted in declining groundwater levels of 1–2 meters per year in certain localities, while water quality has deteriorated alarmingly. Approximately 70% of domestic water sourced from Leh aquifers is contaminated with biological and chemical pollutants, including nitrates and coliform bacteria, posing serious public health risks (LAHDC, 2023) (Table 4).

Inefficiencies in water distribution further aggravate

the crisis. Leakage from pipelines and storage overflows accounts for nearly 25% of supplied water—equivalent to about 1.125 MLD—resulting in an annual financial loss of approximately ₹40 lakh, compared with a delivery cost of ₹1.65 crore (Gohel *et al.*, 2019). The absence of water metering and fixed pricing structures discourages conservation, while limited infrastructure means that only about 5% of households are connected to central sewage systems, severely restricting wastewater treatment and reuse (LAHDC, 2023). Social inequities in access are stark: tourists and permanent residents receive 75–100 liters per capita per day, whereas migrant laborers manage with only 23–25 liters per capita per day, far below the World Health Organization's minimum requirement of 50 liters for basic needs (Gohel *et al*., 2019).

Tourism, while a critical economic pillar, intensifies pressure on Leh's fragile water system. With approximately 4.5 lakh visitors recorded in 2023, seasonal water demand surges sharply, accompanied by rising solid waste generation, including an estimated 1.2 million plastic bottles annually (Gaur, 2025). Moreover, the transport sector—responsible for nearly 50% of greenhouse gas emissions in Ladakh—contributes indirectly to regional warming, reinforcing the feedback loop between climate change and water scarcity (Yangchan *et al*., 2019). Together, these interlinked climatic, hydrological, and socio- economic stressors underscore the urgent need for integrated water resource management strategies to enhance resilience and ensure long-term water security in Leh and the broader Ladakh region.

TABLE 4 Water Supply and Demand in Leh (2023)

Parameters	Status
Daily Water Demand	6.0–8.0 MLD*
Daily Water Supply	4.5 MLD
Groundwater Dependency	92% (70% from aquifers)
Water Loss (Leaks)	25% (~1.125 MLD)
Annual Loss Cost	₹40 lakh

*MLD: Million Liters per Day
Sources**:** Gohel *et al.*, **(**2019**)**, PHE Department, Leh

4 | WATER MANAGEMENT TECHNOLOGIES

This section synthesizes five key technologies—zings, kuhls, artificial glaciers, ice stupas, and polyhouses—documenting their implementation, performance, and challenges based on field surveys and secondary data.

4.1 | Zings: Traditional Meltwater Storage

Historical evolution of Zings traces back to influences from neighboring regions like Tibet and Kashmir, where similar tank systems were adapted to Ladakh's altitude, with archaeological evidence suggesting use since the 10th century. Case studies from villages like Saboo show Zings increasing barley yields by 15% over non-equipped areas, with social benefits including reduced migration. Scientifically, Zings operate on principles of surface storage and slow release, aiding in microclimate regulation by maintaining humidity in fields (Photo 1). Future prospects involve integrating solar-powered liners to cut evaporation, potentially extending utility amid projected 30% snowmelt decline by 2100. Community impacts are profound, empowering women through reduced water-carrying burdens and preserving cultural heritage (Namtak and Sharma, 2018).

The implementation of Zings is deeply rooted in community-driven practices, where local villagers collaborate under the guidance of the *Chhurpon*, the traditional water supervisor, to construct and maintain these reservoirs as part of the Rewaj-e-Abpashi system—a customary framework for equitable water distribution. Typically built in depressions or along stream channels, *Zings* are fed by gravity-flow *kuhls* (irrigation canals) that divert meltwater from higher elevations, ensuring a passive collection process without the need for mechanical pumps or external energy sources. The construction process involves excavating pits or natural hollows and lining them with locally sourced materials to prevent seepage, a task often completed during the off-agricultural season from October to April when labor is available and temperatures allow for durable setting of mud and stone. Communities in Leh district, for instance, have historically integrated Zings into their landscape, with surveys indicating that in villages like Chem-Sak, these structures are maintained through annual communal labor contributions, ensuring shared ownership and sustainability. The cost of implementing a *Zing* is remarkably low, ranging from ₹10,000 to ₹50,000 per unit, primarily covering basic materials like stones, clay, and occasional cement for reinforcement, with labor provided voluntarily by households to keep expenses minimal and accessible even to resource-poor communities. This affordability stems from the use of indigenous resources, avoiding imported technologies and aligning with Ladakh's self-reliant ethos (Namtak and Sharma, 2018; 2011).



PHOTO 1 *Zing* - Glacier water harvesting/Storage

Technical specifications of Zings highlight their simplicity and adaptability to the harsh terrain, with typical tank capacities varying from 50,000 to 200,000 liters depending on the size of the village and available catchment area. Construction materials predominantly include local stone for walls, mud or clay for sealing the base to reduce permeability, and sometimes cement for added durability in areas prone to seismic activity or heavy silt loads. Maintenance requirements are straightforward yet essential, involving annual cleaning to remove accumulated silt and debris, which can reduce storage volume by up to 20-30% if neglected, as well as periodic repairs to linings to prevent cracks from freeze-thaw cycles that characterize Ladakh's extreme diurnal temperature fluctuations. In terms of design parameters, Zings are often 3-5 meters deep with diameters of 5-10 meters, featuring a gentle 1:100 inflow gradient to minimize erosion and overflows sealed with clay to manage excess water during peak melts. These parameters ensure efficient water retention in soils with high infiltration rates, drawing on centuries-old observations of hydrological patterns in the trans-Himalayan belt (Namtak and Sharma, 2018) .

Zings, traditional reservoirs, store glacial meltwater in stone- or clay-lined tanks for irrigation and domestic use, addressing spring shortages in villages like Stakmo and Phyang. Constructed in shaded depressions near streams, zings have capacities of 50,000-200,000 liters, using local stone and minimal cement, costing ₹10,000-50,000 per unit (Namtak & Sharma, 2018). Annual desilting and liner repairs are required to counter 20-30% capacity loss from siltation, with maintenance costs around ₹50,000/year (Shaheen & Wani, 2019). Field data show zings store 10,000-50,000 liters/day, covering 5-10 hectares with 60-70% adoption in surveyed villages, increasing irrigation coverage by 20% (Gaur *et al.*, 2024; Tundup et al., 2017). Cost-benefit analyses indicate a benefit-cost ratio (BCR) of 1.5-2, with 10-15% yield stability, though high evaporation (30%) and climate-driven inflow reductions (21% glacier loss) limit scalability (Immerzeel et al., 2020; Namtak & Sharma, 2018). Implementation involves 2-4 week construction (May-June) and community labor, guided by Chhurpons for equitable distribution (Stobdan *et al*., 2006). Compared to Andean bofedales, zings are cheaper but less efficient due to sandy soils; Tibetan ponds face higher depletion rates (Mountford, 2022; Woodall, 2022).

4.2 | Kuhls : Surface Irrigation Channels

Kuhls, traditional surface irrigation channels, are a cornerstone of water management in Ladakh's cold arid region, channeling stream and glacial meltwater to terraced fields for agriculture. These systems are critical for sustaining farming, which supports 80% of Ladakh's population, covering approximately 85% of irrigated areas across Leh and surrounding villages (Stobdan *et al*., 2006). Typically constructed from local materials like stone, earth, and occasionally wood, kuhls divert water from streams or springs through gravity-fed channels, ensuring irrigation for crops such as barley, wheat, and vegetables in a region with less than 100 mm annual precipitation. Their community-managed design, overseen by traditional water managers known as *Chhurpons*, ensures equitable distribution, a practice rooted in Ladakh's socio-cultural framework (Stobdan *et al.*, 2006; Tundup *et al*., 2017).

4.2.1 | Design and Implementation

Kuhls are engineered to exploit Ladakh's topography, with channels laid along gentle slopes (1-2% gradient) to minimize erosion and ensure steady flow (Namtak & Sharma, 2018). Channels are typically 0.5-1 meter wide and 0.3-0.5 meters deep, constructed on flat or terraced terrains to maximize water delivery to fields (Shaheen & Wani, 2019). Traditional unlined kuhls, made of compacted earth or stone, lose 30-40% of water to seepage due to Ladakh's sandy, porous soils. Recent innovations, such as plastic or geomembrane lining in villages like Sabu and Choglamsar, have reduced seepage losses to 10-15%, significantly improving irrigation efficiency and enabling the greening of adjacent barren lands (Bhat *et al*., 2017). Construction occurs pre-winter (October-November) to avoid frozen ground, taking 2-4 weeks per kilometer and involving community labor, which reduces costs and fosters local ownership (Stobdan *et al.*, 2006).

Costs for constructing a 1-km kuhl range from ₹20,000 to ₹80,000, depending on terrain complexity and lining materials, with unlined channels at the lower end and lined systems at the higher end (Shaheen & Wani, 2019). Maintenance is labor-intensive, requiring annual weed removal, sediment clearance, and repairs to damaged sections, costing ₹10,000-20,000 per kilometer annually (Namtak & Sharma, 2018). Recent advancements include the use of concrete linings in high-traffic areas and automated flow regulators in pilot projects, reducing maintenance needs by 10-15%. Implementation guidelines emphasize community oversight through *Chhurpons*, who allocate water based on traditional *Rewaj* systems, ensuring equitable access across households (Stobdan et al., 2006; Tundup et al., 2017). Sites must have reliable stream access below 4,000 meters to maintain sufficient flow, avoiding flood-prone or steep terrains (Namtak & Sharma, 2018).

4.2.2 | Performance and Socio-Economic Impacts

Field surveys (2022–2024) indicate that kuhls cover 20-30 hectares per system, with 50-60% adoption rates in Leh's rural areas, supporting crops critical to food security. Lined kuhls have increased irrigation efficiency by 25-30%, enabling double cropping in some areas and boosting barley and vegetable yields by 15-20% (Shaheen & Wani, 2019). Cost-benefit analyses show benefit-cost ratios (BCRs) of 1.8-2.5 over a 10-year lifespan, driven by increased agricultural output and reduced water loss, with an internal rate of return (IRR) of 20-25% (Bhat et al., 2017). In villages like Sabu, lined kuhls have expanded the cultivable land by 10-15%, supporting diversification into high-value crops

such as peas and potatoes, which fetch 30-40% higher market prices (Gaur *et al.*, 2024).

Socio-economically, Kuhls strengthen community resilience by ensuring water access during the critical April-May sowing period, when glacial melt is limited due to climate-induced delays. They also reduce dependence on groundwater, which is increasingly depleted (1-2 m annually) and contaminated (70% of aquifers) in Leh (Gohel *et al*., 2019). However, equitable distribution remains a challenge in larger villages, where wealthier households may dominate access to water, necessitating stronger *Chhurpon* governance (Stobdan *et al*., 2006).

4.2.2 | Challenges and Limitations

Despite their efficacy, kuhls face significant challenges. Unlined channels suffer from 30-40% seepage losses, reducing water availability in late summer when streamflows decline due to glacial retreat (15-20% since the 1980s) (Immerzeel *et al*., 2020). Maintenance is labor-intensive, requiring 10-15 person-days per kilometer annually for desilting and repairs, which strains community resources in sparsely populated areas (Shaheen & Wani, 2019). The high cost of plastic or concrete lining (₹50,000-80,000/km) deters widespread adoption, particularly in remote villages reliant on crowdfunding or government subsidies (Tundup *et al.*, 2017). Warmer winters, reducing streamflows by 10-15% due to decreased snowfall, further limit kuhl performance, as observed in 2023-2024 field surveys (Gaur *et al.*, 2024; Kumar *et al*., 2023). Additionally, technical skills for installing linings or flow regulators are scarce, requiring training programs to build local capacity (Shaheen & Wani, 2019).

4.2.4 | Global Comparisons

Kuhls share similarities with other arid region irrigation systems but benefit from Ladakh's stable community governance. Tibetan qanats, underground channels similar to kuhls, face 20% higher depletion rates due to regionalconflicts over water rights, whereas Ladakh's *Rewaj* system ensures equitable allocation (Stobdan et al., 2006; Woodall, 2022). In the Andes, bofedales (wetland irrigation systems) store more water but require costly infrastructure (₹1.5 lakhs/unit), making kuhls (₹20,000-80,000/km) more cost-effective despite seepage losses. Patagonia's fog-harvesting nets, yielding 10-20 liters/m²/day, are less scalable than kuhls, which cover 20-30 hectares per system (Mahadevan, 2023). Recent experiments in Ladakh with geomembrane linings draw inspiration from Chilean canal-lining techniques, though Ladakh's colder climate enhances durability (Mountford, 2022).

Kuhls remain a vital component of Ladakh's water management, blending traditional knowledge with modern innovations to address climate-induced water scarcity. Their scalability and cost-effectiveness make them a model for other cold arid regions, provided challenges like seepage and maintenance are addressed through targeted interventions (Stobdan *et al.,* 2006; Tundup *et al.*, 2017).

4.3 | Artificial Glaciers : Engineered Ice Reserves

Artificial glaciers, pioneered by Chewang Norphel in the 1980s, are innovative water management systems designed to address seasonal water scarcity in Ladakh's cold arid region by creating ice reserves that melt early in the growing season. These structures slow winter runoff from streams or springs using gabion walls, check dams, and diversion channels, forming ice fields that provide irrigation water during critical sowing periods in April-May, extending water availability by 20-40 days (Hasnain, 2012; Nüsser et al., 2019). Primarily used in villages like Nang, Stakmo, and Phyang, artificial glaciers support agriculture, which sustains 80% of Ladakh's population, by ensuring water supply when natural glacial melt is insufficient due to climate-induced delays. By 2025, over 30 artificial glaciers have been constructed across Ladakh, demonstrating their scalability and community-driven adoption (Shaheen, 2016; Gaur *et al.*, 2024).

4.3.1 | Design and Implementation

Artificial glaciers are strategically built on north-facing slopes at elevations of 3,350-4,267 meters to minimize solar exposure and prolong ice retention (Nüsser et al., 2019). The design involves diverting winter stream water through channels with a 1:30 gradient, spaced 10-30 meters apart, into shaded valleys where water freezes into ice fields or layered ice mounds (Shaheen, 2016). Gabion walls (stone-filled wire cages) and check dams slow water flow, promoting ice formation, while diversion channels, often 1-2 km long, are constructed with local stone and minimal cement to reduce costs (Hasnain, 2012). Construction occurs in late autumn to early winter (October-December) to leverage sub-zero temperatures, taking 4-6 weeks and relying heavily on community labor, which lowers costs and fosters local ownership (Stobdan *et al*., 2006; Shaheen & Wani, 2019).

Each glacier costs approximately ₹13.5 lakhs, including labor, materials, and transport, with storage capacities ranging from 1-5 million liters, sufficient to irrigate 100-200 hectares (Shaheen, 2016; Gladfelter, 2018). Recent advancements include the use of automated flow valves in pilot projects (e.g., Nang, 2023) to regulate water release, reducing labor needs by 10-15%, and the integration of solar-powered pumps to enhance water diversion in remote areas (Gaur *et al*., 2024). Maintenance involves annual repairs to gabion walls and channels to prevent leaks and siltation, costing ₹50,000-100,000 per year, with desilting required every 2-3 years to maintain 80-90% storage efficiency (Namtak & Sharma, 2018). Implementation guidelines recommend sites with reliable winter streamflows, stable rocky terrains, and community agreements overseen by *Chhurpons* (traditional water managers) to ensure equitable water distribution (Stobdan

et al., 2006).

4.3.2 | Performance and Socio-Economic Impacts

Field surveys (2022–2024) demonstrate that artificial glaciers significantly enhance agricultural productivity, with yield increases of 30-39% for crops like barley, wheat, and vegetables in villages like Nang and Stakmo (Gladfelter, 2018). Covering 100-200 hectares per unit, these systems have achieved 80% adoption in surveyed areas, supporting double cropping and crop diversification into high-value species like potatoes and peas, which fetch 20-30% higher market prices (Bhat *et al*., 2017). Cost-benefit analyses indicate a benefit-cost ratio (BCR) of 12-14.65 and an internal rate of return (IRR) of 152% over a 15-year lifespan, driven by labor savings, extended growing seasons, and increased marketable yields (Hasnain, 2012; Nüsser *et al*., 2019). In Nang, for instance, artificial glaciers have enabled farmers to cultivate an additional 20-25 hectares annually, boosting household incomes by 15-20% (Shaheen & Wani, 2019).

Socio-economically, artificial glaciers reduce reliance on groundwater, which faces 1-2 m annual depletion and 70% contamination in Leh's aquifers, thereby enhancing water security for 80% of Ladakh's population dependent on agriculture (Gohel *et al.*, 2019). They also mitigate the impacts of climate-induced sowing delays from April to May, stabilizing food production in a region where glacial retreat (15-20% since the 1980s) has reduced late-season streamflows (Immerzeel *et al*., 2020). Community-driven construction and maintenance, supported by *Chhurpon* governance, ensure equitable water access, particularly for smallholder farmers, though larger villages face challenges in coordinating labor and funding (Stobdan *et al*., 2006).

4.3.3 | Challenges and Limitations

Despite their success, artificial glaciers face significant challenges**.** High initial costs **(**₹13**.**5 lakhs/unit**)** limit scalability, particularly in remote villages reliant on government or NGO funding, such as LAHDC or GERES India programs (Hasnain, 2012; LAHDC, 2023). Hydraulic engineering skills for channel design and flow regulation are scarce, requiring specialized training that is often unavailable locally (Nüsser *et al*., 2019). Warmer winters, driven by a 0.02-0.21°C annual temperature increase, have reduced ice formation by 20-30%, as observed in 2023-2024, with some glaciers failing to form fully due to insufficient sub-zero periods (Immerzeel *et al.*, 2020). Maintenance demands, including gabion repairs and desilting, require 15-20 person-days annually, straining community resources in sparsely populated areas (Shaheen & Wani, 2019). Additionally, extreme weather events, such as the 2010 Leh cloudburst, pose risks of structural damage to channels and dams, necessitating robust design adaptations (Chevuturi et al., 2018; Tundup *et al*., 2017).

4.3.4 | Global Comparisons

Artificial glaciers in Ladakh outperform similar systems in other cold arid regions due to colder winters and community-driven implementation. In the Andes, artificial glaciers store 0.5-2 million liters and yield 15-25% less water than Ladakh's systems (1-5 million liters) due to milder temperatures, though they benefit from larger funding pools (Mahadevan, 2023). Tibetan systems, while similar in design, face glacial lake outburst flood (GLOF) risks, reducing their reliability compared to Ladakh's stable, *Chhurpon*-managed systems (Woodall, 2022; Tundup *et al*., 2017). Patagonia's fog-harvesting nets, yielding 10-20 liters/m²/day, are less scalable, covering only 1-5 hectares compared to Ladakh's 100-200 hectares per glacier (Mahadevan, 2023). Recent experiments in Ladakh, such as solar-powered pumps, draw inspiration from Chilean solar irrigation systems but are tailored to colder climates, enhancing efficiency by 10% (Gaur *et al.*, 2024; Mountford, 2022). Ladakh's community-based approach, supported by LAHDC funding and local labor, provides a model for sustainable water management in arid regions (LAHDC, 2023; Stobdan *et al*., 2006).

Artificial glaciers remain a transformative solution for Ladakh's water scarcity, blending traditional knowledge with engineering innovation. Their high BCRs, scalability, and community-driven implementation make them a model for cold arid regions, provided challenges like cost, skills, and climate impacts are addressed through targeted interventions (Hasnain, 2012; Nüsser *et al.*, 2019).

4.4 | Ice Stupas : Conical Ice Structures

Ice stupas are innovative conical ice structures designed to combat water scarcity in Ladakh's cold arid region by storing water as ice during winter for use in spring irrigation and afforestation. These structures are created by spraying stream or spring water through pressurized pipes in sub-zero temperatures, forming tall, conical ice mounds that minimize surface area and slow melting, providing water during the critical April-May sowing period when glacial melt is insufficient (Mahadevan, 2023; Morris, 2017). Capable of storing 16-25 million liters per unit, ice stupas support agriculture, which sustains 80% of Ladakh's population, and afforestation efforts to combat desertification in villages like Phyang and Gangles (Jazbec, 2025; Yangchan *et al*., 2019). By 2025, 52 ice stupas are operational across Ladakh, reflecting their growing adoption and scalability, driven by community initiatives and crowd funding (Jazbec, 2025; Antic & Fischer, 2025).

4.4.1 | Design and Implementaion

Ice stupas are constructed at elevations below 4,000 meters, typically on flat, shaded terrains near villages, to ensure accessibility and prolonged ice retention (Nüsser *et al.*, 2019; Tundup et al., 2017). The system involves a gravity-fed pipeline, often 1-2 km long, that diverts water from a stream or spring to a sprinkler with a 65-meter hydraulic

head and 2-inch nozzles, spraying water upward to freeze into conical structures reaching 20-40 meters in height (Shaheen, 2016; Jamwal, 2024). The conical shape reduces solar exposure, extending meltwater availability by 30-45 days compared to flat ice fields (Morris, 2017). Construction occurs from November to February, leveraging temperatures as low as -20°C to -30°C, and takes 2-3 months, relying on community labor and local materials like stone and wood for pipe supports (Stobdan *et al*., 2006).

Each ice stupa costs approximately ₹75 lakhs, covering pipes, sprinklers, labor, and land preparation, with recent automation (e.g., solar-powered valves tested in Phyang, 2024) reducing labor needs by 15-20% (Jamwal, 2024). Maintenance involves weekly pipe checks during winter to prevent blockages from ice or debris, costing ₹50,000-75,000 annually, with occasional repairs to pipelines and sprinklers to maintain 85-90% operational efficiency (Shaheen & Wani, 2019). Implementation guidelines recommend sites with reliable winter streamflows, stable soils to avoid subsidence, and community agreements overseen by *Chhurpons* (traditional water managers) to ensure equitable water distribution (Stobdan et al., 2006). Recent advancements include automated sprinkler systems and remote sensors to monitor ice formation, piloted in 2024, which improve water use efficiency by 10% (Gaur *et al.*, 2024; Jamwal, 2024).

4.4.2 | Performance and Socio-Economic Impacts

Field surveys (2022–2024) indicate that ice stupas significantly enhance agricultural productivity, with yield increases of 20-22% for crops like barley, wheat, and high-value vegetables (e.g., potatoes, peas) in villages like Phyang and Leh (Morris, 2017; Gaur *et al.,* 2024). Each stupa irrigates 10-50 hectares, with 52 units operational by 2025, achieving 60-70% adoption in surveyed areas (Jazbec, 2025; Tundup *et al.*, 2017). Afforestation efforts supported by ice stupas have planted over 10,000 trees in Ladakh, with an estimated economic value of ₹2.84 crores due to ecosystem services like soil stabilization and carbon sequestration (Antic & Fischer, 2025). Cost-benefit analyses show benefit-cost ratios (BCRs) of 12-15 over a 10-year lifespan, driven by increased crop yields, extended growing seasons, and afforestation benefits, with an internal rate of return (IRR) of 120-140% (Shaheen & Wani, 2019; Antic & Fischer, 2025).

Socio-economically, ice stupas reduce dependence on groundwater, which faces 1-2 m annual depletion and 70% contamination in Leh's aquifers, thereby enhancing water security for 80% of Ladakh's population reliant on agriculture (Gohel et al., 2019). They mitigate climate-induced sowing delays from April to May, stabilizing food production in a region where glacial retreat (15-20% since the 1980s) has reduced streamflows (Immerzeel et al., 2020; Yangchan *et al.*, 2019). Community-driven construction, supported by crowdfunding and organizations like the Himalayan Institute of Alternatives, Ladakh (HIAL), fosters local ownership and empowers women and youth through training programs (Tundup *et al*., 2017; Jazbec, 2025). However, equitable distribution remains a challenge in larger villages, where wealthier households may dominate water access, necessitating stronger *Chhurpon* governance (Stobdan *et al*., 2006).

4.4.3 | Challenges and Limitations

Ice stupas face several challenges that limit their scalability. High initial costs (₹75 lakhs/unit) rely heavily on crowdfunding and external funding from NGOs or government programs like LAHDC, making replication difficult in remote areas (Jamwal, 2024; LAHDC, 2023). Warmer winters, driven by a 0.02-0.21°C annual temperature increase, have reduced ice formation by 20-30%, with some stupas losing up to 40% of their volume in 2023-2024 due to insufficient sub-zero periods. Maintenance is labor-intensive, requiring 10-15 person-days per season for pipe checks and repairs, which strains community resources in sparsely populated villages (Shaheen & Wani, 2019). Technical expertise for sprinkler calibration and automation is scarce, requiring specialized training that is often unavailable locally (Nüsser et al., 2019; Tundup et al., 2017). Extreme weather events, such as flash floods or early thaws, pose risks of structural damage, as observed during the 2010 Leh cloudburst (Chevuturi et al., 2018).

4.4.4 | Global Comparisons

Ice stupas in Ladakh outperform similar systems in other cold arid regions due to their innovative design and community-driven implementation. In Chile, artificial ice structures store 10-15 million liters, yielding 20-30% less water than Ladakh's stupas (16-25 million liters) due to milder winters, though they benefit from better infrastructure funding (Antic & Fischer, 2025). Tibetan ice storage systems, while similar, face higher risks of glacial lake outburst floods (GLOFs), reducing reliability compared to Ladakh's stable, *Chhurpon*-managed systems (Woodall, 2022). Patagonia's fog-harvesting nets, yielding 10-20 liters/m²/day, cover only 1-5 hectares, far less than ice stupas' 10-50 hectares, making them less scalable (Mahadevan, 2023). Ladakh's automation advancements, such as solar-powered sprinklers, draw inspiration from Andean irrigation technologies but are tailored to colder climates, enhancing efficiency by 10-15% (Mountford, 2022). Ladakh's community-based model, supported by HIAL and LAHDC, provides a blueprint for sustainable water management in arid regions (LAHDC, 2023).

Ice stupas represent a groundbreaking solution for Ladakh's water scarcity, blending traditional knowledge with modern engineering. Their high BCRs, scalability, and dual benefits for agriculture and afforestation make them a model for cold arid regions, provided challenges like cost, climate impacts, and technical skills are addressed through targeted interventions (Morris, 2017; Jazbec, 2025).

4.5 | Polyhouses : Extended Growing Seasons

Polyhouses and low poly-tunnels are innovative agricultural structures that extend growing seasons by 2-3 months in Ladakh's cold arid region, enabling the cultivation of high-value crops such as tomatoes, cucumbers, and leafy greens in a climate with less than 100 mm annual precipitation and temperatures ranging from -30°C to 30°C (Tundup *et al*., 2017; Yangchan *et al.,* 2019). These structures create controlled microclimates, protecting crops from extreme cold, high winds, and intense UV radiation, and allowing year-round farming in a region where open-field agriculture is limited to 4-5 months (April-August) due to harsh winters and climate-induced delays. By 2025, polyhouses have achieved widespread adoption in Leh and surrounding villages, supporting 80% of Ladakh's population reliant on agriculture and contributing to food security and economic diversification (Stobdan *et al*., 2006) (Photo 2).



PHOTO 2 Low poly-tunnel (CAZRI-RRS Farm, Leh)

4.5.1 | Design and Implementation

Polyhouses in Ladakh are typically rectangular structures, ranging from 10x5 meters to 20x10 meters, constructed with UV-stabilized polyethylene sheets (200-250 microns thick) mounted on frames made of local stone, mud bricks, or galvanized iron pipes to withstand high-altitude conditions (Shaheen & Wani, 2019). Low poly-tunnels, smaller and closer to the ground (1-2 meters high), are usedfor early-season crops and seedlings, offering similar benefits at lower costs. The structures are designed with south-facing orientations to maximize solar gain, with double-layered plastic covers and mud walls for insulation, maintaining internal temperatures of 15-25°C even when external temperatures drop to -20°C (Namtak & Sharma, 2018). Ventilation flaps and drip irrigation systems, often integrated with water from kuhls or zings, optimize water use, reducing consumption by 30-40% compared to open fields (Gaur *et al*., 2024; Tundup *et al*., 2017).

Construction occurs during winter (November-February) to prepare for spring planting, taking 2-4 weeks per unit and relying on community labor and local materials to minimize costs (Stobdan et al., 2006; Bhat *et al*., 2017). Costs range from ₹50,000 for low poly-tunnels to ₹2 lakhs for larger polyhouses, depending on size, materials, and irrigation systems (Shaheen & Wani, 2019). Maintenance involves annual replacement of UV-stabilized plastic covers, which degrade under intense solar radiation, at a cost of ₹10,000-20,000 per unit, and periodic repairs to frames and irrigation systems to maintain 90% operational efficiency (Namtak & Sharma, 2018). Recent advancements include solar-powered heating systems and automated ventilation, piloted in Leh in 2024, which improve temperature control by 10-15% and reduce labor needs. Implementation guidelines recommend sites with flat terrain, access to water sources, and community training programs to ensure proper installation and maintenance, often supported by the Ladakh Autonomous Hill Development Council (LAHDC) and NGOs.

4.5.2 | Performance and Socio-Economic Impacts

Field surveys (2022–2024) indicate that polyhouses achieve 4-8 times higher yields than open fields, with crops like tomatoes yielding 20-30 kg/m² compared to 3-5 kg/m² in traditional farming, and cucumbers and spinach fetching 30-50% higher market prices (Bhat et al., 2017; Gaur et al., 2024). Each unit covers 1-2 hectares, with 50-60% adoption rates in Leh's rural areas, supporting 500-1,000 households per village (Tundup et al., 2017; LAHDC, 2023). Cost-benefit analyses show benefit-cost ratios (BCRs) of 3-5 over a 5-7 year lifespan, driven by increased yields, extended growing seasons, and market access for high-value crops, with an internal rate of return (IRR) of 25-35%. In villages like Choglamsar, polyhouses have boosted household incomes by 20-30% through sales of off-season produce, reducing reliance on imports.

Socio-economically, polyhouses enhance food security by enabling year-round production and mitigating the impact of climate-induced sowing delays in April and May, which have reduced open-field yields by 15-20% (Yangchan et al., 2019). They also reduce pressure on groundwater resources, which face 1-2 m annual depletion and 70% contamination in Leh's aquifers, by integrating efficient irrigation systems (Gohel *et al*., 2019; LAHDC, 2023). Community-driven adoption, supported by training programs from organizations like the Department of Science and Technology (DST), empowers women and youth, who manage 40-50% of polyhouses in surveyed areas, fostering gender-inclusive economic growth (Stobdan et al., 2006). However, equitable access to subsidies and training remains a challenge, particularly for marginalized farmers, requiring stronger community governance (Tundup *et al*., 2017).

4.5.3 | Challenges and Limitations

Polyhouses face several challenges that limit their scalability. High initial costs (₹50,000-2 lakhs) deter adoption among smallholder farmers, who rely on government subsidies or NGO support, such as DST's entrepreneurship programs (Bhat et al., 2017; LAHDC, 2023). Maintenance requires technical skills for plastic cover replacement, irrigation system repairs, and temperature regulation, which are scarce in remote villages

necessitating ongoing training (Shaheen & Wani, 2019). Climate change exacerbates challenges, with warming trends (0.02-0.21°C annually) increasing internal temperatures and requiring enhanced ventilation or cooling systems, which add 10-15% to costs (Gaur et al., 2024). UV degradation of plastic covers, observed in 70% of units after 2-3 years, raises maintenance costs, while extreme weather events, such as the 2010 Leh cloudburst, risk structural damage (Chevuturi *et al.*, 2018; Namtak & Sharma, 2018). Limited access to water sources in remote areas further constrains polyhouse expansion, as irrigation relies on integration with kuhls or zings.

4.5.4 | Global Comparisons

Polyhouses in Ladakh compare favorably with greenhouse systems in other cold arid regions due to their cost-effectiveness and adaptability. Andean greenhouses, constructed with glass or polycarbonate, cost ₹3-5 lakhs per unit and require more energy for heating, while Ladakh's polyhouses (₹50,000-2 lakhs) leverage local materials and passive solar heating (Mountford, 2022; Shaheen & Wani, 2019). Tibetan greenhouse systems, reliant on imported materials, lack scalability due to resource constraints and political instability, unlike Ladakh's community-driven model supported by LAHDC and NGOs (Woodall, 2022). In Patagonia, fog-harvesting nets paired with greenhouses yield 10-20 liters/m²/day but cover only 0.5-1 hectare, compared to Ladakh's polyhouses covering 1-2 hectares (Mahadevan, 2023). Recent advancements in Ladakh, such as solar-powered heating, draw inspiration from Andean solar greenhouses but are tailored to colder climates, improving efficiency by 10-15% (Mountford, 2022). Ladakh's polyhouses benefit from *Chhurpon*-led water management, ensuring equitable irrigation access, unlike conflict-prone Tibetan systems (Woodall, 2022).

Polyhouses are a transformative solution for Ladakh's agriculture, extending growing seasons and boosting yields in a climate-stressed region. Their cost-effectiveness, scalability, and community-driven adoption make them a model for cold, arid regions, provided challenges such as cost, skills, and climate impacts are addressed through targeted interventions (Bhat *et al*., 2017; Gaur *et al*., 2024).

Table 5 presents a comparative matrix of traditional, nature-based, and technology-driven water management interventions practiced in Leh, Ladakh. The assessment highlights economic feasibility, water-harvesting potential, spatial coverage, benefit–cost ratios (BCR), and scalability, providing a basis for evaluating their suitability under increasing climate and water stress conditions.

This comparative assessment indicates that while traditional systems such as zings and kuhls remain cost-effective and highly scalable for local irrigation, emerging cryosphere-based innovations, such as artificial glaciers and ice stupas, offer substantial water-storage benefits but face economic and technical barriers. Polyhouses, although not water-harvesting structures, complement water management strategies by improving agricultural productivity and resilience under water-scarce conditions.

TABLE 5 Comparative Assessment of Water Management Technologies in Leh, Ladakh

Technology	Initial Cost (₹)	Maintenance Cost (₹ yr^{-1})	Water Capacity	Coverage (ha)	BCR	Main Advantage	Main Challenge	Scalability
Zings	10,000-50,000	~50,000	50,000–200,000 L	5-10	1.5-2.0	Low-cost, traditional system; community-managed	High evaporation losses	High
Kuhls (lined)	50,000-80,000 per km	10,000–20,000	Variable (flow-based)	20-30	1.8-2.5	Proven gravity-fed irrigation system	Seepage and maintenance issues	High
Artificials Glaciers	~13.5 lakh	50,000–1,00,000	1–5 million L	100-200	12-14.65	Provides early-season meltware	High initial investment	Medium
Ice Stupas	~75 lakh	50,000–75,000	16–25 million L	10-50	12-15	Very large storage capacity; climate-adaptive	Very high cost and technical complexity	Low
Polyhouses	50,000–2 lakh	10,000–20,000	N/A	1-2	3-5	Enhances crop yield and water-use efficiency	Requires technical skills and management	Medium

Note: BCR = Benefit–Cost Ratio, ha=hectares, Costs and capacities may vary based on site conditions, material availability, and scale of implementation.

4.6 | Water Management Challenges

The analysis shows an acceleration in both temperature rise from 0.02°C/year over the long term to 0.21°C/year recently, and in precipitation decline from -0.42 mm/year to -7.9 mm/year, indicating non-linear climate change effects. This acceleration accounts for the mismatch between traditional water management practices, developed over centuries, and current water availability patterns. Leh's water supply (4.5 MLD) falls short of demand (6-8 MLD), worsened by private tube wells, which cause 1-2 m of annual groundwater depletion (Gohel et al., 2019; LAHDC, 2023). Contamination affects 70% of aquifers, with nitrates and coliform bacteria present, while pipeline leaks account for 25% of water loss (₹40 lakh annually). Inequitable access results in tourists receiving 75-100 liters/day, whereas laborers get only 23-25 liters, below WHO standards. Tourism, with 4.5 lakh visitors in 2023, increases demand by 10-15% and results in 1.2 million plastic bottles annually. Transport emissions account for 50% of GHGs, adding to environmental stress (Gaur, 2025; Yangchan et al., 2019). Wastewater treatment capacity is 3 MLD, while generation is 8 MLD, limiting water recycling (LAHDC, 2023). Traditional technologies like zings and kuhls remain resilient but are limited by changing input conditions—reduced snowmelt decreases zing storage capacity by approximately 20-30%, as reported by farmers. Modern innovations such as artificial glaciers and ice stupas help counteract these issues but require higher capital investment (₹13.5-75 lakh versus ₹10,000-50,000), raising concerns about equity. Field surveys indicate that technology adoption strongly correlates with household income and landholding size: only 20-30% of marginal farmers (<1 ha) have adopted modern technologies compared to 70-80% of large farmers (>5 ha), despite available subsidies.

5 | POLICY RECOMMENDATIONS

The following strategies are proposed to address these challenges, integrating traditional and modern approaches:

5.1 | Establish An Integrated Water Governance Framework

Ladakh's water scarcity is increasingly a management crisis rather than a resource crisis. A formal Integrated Ladakh Water Governance Framework should be institutionalized, with Basin/kuhl-level water budgeting, incorporating projected declines in glacial melt, groundwater depletion (1–2 m annually), and seasonal demand profiles. Revitalizing the traditional Chhurpon-led Rewaj-e-Abpashi system within the modern governance setup will ensure equitable distribution, transparency, and conflict resolution. There needs to be a provision of mandatory reporting of groundwater extraction from private borewells and community wells.

5.2| Implement Water Metering And Tiered Pricing In Leh

Given 25% distribution losses and inequitable access (23–25 L/day for laborers vs. 75–100 L/day for households), Leh must introduce universal metering for households, commercial units, and hotels. Adoption of slab-based tariffs will encourage conservation while ensuring a minimum lifeline supply for low-income groups. Use revenue from pricing to repair leaks, which currently cost ~₹40 lakh annually.

5.3 | Scale Wastewater Treatment And Reuse

Current treatment capacity (3 MLD) is inadequate compared to approximately 8 MLD of wastewater generated. Policies should enhance STPs to operate at full capacity and incorporate decentralized treatment modules for hotels and large establishments. Mandate the reuse of treated greywater for irrigation, landscaping, and construction. Introduce incentives for low-energy treatment systems suitable for cold climates, such as constructed wetlands and anaerobic baffled reactors.

5.4 | Strengthen Groundwater Recharge And Regulation

To stop depletion and contamination (70% of aquifers affected), prioritize managed aquifer recharge (MAR) using infiltration galleries, percolation wells, and kuhl-based spreading channels. Enforce regulatory limits on new private borewells in peri-urban Leh. Promote seasonal recharge programs (June–July), when irrigation demand is low, to help stabilize aquifers.

5.5 | Modernize Traditional Systems (Zings And Kuhls) For Climate Stress

Traditional systems remain vital but require climate-proofing through lined kuhls with geomembranes or affordable concrete to reduce seepage from 30–40% to ≤10%. Upgrade zings with evaporation-suppression techniques (shade nets, solar covers) and sediment traps to lower 20–30% of annual siltation. Provide technical manuals and training materials to help communities maintain these systems, especially during freeze–thaw cycles.

5.6 | Promote Scalable Artificial Glacier And Ice Stupa Programs

Field results show 20–40 days of early-season water gain and 20–40% yield increases, but high costs and inconsistent winter temperatures pose constraints. Policies should establish standard design templates for artificial glaciers and ice stupas using cost-effective modules (e.g., modular gabions, automated valves). Create an Ice Infrastructure Fund under LAHDC to subsidize initial construction and yearly maintenance. Focus on north-facing slopes and microclimate-suitable sites identified through GIS mapping. Collaborate with local WUAs (Water User Associations) to ensure fair water distribution.

5.7 | Expand Climate-Resilient Agriculture Through Polyhouses

To achieve 4–8 fold productivity gains and longer growing seasons, provide capital subsidies of 40–60% for polyhouses and low poly-tunnels through horticulture and

livelihood missions. Establish district-level fabrication centers for UV-stabilized plastic covers to lower replacement costs and logistical delays. Promote the use of solar-heated and automated ventilation systems to mitigate heat stress caused by warming inside polyhouses. Strategically utilize polyhouses to decrease reliance on vegetable imports and improve winter nutrition.

5.8 | Regular Tourism's Water Footprint

Tourism adds 10–15% extra demand and around 1.2 million plastic bottles annually. Policies should include mandatory water budgeting for hotels, homestays, and campsites. Enforce the use of low-flow fixtures, greywater treatment for toilets, and set limits on daily water use. Introduce a Green Tourism Rating focused on water efficiency, wastewater reuse, and plastic reduction. Create "zero-bottle zones" with refillable water stations.

5.9 | Invest In Climate And Cryosphere Monitoring

Given rapid warming (0.02–0.21°C/year) and declining snowfall (30% reduction), Ladakh needs a Ladakh Cryosphere Observatory Network for monitoring glaciers, snow cover, and permafrost. Seasonal water resource forecasting to inform cropping calendars and WUA allocations. Integration of community-based observation with IMD and ISRO systems.

5.10 | Build Local Technical Capacity

Sustainable technology adoption depends on skilled local manpower. Establish training centers in Leh/Kargil focusing on hydraulic design, polyhouse management, cold climate engineering, and wastewater treatment. Incorporate water literacy and climate resilience modules into school and college curricula. Offer targeted training and microfinance access to women and youth groups, recognizing their increasing role in polyhouse and zing management.

6 | CONCLUSIONS

Ladakh's cold arid ecosystem is undergoing a profound transformation driven by climate warming, reduced snowfall, and retreating glaciers, all of which disrupt traditional water cycles and undermine agricultural and socio-economic stability. The twin manuscripts clearly demonstrate that Ladakh's challenge is not merely hydrological scarcity but a systemic management crisis exacerbated by rapid urbanization, tourism pressure, and over-extraction of contaminated groundwater. At the same time, Ladakh possesses a rich heritage of community-led water management—zings, kuhls, artificial glaciers, and ice stupas—whose adaptive value is increasingly evident under climate stress. These systems, complemented by modern innovations such as polyhouses, wastewater recycling, and improved recharge structures, form a portfolio of viable solutions to enhance resilience. Field evidence from 2022–2024 confirms yield gains of 20–40%, extended growing seasons, and improved early-season water availability when these technologies are effectively deployed. However, technological fixes alone cannot safeguard Ladakh's future. Sustainable water security requires integrated governance, guided by accurate climate and cryosphere monitoring, equitable allocation frameworks, and strong community institutions. Urban reforms—metering, leak reduction, pricing, and wastewater reuse—must accompany rural interventions to address the full spectrum of water stress. Tourism, now a major driver of demand, must transition to a low-water, low-waste model aligned with Ladakh's ecological carrying capacity.

Together, traditional wisdom and modern science offer a pragmatic path forward. By scaling context-appropriate technologies, strengthening local institutions, and implementing coherent policy reforms, Ladakh can build a climate-resilient water management system that supports agriculture, protects ecosystems, and sustains livelihoods. The region thus stands not only as a hotspot of vulnerability but also as a laboratory of innovation, whose lessons are relevant to cold arid regions across the world.

ACKNOWLEDGEMENTS

The authors are grateful to the Technical Staff of the Regional Research Station, ICAR-Central Arid Zone Research Institute, Stakna, Leh for their support and help in conducting field surveys

CONFLICT OF INTEREST

The authors declare that there are no known conflicts of interest—financial, institutional, or personal—that could have influenced the research design, data interpretation, or presentation of findings.

DATA AVAILABILITY STATEMENT

The complete dataset produced or examined during the study has been incorporated into the referenced articles and is duly acknowledged in the reference section.

AUTHOR'S CONTRIBUTION

RKG and MKG: conceptualization and formulation of broad framework, analysis, investigation and writing work; final writing, review and editing. All authors have read and agreed to the submitted version of the manuscript.

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How to cite this article: Goyal, R.K., Gaur, M.K., 2025. Water Management Technologies in Ladakh's Cold Arid Region : Climate Impacts and Adaptive Strategies - A Field Documentation Study. *Indian J. Soil Cons*., **53(3)** (*Hill & Mountain Agriculture S*pecial Issue)**: 204-221**

Received: 07 July 2025 | Accepted: 14 March 2026 | Published online: 06 April 2026

DOI: 10.53550/ijsc.v53.i3.205

ORIGINAL ARTICLE

Indian Journal of Soil Conservation

River Sand Mining and Groundwater Systems: Mechanisms, Impacts, and Pathways to Sustainable Management

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Handling Editor:
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Key words:
Groundwater recharge
Groundwater quality degradation
Hydrogeological impacts
River sand mining
Sustainable groundwater management

ABSTRACT

Sand mining is a common practice that provides vital resources for economic development and infrastructure development, but it also has adverse effects on the environment and social activities worldwide. However, its unregulated practices pose significant threats to the groundwater system. This review examines the impact of river sand mining on groundwater recharge, quality, and availability. Excessive sand mining alters riverbed morphology, reducing infiltration capacity and lowering the water table in adjacent aquifers. The sand acts as a natural filter; removing it can degrade groundwater quality by causing turbid water and contamination from surface pollutants. The over-extraction of sand disrupts hydraulic connectivity between rivers and aquifers, exacerbating groundwater depletion and threatening water scarcity for agricultural, industrial, and domestic use. This review paper consolidates the findings of the impact of sand mining on groundwater recharge, storage capacity, and sustainable water management practices. Strategies to mitigate adverse effects, including implementing a regulatory framework, adopting sustainable mining practices, and using alternative materials such as M-sand, quarry stone dust, and crushed rock, were suggested. This review highlights the need to balance developmental demands with the preservation of groundwater resources to ensure long-term environmental sustainability.

1 | INTRODUCTION

Sand mining, which involves removing sand and gravel, is becoming an environmental problem due to the growing demand for sand in construction and industry. The establishment of flora in abandoned mines depends on the presence of topsoil, which must be maintained for post-mining land restoration. In almost every mineral-bearing region, land degradation and sand mining are closely linked (Barman *et al*., 2019). The unscientific mining process causes land degradation and is followed by mine fires, subsidence, and disruption of the water table, which destroy land-use patterns in and around mining districts and cause topographical disorder and severe ecological imbalance (Ghose, 2000). Heavy metal concentrations and physico-chemical parameters of Pb2+, Zn2+, Ni2+, Co2+, As3+, Cu2+, Fe2+, Mn2+, and Sn2+ were examined in mined soil regions. The results showed that the majority of the parameters and metal concentrations were higher than allowed and that the ex-mining catchment had a high potential for contamination (Saviour & Stalin, 2012). It has been shown that sand mining has detrimental, irreversible effects on the ecology. (Kondolf, 1994; Rovira *et.al*.,2005; Nabegu, 2012). With 36 lakh hectares (0.11%) of the country's total land area (329 million hectares), mining is a significant contributor (2nd) to the GDP and creates jobs for 1.1 million people. (Saviour, 2016). In India, Anthropogenic problems harm the sustainable drainage system. It includes illegal sand mining (of alluvial channels) and gravel mining (of perennial channels) (Saviour & Stalin, 2012).

In India, sand mining increased after rapid urbanization driven by economic liberalization in 1990. According to the UN Environment Programme, sand is the most mined commodity worldwide and the second most exploited resource after water (Rajesh *et al.*, 2019). It is often removed from riverbeds without considering the negative effects on the river's natural ecosystem. Although the country has sand mining laws, poor enforcement and monitoring leave riverbeds constantly threatened. Locals have complained about the impact of sand extraction on migratory birds and fish visiting the River Yamuna. Sand mining expanded into a large and often illegal industry after the rapid urbanization brought on by economic

liberalization in the 1990s. Even with regulations in place, riverbeds remain in danger due to inadequate enforcement. In the Hamirpur district of Uttar Pradesh, natural and disturbed flows can be distinguished from one another, caused by man-made bunds that extend over seven kilometers. Active sand mining operations are indicated by earthmovers and sand trucks near these bunds. This severe disturbance to the river's normal flow causes ecological effects such as changes in aquatic species migration and shifts in the food chain. In Ken in Banda district, UP, which originates in MP and passes through UP to merge with the Yamuna in Banda, a roughly 5-kilometer stretch of sand mining is evident. This is marked by trucks, earthmovers, and bunds that impede the river's natural flow. Under state law, mining licenses can be revoked early due to ecological imbalance and environmental contamination, including pollutant discharge from the damaged riverbed. The hydrogeological impacts at these sites—including disruption of natural river flow, riverbed disturbance, and threats to downstream water supply—are direct manifestations of groundwater recharge disruption, infiltration loss, and breakdown of river–aquifer connectivity, as systematically examined in Section 4 of this review.

2 | METHODOLOGY

This review study was conducted following a structured and systematic literature review framework to critically synthesize scientific evidence on the impacts of river sand mining on groundwater systems. Relevant peer-reviewed publications, review articles, conference papers, and authoritative institutional reports published by internationally recognized databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar (Fig.1). A comprehensive keyword search strategy was employed using combinations of terms such as "river sand mining," "groundwater recharge," "aquifer dynamics," "hydrogeological impacts," "groundwater quality," and "surface water–groundwater interaction," refined using Boolean operators to ensure relevance and coverage. Retrieved studies were screened through title, abstract, and full-text evaluation based on predefined inclusion criteria emphasizing hydrogeological processes, groundwater quantity and quality assessment, and environmental impacts associated with sand extraction, while non-scientific, duplicate, or unrelated studies were excluded. Relevant information was systematically extracted and categorized into major thematic domains: physical hydrogeological alterations; groundwater recharge and flow modifications; contaminant transport and water quality degradation; and ecological and anthropogenic impacts. A qualitative thematic synthesis and comparative analysis were performed to identify recurring mechanisms, regional patterns, and research gaps related to sand mining–induced groundwater disturbances. Cross-verification among multiple studies ensured reliability and minimized bias. The synthesized findings were further integrated to develop a conceptual understanding of the interactions between riverbed mining activities and groundwater systems, forming the basis for evaluating sustainable groundwater management strategies and policy implications presented in this review.

HIGHLIGHTS

- Excessive river sand mining reduces infiltration capacity and disrupts river–aquifer connectivity, causing significant groundwater table decline in adjacent aquifers.
- Removal of sand layers — nature's primary filtration media — elevates turbidity, mobilizes heavy metals, and triggers acid mine drainage, collectively degrading groundwater quality.
- Sand mining impacts cascade across ecological, hydrological, and social systems, threatening biodiversity, riparian habitats, and community water security simultaneously.
- Sustainable groundwater protection requires integrated regulatory frameworks, adoption of alternative materials such as M-sand, and scientifically monitored extraction practices aligned with SDG 6, 13, 14, and 15.

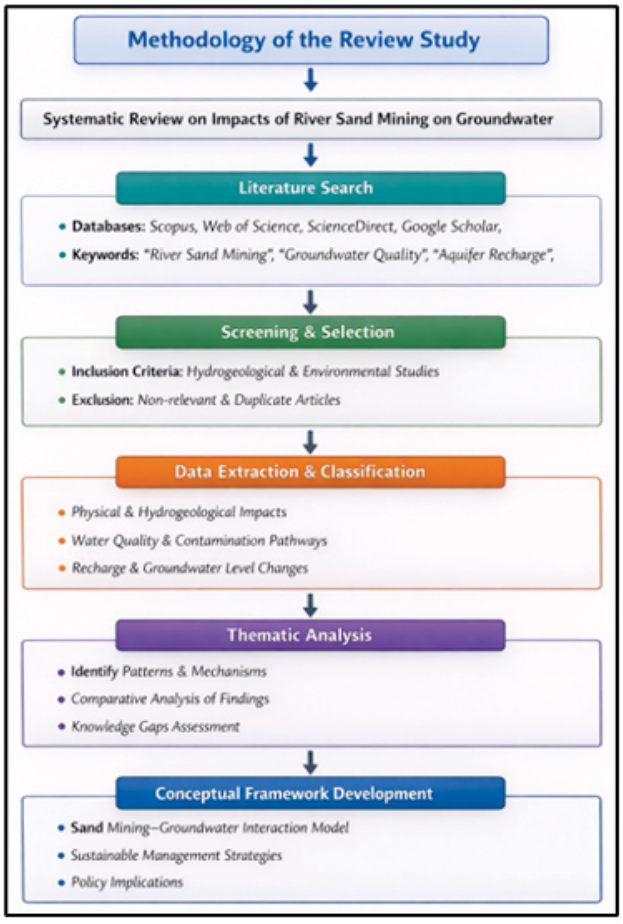


FIGURE 1 Overview of the study's methodology

3 | RESULTS AND DISCUSSION

3.1 | Mechanistic Impact of Sand Mining on Ground Water Recharge

The conceptual mechanisms illustrating the influence of river sand mining on groundwater recharge are presented in Fig. 2. Under natural conditions, permeable sand layers in riverbeds act as effective filtration media that facilitate infiltration and maintain strong hydraulic connectivity between the river channel and adjacent alluvial aquifers. These permeable sediments allow efficient exchange between surface water and groundwater, sustaining groundwater recharge, regional flow systems, and river baseflow.

However, excessive sand extraction disrupts these natural recharge processes. Removal of the permeable sand layer reduces infiltration capacity and weakens river–aquifer connectivity. In addition, mining activities often cause riverbed incision and channel deepening, which alter hydraulic gradients and promote groundwater drainage toward the river channel. These changes can result in the formation of localized cones of depression and reduced groundwater storage in surrounding aquifers. Consequently, sand mining significantly decreases groundwater recharge efficiency and may contribute to long-term groundwater depletion in riverine environments

3.2 | Environmental Impacts of Sand Mining

Environmental impacts of sand mining are broadly classified into physical, chemical, biological, and anthropogenic components based on findings from existing literature (Fig. 3). These interconnected impacts influence river morphology, groundwater systems, water quality, ecosystem health, and human activities (Barton N. and Mini G., 2013). This classification provides a structured framework for synthesizing previous studies and evaluating sustainable management approaches in this review paper..

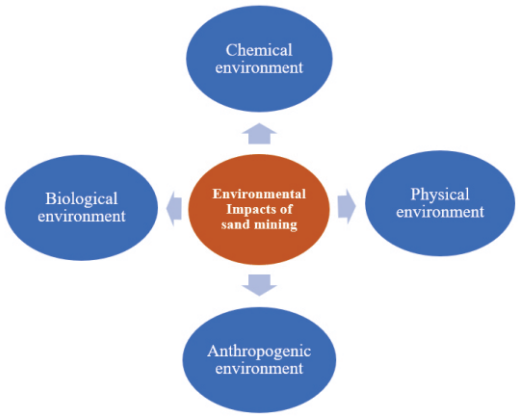


FIGURE 3 Environmental impacts of sand mining

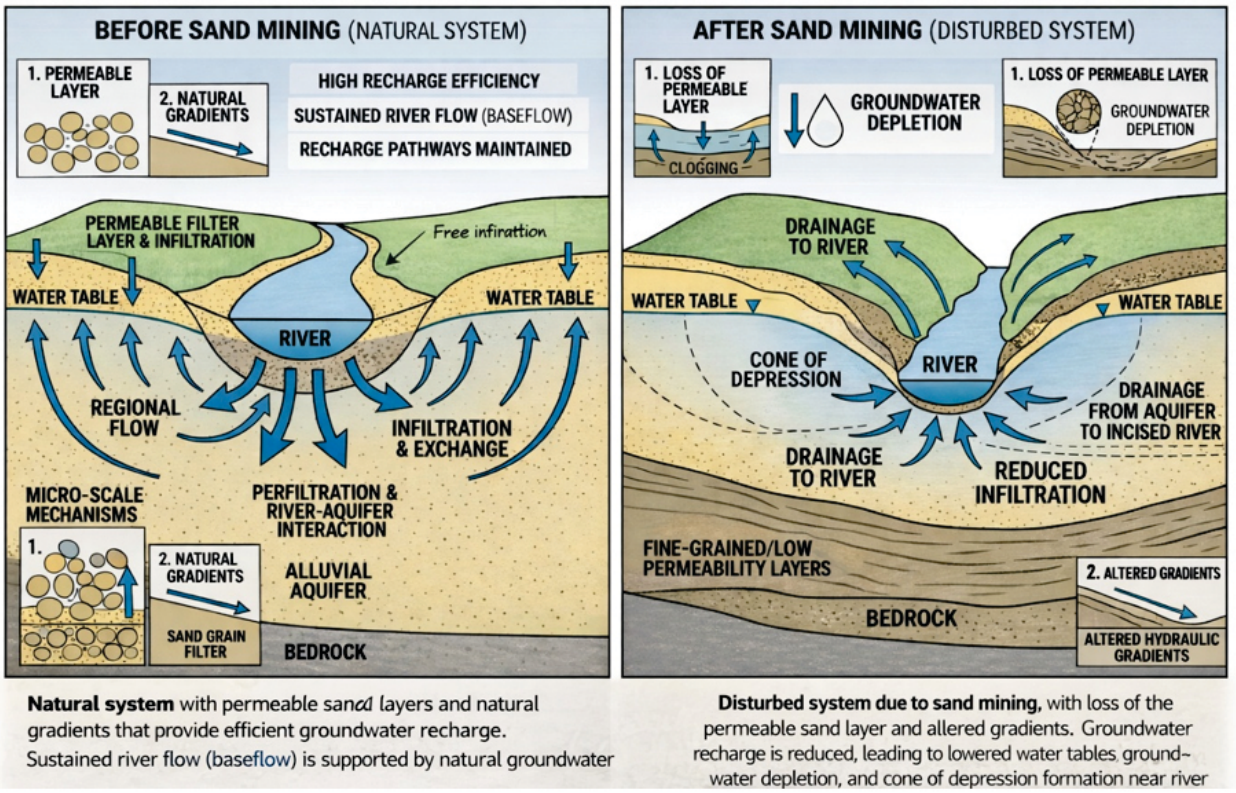


FIGURE 2 Mechanistic impact of river sand mining on groundwater recharge

3.2.1 | Turbidity

Turbidity is a key environmental impact associated with sand mining, especially in aquatic ecosystems. When sand is extracted from riverbeds, coastal areas and lakes, it disturbs the sediments, causing them to become suspended in the water. This suspension increases the water turbidity, leading to several environmental concerns.

Increased turbidity reduces light penetration leads to blocks sunlight from penetrating the water column, impacting photosynthesis in aquatic plants and phytoplankton. These organisms are from the base of the food web, so they are reduced photosynthesis can ripple through the entire ecosystem, affecting fish and other wildlife dependent on these resources. The oxygen depletion in aquatic systems leads to higher sedimentation rate, covering the organisms living in the bottom and reducing oxygen levels in the substrate. When the oxygen levels drop, it can lead to hypoxic conditions, stressing or even killing fish and other aquatic species. Fine sediments can settle over gravel beds used by fish, particularly species like salmon and trout, which lay their eggs in these areas. Increased turbidity and sedimentation can smother eggs and larvae, severely affecting the fish population. Turbid water is often associated with higher concentrations of pollutants, as partials suspended in water can bind with metals, pesticides and other toxins. These substances can travel towards downstream, spreading pollution and affecting water quality for communities and ecosystems.

3.2.2 | Bird Habitat

The negative environmental impacts of sand mining, particularly on fish, crocodiles, turtles, otters, birds and river dolphins. Many bird species, including the Indian skimmer, black-bellied tern, river tern, great thick-knee and river lapwing, find that rivers transitory sand islands, which provide an abundance of food for birds, are perfect places for them to nest. These sandbar nesting birds' breeding sites are being deteriorated by extensive sand mining, which may ultimately cause a reduction in their number. (Grbes *et al*., 2024 and Kajtoch *et al.*, 2024).

3.2.3 | Riparian Habitat, Flora and Fauna

The area along rivers and streams, is crucial for maintaining ecological health, supporting a diverse array of flora and fauna. These habitats provide essential resources like water, food and shelter for many species, including birds, fish, amphibians and mammals. The vegetation, such as willows, reeds and grasses, stabilizers riverbanks, strongly linked to the stability of channel bed and banks. Habitat degradation affects the natural nutrient cycle, impacting flora that rely on stable sediment layers (Kumar *et al.,* 2024). As riparian vegetation is cleared or degraded, local wildlife lose essential shelter and food sources, leading to biodiversity loss and altered ecosystem dynamics.

4 | Groundwater

4.1 | Impact on Aquifers-Confined, Unconfined

The complex hydrologic reactions can arise from the influence of sand mining, even if drainage to the mine is not involved. Dewatering from confined to unconfined conditions in bedrock aquifers is one reaction to water loss into new void space produced by bedding separations and fractures. (Bozeman, 2002). This dewatering process has been little studied but accounts for several hydraulic and geochemical effects of longwall mining (Booth, 2007). The increasing fracture permeability affects heads because upper aquifers in high relief areas lose water through fractured aquitards to lower aquifers and because the higher permeability lowers hydraulic gradients and up-gradient heads, and increases down-gradient discharge (Mace and Jones, 2023).

4.2 | Stability of Structures

The eroding of riverbanks**,** deteriorating coastal areas, lead to a reduced groundwater table and diminishing soil water quality, sand mining has a substantial negative influence on structural stability. This extraction eliminates the natural buffers that sustain coastal dunes, riverbanks and houses along the shore. Additionally, mining causes plant loss, subsidence and soil compaction, which weakens slope stability and increases the risk of landslides. In addition to endangering the surrounding infrastructure's foundations, this unreliability increases the risk of structural damage to the ecological system.

4.3 | Water Quality

Total suspended solids (TSS), magnesium (Mg), turbidity, and iron (Fe) levels in water samples taken downstream of the river near the mining site above WHO guidelines, which may be used to assess physiochemical analysis in sand mining sites (WHO) standards (Akankali *et al*., 2017, Candeias et al., 2018, Lekomo et al., 2021 and Bhattacharya *et al.*, 2019). The current condition of seawater quality has decreased due to increasing sedimentation, altering water flow and introducing pollutants (Doloksaribu *et al*., 2020, Hemalatha *et al*., 2025). Additionally, sand mining can cause erosion, increasing nutrient runoff and pollutant loads, including heavy metals and organic contaminants, which degrade water quality. The altered flow patterns can also lead to changes in water temperature, dissolved oxygen levels, and pH, further affecting aquatic life and potentially contaminating drinking water sources (Poonia *et al.,* 2024).

4.4 | Biological Environment

Biologically, SOC (Soil Organic Carbon) serves a food source for soil microorganisms, which are essential for nutrient cycling and maintaining soil fertility (Paustian *et al.*, 2019; Mirzaee *et al.*, 2020; Li *et al.*, 2018). Furthermore, the SOC content of agricultural and natural soil affected by mining activities can exert significant direct and indirect impacts on the environment (Ussiri *et al*., 2014). Mining activities have direct consequences such as the removal of vegetation, excavation resulting in loss of soil and overburden, permanent changes to the landscape and geological formations and disruptions to surface and subsurface hydrological systems (Shrestha and Lal, 2011).

Therefore, mining directly impacts SOC levels by removing or disturbing surface soils, which leads to the loss or degradation of soil organic matter (Zhu *et al.*, 2024).

4.4.1 | Health Hazards

Air quality is one of the most often mentioned environmental issues related to industrial sand mining, particularly in relation to crystalline silica particles that can be ingested. Inflammation of the lung and other respiratory tissues, known as silicosis, eventually results in fibrosis, a hardening of the lungs that impairs breathing efficiency (Orr and Krumenacher, 2015).

4.5 | Climate

Sand mining has significant effects on the climate and the environment, primarily due to its unregulated and often destructive practices. The extraction of sand from rivers and marine ecosystems leads to erosion, habitat destruction, and increased vulnerability of coastlines to sea level rise, ultimately exacerbating climate-related issues (Nguyen *et al.,* 2024). In many regions, sand mining is occurring at unsustainable rates, with estimates suggesting the extraction of between 32 billion and 50 billion tonnes of sand and gravel annually (Mia *et al*., 2024; Ravanashree *et al.,* 2025). This unsustainable harvesting contributes to a decline in biodiversity and pollution of water bodies, which in turn threatens livelihoods dependent on fishing and agriculture (Akanwa *et al*., 2021). Moreover, the loss of natural sediment flow, particularly in river deltas, increases the likelihood of flooding as these areas lack the necessary sediment to build resilience against water surges. Consequently, effective regulation and alternative materials are crucial to mitigate the environmental and climatic impacts of sand mining

4.5.1 | Destruction of Riparian Vegetation

The destruction of riparian vegetation due to sand mining significantly impacts ecological health and riverine system stability (Rentier *et al*., 2022). Additionally, heavy machinery compacts the soil, which increases erosion by decreasing soil infiltration and generating overland flow. (Padmalal *et al*., 2014). Riparian zones, which act as a buffer zone between terrestrial and aquatic ecosystems, are degraded during sand extraction processes (Bhattacharya *et al.,* 2020). This disruption of land leads to a loss of biodiversity (Rathoure *et al*., 2020). Removing vegetation exacerbates soil erosion and increases river sediment load, altering hydrological regimes and potentially leading to riverbank collapse. Additionally, a lack of vegetation lowers the ecosystem's capacity to filter contaminants, which lowers the quality of the water. Water temperature is also impacted by the loss of shade from riparian vegetation, which can harm aquatic life, especially species that are sensitive to temperature. Sustainable sand mining methods and riparian vegetation restoration are crucial to lessen these effects and guarantee the resilience of riverine ecosystems.

4.5.2 | Acid Mine Drainage Formation

A mine with acid mine drainage (AMD) has the potential for long–term divesting impacts on rivers, streams and aquatic life. It concerns many metals such as gold, copper, silver and molybdenum, are often found in rock with sulphide minerals. When the sulphuric acid was dissolved with other harmful metals in the surrounding rocks.(Saviour, 2012) this harmful mineral may runoff into streams or rivers or leach into groundwater. The formation of acid mine drainage is a complex biological and mineral dissolution process Dold, 2014. This AMD has several environmental consequences, such as water quality degradation, Soil and Vegetation damage and Toxicity and Bioaccumulation in the food chain. The AMD in sand mining sites underscores the need for sustainable mining practices, proper management of sulfide-bearing sand deposits and effective treatment solutions to mitigate environmental impacts (Skousen *et al*., 2019, Ashraf *et al*., 2011 and Mishra and Lal, 2024).

4.5.3 | Erosion and Sedimentation

The extraction of sand from river bed disrupts the natural sediment balance within the river system and it is the rate of extraction exceeds the rate of deposition. This disruption affects the river morphology, aquatic habitats, water quality and downstream areas. Because of these impacts highlight the causes of increased riverbank erosion, lowering of riverbeds, sedimentation, and habitat disruption, altering of natural sediment transport, and decreased water quality and aquatic life (Padmalal and Maya, 2014 and Aliyu *et al*., 2021). With considerable sand mining operations, the disturbed river became deep and narrow, causing erosion both upstream and downstream of the mining sites.

4.6 | Impact on Groundwater

Mining operations result in an increase in the sediment load in surrounding bodies of water, which worsens the quality of the water. This debris can seep into the groundwater system and clog the aquifer material's pores, lowering its permeabil ity and lowering the quality of the water. Groundwater can g et contaminated with heavy metals and other dangerous mat erials due to chemical contaminants that seep in from minin g equipment, lubricants, and unintentional spills (Siddharam *et al*., 2025). By the effect of surface water and groundwater interaction leads to a reduction in stream flow and diminishes the natural recharge of adjacent groundwater systems (soni, *et al.*, 2020). Sand mining destroys the surface and groundwater aquifer zones, leading to increased runoff and reduced filtration, which impacts groundwater recharge quality.

4.6.1 | Extensive Aquifer Dewatering

Sand mining involves the removal of overlying material, which can lower the water table. This process disrupts the natural recharge of groundwater, reducing the availability of groundwater for surrounding ecosystems and human use (Choudhary *et al.*, 2023). Mining activities can penetrate aquifers, causing a direct drawdown of water levels. This can result in a decrease in the aquifer's ability to store water and disrupt the natural flow paths within the aquifer system.

4.7 | Acid mine Drainage and Contaminant Leaching

Contaminated mining in soils can contribute to heavy metal pollution of nearby farmlands under rainfall conditions. The concentrations of heavy metals such as Cr, Ni, Cu, Zn, As, Cd, and Pb in these soils are often several to even twenty times higher than their natural background contaminated mining soils were several or even twenty times higher than their corresponding background values, In contrast, a significant amount (>50 %) of Cd, Zn, Cu and Pb were found in mobile forms (wang *et al.,* 2024). Sulfuric acid is formed during mining when when the sulphides in the rock are removed and exposed to air and water. This acid water dissolves with other harmful minerals in the surrounding rock. This acid mine drainage may runoff into streams, rivers and leach into groundwater. It impacts plants, fish and animals. Acid-mined streams have a pH value of 4 or lower (battery acid) (saviour, 2012).

4.8 | Impact on Physical Hydrogeology

Both surface water and groundwater can be impacted by subsidence. The pre-mining surface water and groundwater parameters usually determine how much such impacts modify the land use. Hydrologic systems are impacted by mining subsidence in ways that alter both water quality and quantity. If surface water such as streams, lakes and ponds are directly or indirectly related to open cracks, fissures, or pits created by subsidence, there may be a partial or whole loss of water that is drained to lower strata or mine workings. This kind of water resource depletion can affect aquatic life forms (SME, 1986), other life forms that may rely on surface water systems, and the appropriateness (quality and quantity) of those resources.

4.9 | Impacts on Local Groundwater Drainage, Flow and Discharge

The underground mine forms a new channel for the movement of water and air that did not previously exist. Groundwater seeping into the mine may come into contact with freshly exposed rock surfaces containing reactive and soluble minerals. The quality of groundwater in a mined area can be altered by mineralized rock, potentially leading to elevated metal concentrations. When an underground mine extends into the saturated zone, seeping water creates a hydraulic gradient that induces flow toward the mine, resulting in a decline in surrounding water levels, seeping water creates a hydraulic gradient that induces (Rajesh *et al*., 2025). There is usually a direct relationship between the depth of mining and static water level, results from water levels will decline more as the mine goes deeper and also decline relative to the location of the mine both aerially and vertically relative to recharge/discharge sources (Mining, 1997). Fractured rock within the groundwater strata can enhance vertical flow, leading to overlying aquifer drainage.

4.10 | Linkages Between Sand Mining Impacts on Groundwater and Sustainable Development Goals (SDGs)

The impacts of river sand mining on groundwater are closely linked with several United Nations Sustainable Development Goals (SDGs), particularly those related to water security, ecosystem protection, and climate resilience (Fig. 4). Excessive sand extraction alters riverbed morphology, reduces natural infiltration capacity, and disrupts surface water–groundwater interactions, resulting in declining groundwater levels and deterioration of water quality, directly affecting SDG 6 (Clean Water and Sanitation). Lowered groundwater tables and reduced recharge further weaken ecosystem resilience to climatic variability, contributing to challenges addressed under SDG 13 (Climate Action). In addition, sediment disturbance and increased turbidity degrade aquatic habitats, threatening biodiversity and aligning with concerns under SDG 14 (Life Below Water), while land degradation, vegetation loss, and ecosystem imbalance associated with mining activities impact terrestrial environments linked to SDG 15 (Life on Land). Therefore, sustainable regulation of sand mining and integrated groundwater management are essential to support progress toward these interconnected SDGs and ensure long-term environmental sustainability (Fig. 4).

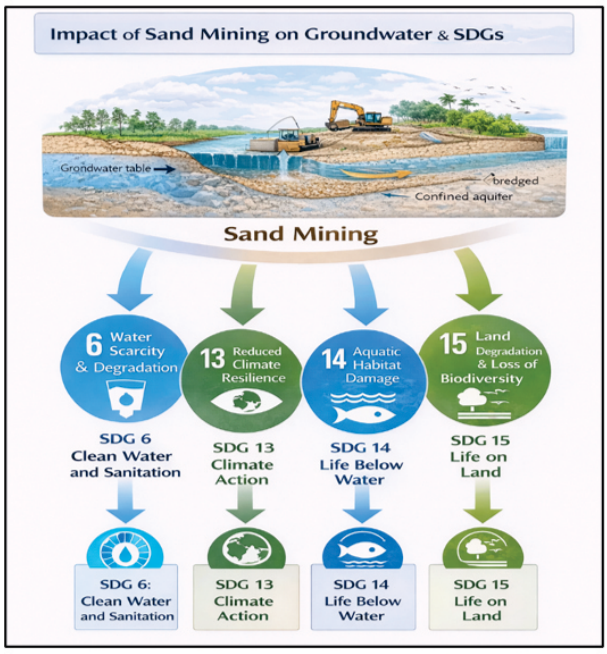


FIGURE 4 Conceptual illustration showing the impacts of river sand mining on groundwater systems and their linkages to key Sustainable Development Goals (SDGs), including clean water, climate action, aquatic ecosystem protection, and terrestrial biodiversity conservation

TABLE 1 Comparative synthesis of key studies examining the impacts of river sand mining on groundwater systems.

Study	Study Area/ Context	Focus of Study	Groundwater/ Hydrological Parameter Affected	Key Findings	Reported Magnitude / Quantitative Indicator
Kondolf (1994)	California, USA	Instream gravel and sand mining	River–aquifer interaction and channel morphology	Instream mining causes riverbed incision and reduces groundwater recharge potential.	Riverbed incision of 1–3 m reported in intensively mined reaches; significant reduction in lateral recharge to adjacent aquifers
Padmalal & Maya (2014)	Indian rivers	Environmental impacts of sand mining	Groundwater recharge and sediment balance	Excessive sand extraction reduces infiltration and disrupts natural recharge processes.	Infiltration capacity reductions of up to 40–60% reported in heavily mined riverbed sections
Rentier & Cammeraat (2022)	Global review	Environmental impacts of river sand mining	Sediment transport and hydrological connectivity	Sand mining alters river morphology and affects groundwater recharge pathways.	Global sand extraction estimated at 32–50 billion tonnes annually; hydrological connectivity loss qualitatively assessed across multiple basins
Koehnken *et al.,* (2020)	Global river basins	Sand mining impacts on freshwater ecosystems	River hydrology and sediment dynamics	Large-scale sand extraction modifies sediment balance and river hydrology.	Sediment deficits of 50–100% of natural supply reported in several intensively mined rivers globally
Naganna *et al.,* (2017)	Conceptual hydrogeological systems	Streambed hydraulic conductivity	Stream–aquifer interaction	Sediment characteristics control hydraulic conductivity and groundwater exchange.	Streambed hydraulic conductivity can decline by one to two orders of magnitude following removal of coarse sand layers
Ciszewski & Sobucki (2022)	Mining-affected rivers	Mining-induced subsidence	Riverbed stability and groundwater pathways	Subsidence caused by mining alters groundwater flow pathways.	Subsidence-induced channel adjustments of 0.5–2.0 m vertical displacement reported; qualitative assessment of groundwater pathway alteration.
Barman *et al*., (2019)	Alluvial rivers	Sand mining effects on channel flow	Channel hydraulics and sediment transport	Mining modifies flow characteristics influencing groundwater recharge.	Mining pit migration rates of several metres per year documented; recharge reduction qualitatively assessed.
Rovira *et al*., (2005)	Tordera River, Spain	Gravel mining impacts	Sediment budget and hydraulic gradient	Historical mining altered sediment dynamics and river–aquifer interactions.	Sediment budget deficit of approximately 60,000 m^3/year attributed to historical mining; channel incision of ~1 m over study period.
Aliyu et al., (2021)	River systems in Nigeria	Sand mining impacts on channel morphology	River hydrology and groundwater recharge	Channel morphology changes influence groundwater recharge conditions.	Channel widening of 15–30% and depth increases of up to 1.5 m reported in active mining zones
Ashraf et al. (2011)	Bestari Jaya, Malaysia	Environmental impacts of sand mining	Water quality and sediment transport	Mining increases suspended sediments and potential groundwater contamination.	TSS values exceeding 200 mg/L recorded downstream of mining sites; turbidity levels 3–5 times above baselineed in active mining zones
Saviour (2012)	Global review	Environmental effects of sand mining	Surface water and groundwater quality	Sand mining increases turbidity and degrades aquatic environments.	Heavy metal concentrations (Pb^{2+}, Zn^{2+}, Cu^{2+}) reported at 10–20 times background levels in mined catchments.
Liang & Thomson (2010)	Mining environments	Acid mine drainage processes	Groundwater chemistry and pH	Exposure of sulfide minerals can cause acid drainage and groundwater contamination.	Acid-impacted stream pH values of 4.0 or below recorded; dissolved metal concentrations (Fe, Mn) elevated 5–15 times above ambient levels.

4.11 | Integrated Impacts of River Sand Mining on Groundwater Systems

A synthesis of the reviewed literature (Table 1) indicates that river sand mining influences groundwater systems through interconnected hydro geomorphological and geochemical processes that alter sediment structure, recharge pathways, and river–aquifer interactions (Naganna *et al.,* 2017; Koehnken *et al.*, 2020). Riverbed sand deposits typically act as highly permeable layers that facilitate infiltration and enable dynamic exchange between surface water and adjacent aquifers (Chakraborty, 2021). Excessive extraction of these sediments disrupts the natural filtration and recharge functions of riverbeds, leading to reduced infiltration capacity and declining groundwater levels in surrounding floodplain aquifers (Kondolf, 1994; Padmalal and Maya, 2014; Rentier and Cammeraat, 2022). Studies conducted across multiple river basins have consistently reported that sand removal modifies channel morphology, increases suspended sediment loads, and reduces groundwater recharge potential in nearby areas.

One of the primary mechanisms linking sand mining to groundwater decline is riverbed incision and channel deepening (Ciszewski and Sobucki 2022). Intensive sediment extraction disturbs the natural sediment balance of rivers, causing erosion and lowering of the riverbed elevation (Barman *et al*., 2019; Khoi *et al.,* 2020). These geomorphological changes alter hydraulic gradients between surface water and groundwater systems and may convert gaining streams into losing streams, thereby reducing lateral recharge to adjacent aquifers (Rovira *et al*., 2005; Aliyu *et al*., 2021; Panth *et al*., 2025). Such modifications can significantly influence groundwater flow regimes, particularly in alluvial river basins where river–aquifer connectivity plays a critical role in sustaining groundwater storage.

In addition to hydrological changes, sand mining also contributes to groundwater quality degradation through increased sediment transport and contaminant mobilization. Disturbance of sediments during mining activities generates high concentrations of suspended particles, which may carry nutrients, heavy metals, and other pollutants into groundwater systems (Ashraf *et al.,* 2011; Saviour, 2012). Furthermore, the exposure of sulfide-bearing minerals during mining can trigger acid mine drainage processes that release dissolved metals and lower groundwater pH levels, posing risks to aquatic ecosystems and drinking water sources (Talukder *et al*., 2024; Liang and Thomson, 2010). Recent studies also indicate that sand mining activities can increase turbidity and sediment loads in rivers, which further impacts water quality and hadrochemical processes in connected aquifers.

Hydrogeological alterations caused by mining operations may also affect groundwater flow pathways and aquifer stability. The creation of excavation pits, fractures, and subsidence zones can modify subsurface permeability and generate artificial drainage pathways that redirect groundwater flow toward mining sites. These structural changes may enhance vertical groundwater leakage in fractured rock environments but often result in long-term groundwater depletion in sediment-dominated river basins (Booth, 2005; Mace and Jones, 2023). The magnitude of these impacts varies depending on geological conditions, sediment replenishment rates, and mining intensity. However, a broad consensus across the literature indicates that uncontrolled sand mining disrupts natural recharge processes, alters groundwater flow dynamics, and increases contamination risks.

Overall, the collective evidence demonstrates that sand mining has multidimensional impacts on groundwater systems, including reduced recharge, altered hydraulic gradients, and deterioration of groundwater quality. These effects are particularly pronounced in regions experiencing rapid urbanization and high demand for construction materials. Consequently, recent studies emphasize the need for integrated sediment management, hydrogeological monitoring, and scientifically informed regulation of sand extraction to ensure the sustainable use of groundwater resources and protect riverine ecosystems.

4.12 | Perspective on Sustainable Groundwater Management Plan

Groundwater management is a multifaceted discipline involving the expertise of geologist, engineers, economists and ecologists. However, its fundamental objective revolves around maintaining a long-term balance between supply and demand. In mining areas, groundwater faces significant challenges that threaten both its quantity and quality. Quantity issues can result from extensive aquifer dewatering, disruptions to local groundwater drainage patterns, and alterations to flow and discharge regimes. Quality concerns, on the other hand, often stem from contaminant leaching caused by acid mine drainage and its associated impacts on the physical hydrogeology of the region.

Effective groundwater management requires a comprehensive approach that begins with awareness of both the quality and quantity of available groundwater. Monitoring is essential to identify existing or potential problems, particularly in overexploited or critical areas, such as those under stress from mining and urbanization. Practices such as rainwater harvesting and aquifer recharge are vital for sustainable groundwater use, along with measures like deepening and rejuvenating wells and protecting water bodies. Additionally, clear and widely accepted water laws and rights, or a system of incentives and disincentives, are necessary to regulate groundwater use effectively. Surveillance plays a crucial role in ensuring adherence to these regulatory measures or incentivized practices. Moreover, it is important for government planning and society to recognize the critical importance of groundwater resources.

Strategies for sustainable groundwater development require focused efforts in two key areas: (i) groundwater assessment and (ii) monitoring and regulation. To achieve this, the following recommendations are proposed:

Groundwater management initiatives have to concentrate on safeguarding resources in certain geographical areas designated as "Stress Aquifers." A specific "State Groundwater Policy" that prioritizes sustainability and groundwater conservation must be created in order to handle the particular difficulties faced by regions impacted by mining. This strategy ought to include the creation of thorough "Aquifer Management Plans" that are intended to lessen the effects of mining operations and guarantee the long-term security of groundwater (Raghavendra *et al.,* 2015).

5 | CONCLUSIONS

River sand mining plays an important role in supporting construction activities and economic development; however, unregulated and excessive extraction has emerged as a major threat to groundwater systems and associated ecosystems. This review highlights that sand removal significantly alters riverbed morphology, reduces infiltration capacity, and disrupts the natural interaction between surface water and groundwater. The loss of sand layers, which function as natural filters and recharge media, leads to groundwater table decline, reduced aquifer storage, and deterioration of groundwater quality due to increased turbidity, contaminant transport, and acid mine drainage processes. Beyond hydrogeological impacts, sand mining also contributes to ecological degradation, biodiversity loss, and increased vulnerability of communities dependent on groundwater resources. The synthesis further demonstrates that these impacts are closely linked with global sustainability challenges, particularly those addressed under SDGs related to clean water, climate resilience, and ecosystem protection. Therefore, achieving a balance between resource extraction and environmental conservation is essential for long-term groundwater sustainability.

Key Findings and Recommendations

- Excessive sand mining lowers groundwater tables by reducing natural recharge and altering hydraulic connectivity between rivers and aquifers.
- Removal of sand layers diminishes natural filtration capacity, leading to groundwater quality degradation and increased contamination risks.
- Hydrogeological disturbances such as aquifer dewatering, subsidence, and altered groundwater flow patterns significantly affect water availability.
- Ecological impacts include riparian habitat destruction, biodiversity loss, and degradation of aquatic ecosystems.
- Sand mining pressures directly influence Sustainable Development Goals, particularly SDG 6 (Clean Water and Sanitation), SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land).
- Sustainable groundwater management requires regulated mining practices supported by environmental impact assessments and strict policy enforcement.
- Adoption of alternative construction materials such as manufactured sand (M-sand) and recycled aggregates can reduce dependency on river sand.
- Integrated governance involving policymakers, scientists, and local communities is necessary to ensure effective implementation of sustainable management strategies.

Overall, sustainable regulation, scientific monitoring, and ecosystem-based management approaches are crucial to minimizing the adverse impacts of sand mining and ensuring the protection and resilience of groundwater resources for future generations.

ACKNOWLEDGEMENTS

The authors would like to thank the anonymous reviewers for their valuable comments and constructive suggestions, which significantly improved the quality and clarity of this paper.

CONFLICT OF INTEREST

The authors confirm that there are no known financial or personal conflicts of interest that could have influenced the findings or interpretations presented in this study.

DATA AVAILABILITY STATEMENT

Data is available with the corresponding author and can be provided on request.

AUTHOR'S CONTRIBUTION

B.N. Pavithra contributed to literature collection, data compilation, and preparation of the initial draft of the manuscript; Siddharam assisted in systematic literature review and data analysis; L. Aiswarya contributed to thematic analysis and drafting of specific sections; and R.G. Munivenkatappa, as the corresponding author, conceptualized and designed the study, supervised the overall research work, critically revised the manuscript, and finalized it for submission. M. Sandeepika supported in data interpretation and manuscript organization. J.B. Kambale and Sankeerth K contributed to literature review, editing, and formatting. All authors reviewed and approved the final version of the manuscript.

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How to cite this article: Pavithra, B. N., Siddharam., Aishwarya, L., Munivenkatappa, R.G., Sandeepika, M., Kambale, J.B., and Sankeerth, K., 2025. River Sand Mining and Groundwater Systems : Mechanisms, Impacts, and Pathways to Sustainable Management . *Indian J. Soil Cons*., **53(3)** (*Hill & Mountain Agriculture S*pecial Issue)**: 222-232**

Received: 09 September 2025 | Accepted: 19 December 2025 | Published online: 06 April 2026

DOI: 10.53550/ijsc.v53.i3.206

ORIGINAL ARTICLE

Indian Journal of Soil Conservation

Soil Carbon Fractions and Management Indexes in Dragon Fruit (*Hylocereus spp.*) Cultivation in the Western Himalaya

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Handling Editor:
Dr Rajive K. Singh

Key words:
Carbon pool
Carbon fractions
Himalaya
Pitaya
Soil health

ABSTRACT

Soil organic carbon (SOC) fractions give key insights into soil quality, nutrient cycling, and carbon storage in agriculture and horticulture. However, little research has explored SOC fractionation and carbon dynamics in dragon fruit systems, especially regarding accession differences. This study assesses SOC fractions and carbon management indices among dragon fruit accessions in the northwestern Himalaya to establish a baseline for this emerging crop. Seven accessions—Pink Gujarat (PG), White Gujarat (WG), Yellow Gujarat (YG), Pink Bangalore (PB), White Bangalore (WB), Local Pink Pulp (LPP), and Local White Pulp (LWP)—along with open field conditions (OC) as reference, were evaluated three years after planting. SOC fractions were measured using standard protocols with the modified Walkley-Black method and different acid concentrations. Results showed significant accession-specific variation in SOC fractions ($p<0.05$). Accessions YG, WB, and PB had the highest very labile (3.65-3.84 mg g^{-1}), labile (2.68-2.83 mg g^{-1}), and active carbon pools (6.33-6.67 mg g^{-1}), with 46-86% higher active pools than open field (3.58 mg g^{-1}). PG had the highest non-labile (6.08±0.36 mg g^{-1}) and passive pools (8.66±0.38 mg g^{-1}). CMI ranged from 134.93 to 212.34, with YG highest. Strong correlations between labile fractions and CMI ($r=0.99$) show labile pools drive management index variation. This is the first baseline of SOC fractions in northwestern Himalayan dragon fruit accessions, revealing profiles: YG, WB, PB with higher active carbon, and PG, LWP with more stable carbon. These reflect SOC status three years after planting and serve as references for future monitoring. Long-term studies are needed to see if differences impact sequestration rates and distinguish plant from soil effects. YG, WB, and PB are promising for carbon research.

1 | INTRODUCTION

Globally, soil organic carbon (SOC) is the largest terrestrial carbon pool, vital for soil health and climate regulation by balancing carbon sequestration and greenhouse gases (Kumar *et al.,* 2020; Kaushal *et al.*, 2022). One meter of topsoil stores about 1500 to 2400 Gt of carbon, surpassing vegetation and atmospheric stores (Sanderman *et al.,* 2017). The total carbon pools are approximately 721 Pg for the world (Chen *et al*., 2025), 36 Pg for India (Sreenivas *et al.*, 2016), and 5.4 Pg for the Himalayan region (Tolangay and Moktan, 2020). SOC fractions offer insights into soil resilience, nutrient cycling, and sequestration potential (Pandher *et al.*, 2020; Kumar *et al.*, 2021). Plant species, genotypes, and accessions influence organic matter inputs, affecting carbon pools (Rakesh *et al*., 2021). Soil indices like the Lability Index (LI), Carbon Pool Index (CPI), and Carbon Management Index (CMI) provide systematic assessments of soil quality and carbon dynamics, considering both quantity and quality of SOC. These indices are widely used globally in different ecosystems to evaluate management practices such as agriculture, conservation tillage, and land restoration (Nath *et al.*, 2015; Kumar *et al*., 2024). LI measures labile SOC related to biological activity; CPI compares SOC stocks across sites; CMI detects management effects on soil quality. These indices promote better soil health and management worldwide (Kumar *et al.,* 2020).

Dragon fruit has shown adaptability to various agro-climatic conditions, including semi-arid and subtropical environments (Sahu *et al*., 2025). Its low water needs, heat tolerance, and suitability for marginal lands make it ideal for regions affected by climate change and resource scarcity (Jinger *et al*., 2024). The fibrous roots and drought resistance make it suitable for fragile Himalayan ecosystems. It can grow on degraded soils, sequester carbon, and improve soil structure, supporting sustainable land use and reducing degradation. Recently, the western Himalayan foothills and mid-hills have become new areas for dragon fruit cultivation due to demand, profitability, and government support. These soils are fragile and low in organic matter, requiring careful selection of accessions to boost productivity and restore soil carbon pools (Wakchaure

et al., 2021). Indexes like CPI, LI, and CMI help assess land suitability for sustainable development.

While awareness of dragon fruit's potential in fragile ecosystems grows, research on its effects on soil organic carbon (SOC) fractions and carbon dynamics remains limited (Kakade *et al*., 2020; Satish, 2023). Most studies have focused on yield and management; the impact on SOC fractions—labile, recalcitrant, and intermediate—is not well understood. This study is the first to quantify SOC fractions in northwest Himalaya, linking horticultural practices with soil sustainability. The main goal is to examine SOC fractions and the soil carbon management index across different dragon fruit accessions, hypothesizing (a) that accessions influence SOC dynamics, and (b) that LI and CMI vary among accessions.

2 | MATERIALS AND METHODS

2.1 | Study Site

This experiment was conducted at the CSIR-Institute of Himalayan Bio-resource Technology experimental site in Palampur, Himachal Pradesh. The experimental site falls in the mid-hill range of the northwestern Himalaya. The site is characterized by high rainfall in the monsoon season and moderate temperatures in the winter season. The site is situated at 32°0'05″ N latitude and 76°34'10″ E longitude, at an elevation of 1390 m above mean sea level. The mean annual rainfall in Palampur is 2690 mm. Summer temperatures range from 9.2 °C to 35.4 °C, and winter temperatures range from 3.0 °C to 20.7 °C.

2.2 | Experimental Setup

Seven accessions of dragon fruits of three varieties, viz. pink-skinned with pink flashed, pink-skinned with white flashed, and yellow-skinned with white flashed, were collected from different locations. The three varieties of dragon fruit, viz. pink-skinned with pink pulp, pink-skinned with white pulp, and yellow-skinned with white pulp, were collected from Gujarat, Bangalore, and locally grown on a farmer's field (Kangra, HP). Five accessions were collected from Bangalore and Gujarat, two accessions were grown from the seeds (obtained from farmers' fields), and these fruits were collected from Rajasthan. However, the cuttings of other accessions were collected from Bangalore and Gujarat. The names of the accessions were Pink Gujrat (PG), White Gujrat (WG), Yellow Gujrat (YG), Pink Bangalore (PB), White Bangalore (WB), Local Pink Pulp (LPP), and Local White Pulp (LWP). The experiment was carried out from 2024 to 2025. These accessions were planted in the field in randomized block design (RBD). The plant-to-plant spacing was 1.5m, and the row-to-row spacing was 2.5m (Fig. 1). All the accessions were planted with four replications in the field. Before planting, pits were prepared and filled with a soil–sand–FYM mixture in a 1:1:2 ratio at the time of planting. In addition, 10 kg of FYM was applied annually to each dragon fruit plant. The soil was analyzed before the plantation of dragon fruit to assess the basic soil properties. The results showed a pH of 6.24, SOC of 1.28%, bulk density of 1.05 g cm^{-3} and clay loam texture.

HIGHLIGHTS

- Significant accession-specific variation exists in soil organic carbon fractions among dragon fruit cultivars in the northwestern Himalaya.
- Carbon Management Index effectively discriminates among accessions based on current SOC status, validating its utility as an assessment tool for horticultural systems.
- Accessions YG, WB, and PB show distinct SOC profiles with higher active carbon pools, while PG demonstrates higher passive pools, establishing baseline values for future temporal monitoring studies.

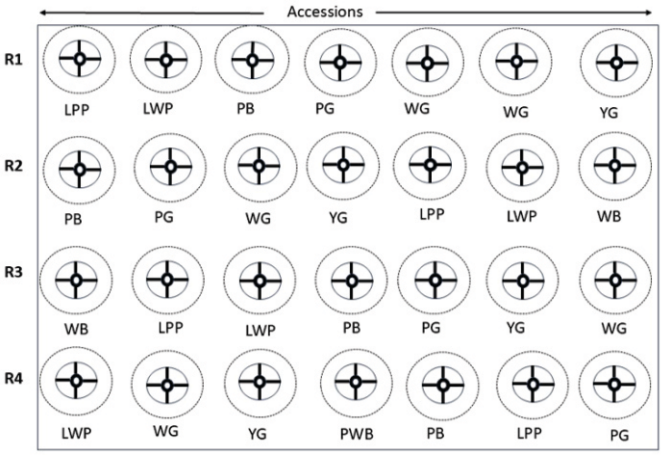


FIGURE 1 Layout of the dragon fruit experiment

2.3 | Soil Sampling

The samples were collected from all accessions of four replications. The soil samples were collected from 0-30 cm soil depth with the help of an auger, as the maximum roots are confined to 30 cm soil depth only in dragon fruit. Four plants were planted around the four directions of a square-shaped concrete pole; soil samples were collected from each direction to cover all four plants, and then all four samples were mixed to obtain a composite sample of about 500 grams. A total of 28 samples were collected from each replication of all seven accessions, and then these four samples were composited to make a single representative sample of one accession in a replication. The experiment was laid out in four replications, so the total number of composite samples was 7 accessions × 4 replications = 28. However, the subsamples were four samples from one pole × 7 accessions × 4 replications = 112. All four plants of an accession were planted around the square-shaped concrete pole (pole in the middle of all four plants), and the distance between one pole and another pole was 1.5 meters. The soil samples were collected within the periphery of each pole to avoid contamination and variability among the samples within the accessions. Additionally, the soil samples were also collected from the open control plot (without dragon fruit), which was adjacent to the dragon fruit plots. Historically, both lands (the dragon fruit plantation site and the open field) had remained barren for approximately 10 years. Prior to this period, some medicinal plants, such as

Curcuma aromatica, were cultivated in the area. Therefore, an adjacent barren field with a similar land-use history was selected as the reference site for soil sampling. The soil samples were air-dried in shade, ground and sieved for the analysis of various C fractions. Open plot existed at the adjoining site also served as the control plot or reference for comparison of dragon fruit accessions for the soil carbon fractions.

2.4 | Analysis For Different Carbon Fractions or Pools In Dragon Fruit Accessions

Five, ten, and twenty milliliters of concentrated sulfuric acid (H_2SO_4) were used in the Modified Walkley and Black Method to determine the various Soil Organic Carbon (SOC) fractions. This corresponds to three acid aqueous solution ratios of 0.5:1, 1:1, and 2:1, which correspond to twelve N, eighteen N, and twenty-four N H_2SO_4 (Chan *et al.*, 2001; Ghosh *et al.*, 2010). The total amount of soil organic C can be divided into four different portions with diminishing oxidizability by oxidizing it with different acid concentrations. According to Chan *et al.,* (2001), the sum of these four fractions represents the total amount of organic carbon found in the soil layer.

SOC can be divided into two groups by separating it into distinct fractions according to their oxidizability: the stable or resistant fraction (Fractions 3 and 4) and the easily oxidizable or labile portion (equivalent to Fractions 1 and 2). For tracking soil quality and determining the soil's potential to store carbon, SOC fractions with varying stability are useful indicators (Blair *et al*., 1995; Chan *et al*., 2001; Baretto *et al*., 2011). While the stable fractions (Fractions 3 and 4) are least affected by management techniques and show only slight variation, the readily oxidizable or labile fractions (Fractions 1 and 2) are more responsive to management practices and exhibit significant variability across treatments. Thus, studying these four fractions in any ecosystem would reasonably indicate the ecosystem's capacity to store and sequester C in soil and its long-term sustainability.

The oxidizability of soil carbon is linked to the active carbon pool (ACP) and the passive carbon pool (PCP), which are computed from four distinct fractions. As the name implies, the passive C pool is the stable, resistant, and less reactive pool that is more difficult to oxidize and extract (Fractions 3 and 4). In contrast, the ACP is the sum of Fractions 1 and 2, which are the easily oxidizable, labile, and active parts. The distribution of carbon between the active and passive pools directly affects the physical, chemical, and biological characteristics of soil and influences the retention of carbon in the atmosphere (Bayer *et al*., 2004). Following standard procedure, the Lability Index (LI), Carbon Pool Index (CPI), and Carbon Management Index (CMI) were computed (Blair *et al*.,1995). The LI and CPI are important parameters for the derivation of CMI. While CPI, as an independent indicator, is not frequently utilized in SOC research, the Lability indicator primarily sheds light on the type or oxidisability of the SOC fractions. According to Sainepo *et al.* (2018), the CMI is commonly recognized as a measure of soil deterioration or improvement in response to changes in land use. It efficiently tracks short-term changes in soil C pools and accounts for both the quantity and quality of SOC (Blair et al., 1995; Benbi *et al*., 2008).

2.5 | Statistical Analysis

The data were checked for adherence to key statistical assumptions prior to the performing ANOVA. The normality of data was tested using Shapiro-wilk test, while homogeneity to variances (homoscedasticity) among the treatments was assessed using levene's test. The different accessions of dragon fruit for carbon fractions and pools, carbon pool index, lability index and carbon management index were compared using analysis of variance (ANOVA). The means comparison in posthoc analysis were performed using Tukey's Honest Significant Difference (HSD) test at a significance level ($p \geq 0.05$) for randomised block design (RBD). Correlation analysis between the different soil C fractions, LI and CMI was also carried out using Pearson's correlation coefficient method. The data for all parameters were analysed using R statistical software (version 4.5.1).

3 | RESULTS AND DISCUSSION

3.1 | Labile Carbon Fractions

The different carbon fractions showed significant variation ($p<0.05$) among all accessions of dragon fruit in the northwestern Himalaya. Significantly ($p<0.05$) higher very labile carbon (Fig. 2) was observed in YG (3.84±0.19 mg g^{-1}) accession, which was statistically at par with WB (3.79±0.23 mg g^{-1}) and PB (3.65±0.22 mg g^{-1}) accessions. Other accessions followed the trend: PG (3.28±0.18 mg g^{-1}) > LWP (2.94±0.15 mg g^{-1}) > LPP (2.76±0.13 mg g^{-1}) > WG (2.60±0.15 mg g^{-1}). Significantly ($p<0.05$) lower very labile carbon was recorded in OC (2.43±0.11 mg g^{-1}) compared to other accessions.

Accession YG (2.83±0.15 mg g^{-1}) also had significantly ($p<0.05$) higher labile carbon (*Fig. 2*), which was statistically at par with WB (2.74±0.16 mg g^{-1}) and PB (2.68±0.13 mg g^{-1}). After PB, higher labile carbon was recorded in PG (2.42±0.11 mg g^{-1}), followed by LWP (2.02±0.12 mg g^{-1}), LPP (1.86±0.11 mg g^{-1}), and WG (1.62±0.08 mg g^{-1}). The minimum labile carbon was recorded in OC (1.15±0.06 mg g^{-1}) when compared to all other accessions.

The active carbon pool (sum of very labile and labile carbon) showed significant variation among accessions ($p<0.05$). Accession YG (6.67±0.39 mg g^{-1}) showed the highest active pool (Table 1 and Fig. 2), which was statistically at par with WB (6.53±0.29 mg g^{-1}). Other accessions followed the pattern: PB (6.33±0.38 mg g^{-1}), PG (5.70±0.34 mg g^{-1}), LWP (4.96±0.24 mg g^{-1}), LPP (4.62±0.24 mg g^{-1}), and WG (4.22±0.21 mg g^{-1}). OC (3.58±0.17 mg g^{-1}) had the lowest active carbon pool among all treatments.

The present study reveals significant accession-specific variation in soil organic carbon fractions among seven dragon fruit accessions in three-year-old plantations in the northwestern Himalaya. All dragon fruit accessions exhibited higher SOC fractions compared to adjacent open field conditions (OC) with similar land-use history, with differences ranging from 18% to 86% depending on the fraction and accession.

The observed SOC fractions under different dragon fruit accessions fall within or near the agronomically expected ranges reported for subtropical orchard and other perennial systems (Kumar et al., 2020; Kaushal *et al*., 2022). The very labile and labile C fractions (2.4–3.8 mg g^{-1} and 1.1–2.8 mg g^{-1}, respectively) are comparable to values reported in tropical fruit-based systems such as mango orchards in eastern India (Ankit *et al.*, 2024) and subtropical orchard systems (Kumar *et al*., 2020).

Accessions YG, WB, and PB demonstrated 46-86% higher active carbon pools (6.33-6.67 mg g^{-1}) compared to open field conditions (3.58 mg g^{-1}). These differences suggest that these accessions are currently associated with soils having higher proportions of readily decomposable carbon sources, which are critical for maintaining short term soil fertility (Sahu *et al.*, 2025). The very labile and labile fractions represent portions of organic matter that are most readily available for microbial decomposition and nutrient cycling, with rapid turnover rates that support a continuous nutrient supply (Kumar *et al.*, 2020).

The observed accession-specific differences in labile pools could be attributed to variations in litter quality, root exudates, and biomass turnover patterns characteristic of different genotypes (Kaushal *et al*., 2022). However, without measurements of root systems, litter composition, or decomposition rates, the specific mechanisms driving these differences cannot be definitively established from the current dataset.

TABLE 1 Soil organic carbon pools (mg g^{-1}) and carbon management indices (Mean±SE) under different dragon fruit accessions.

Accessions	Active pool	Passive pool	Carbon pool index	Lability index	Carbon management index
OC	3.58±0.17^{g}	5.88±0.34^{d}	1.00±0.05^{d}	1.15±0.07^{b}	114.73±5.16^{g}
LPP	4.62±0.24^{e}	6.99±0.34^{c}	1.23±0.06^{c}	1.20±0.07^{b}	147.67±7.24^{e}
LWP	4.96±0.24^{d}	7.86±0.46^{b}	1.35±0.07^{b}	1.18±0.05^{b}	159.55±8.30^{d}
PG	5.70±0.34^{c}	8.66±0.39^{a}	1.52±0.09^{a}	1.20±0.06^{b}	182.42±10.98^{c}
WG	4.22±0.21^{f}	7.12±0.35^{c}	1.20±0.06^{c}	1.13±0.06^{b}	134.93±6.07^{f}
YG	6.67±0.39^{a}	7.81±0.41^{b}	1.53±0.09^{a}	1.39±0.07^{a}	212.34±10.19^{a}
PB	6.33±0.38^{b}	7.86±0.47^{b}	1.50±0.07^{a}	1.35±0.06^{a}	202.75±12.21^{b}
WB	6.53±0.29^{ab}	8.11±0.39^{d}	1.55±0.09^{a}	1.34±0.06^{a}	207.85±9.35^{ab}
p-value	0.001	0.001	0.005	0.62	0.0001

Different letters indicate significant differences ($P < 0.05$). Data with the same letters in the superscript do not differ significantly.

3.2 | Non-labile Carbon Fractions

Significantly ($p \leq 0.05$) higher less labile carbon (Fig. 3) was recorded in YG (2.91±0.18 mg g^{-1}), which was statistically at par with PB (2.88±0.13 mg g^{-1}) and WB (2.82±0.15 mg g^{-1}). Other accessions followed the trend: PG (2.58±0.13 mg g^{-1}) > LWP (2.24±0.11 mg g^{-1}) > LPP (1.97±0.09 mg g^{-1}) > WG (1.74±0.10 mg g^{-1}). OC (1.26±0.08 mg g^{-1}) had the least labile carbon compared to other accessions.

Non-labile carbon (Fig. 3) ranged from 4.62 to 6.08 mg g^{-1}, with significantly (p WG (5.38±0.24 mg g^{-1}) > WB (5.29±0.29 mg g^{-1}) > LPP (5.02±0.29 mg g^{-1}) > PB (4.98±0.26 mg g^{-1}) > YG (4.90±0.24 mg g^{-1}). OC (4.62±0.25 mg g^{-1}) showed the lowest non-labile carbon when compared to all other accessions. Non-labile carbon (Fig. 3) ranged from 4.62 to 6.08 mg g^{-1}, with significantly (p WG (5.38±0.24 mg g^{-1}) > WB (5.29±0.29 mg g^{-1}) > LPP (5.02±0.29 mg g^{-1}) > PB (4.98±0.26 mg g^{-1}) > YG (4.90±0.24 mg g^{-1}). OC (4.62±0.25 mg g^{-1}) showed the lowest non-labile carbon when compared to all other accessions.

The passive pool (sum of less labile and non-labile carbon) showed significant ($p \leq 0.05$) variation (Table 1 and Fig. 3), with the highest value in accession PG (8.66±0.39 mg g^{-1}), followed by WB (8.11±0.39 mg g^{-1}), PB (7.86±0.47 mg g^{-1}), LWP (7.86±0.46 mg g^{-1}), YG (7.81±0.41 mg g^{-1}), and LPP (6.99±0.34 mg g^{-1}). The minimum passive carbon pool was recorded in OC (5.88±0.05 mg g^{-1}) when compared to all other accessions.

Significant variation was also observed in non-labile carbon fractions among dragon fruit accessions, revealing distinct carbon quality profiles. The non-labile carbon pool (4.6–6.1 mg g^{-1}) falls within ranges reported for stabilized organic matter in long-term fruit orchard soils in India and Southeast Asia (Bhattacharyya et al., 2019; Zhou et al., 2022).

Accession PG showed 3% higher stable carbon pools (8.66 mg g^{-1}) compared to the next highest accessions, while maintaining relatively lower active pools. This

contrasts with the YG, WB, and PB accessions, which exhibited higher active: passive ratios. These distinct profiles suggest accession-specific differences in carbon partitioning patterns: YG/WB/PB show profiles that favor active carbon pools (potentially supporting short-term nutrient cycling), while PG and LWP show profiles with higher stable carbon accumulation (potentially favoring long-term carbon retention) (Kaushal *et al.*, 2022).

The estimated contribution of active and passive pools to total SOC in this study—with active fractions comprising approximately 35-45% and passive fractions 55 65%—follows typical distributions reported for perennial orchard soils (Wakchaure *et al*., 2021; Meena *et al*., 2020). Similar partitioning patterns have been documented in perennial and agroforestry systems, indicating that both pools play important roles in soil fertility and carbon storage potential (Meena *et al.*, 2020). However, it is important to note that these spatial differences reflect the current soil organic carbon (SOC) status of the existing plantation, rather than the actual carbon accumulation rates over time. Without pre-planting baseline measurements or temporal monitoring, we cannot distinguish whether these differences reflect plant-driven carbon inputs or pre-existing soil heterogeneity, even though uniform land-use history suggests minimal initial variation.

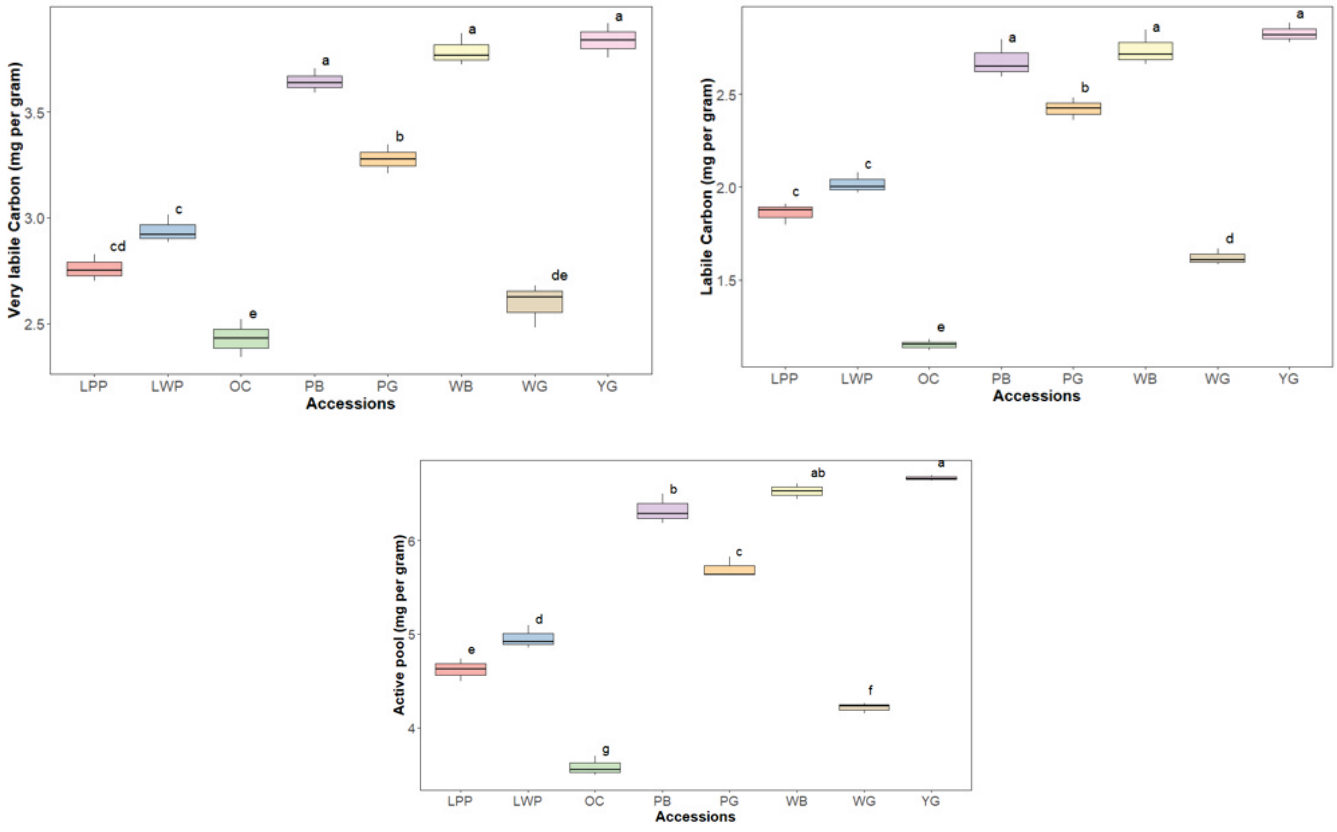


FIGURE 2 Active carbon pools (mg g^{-1}) under different accessories of dragon fruit (mean±se).

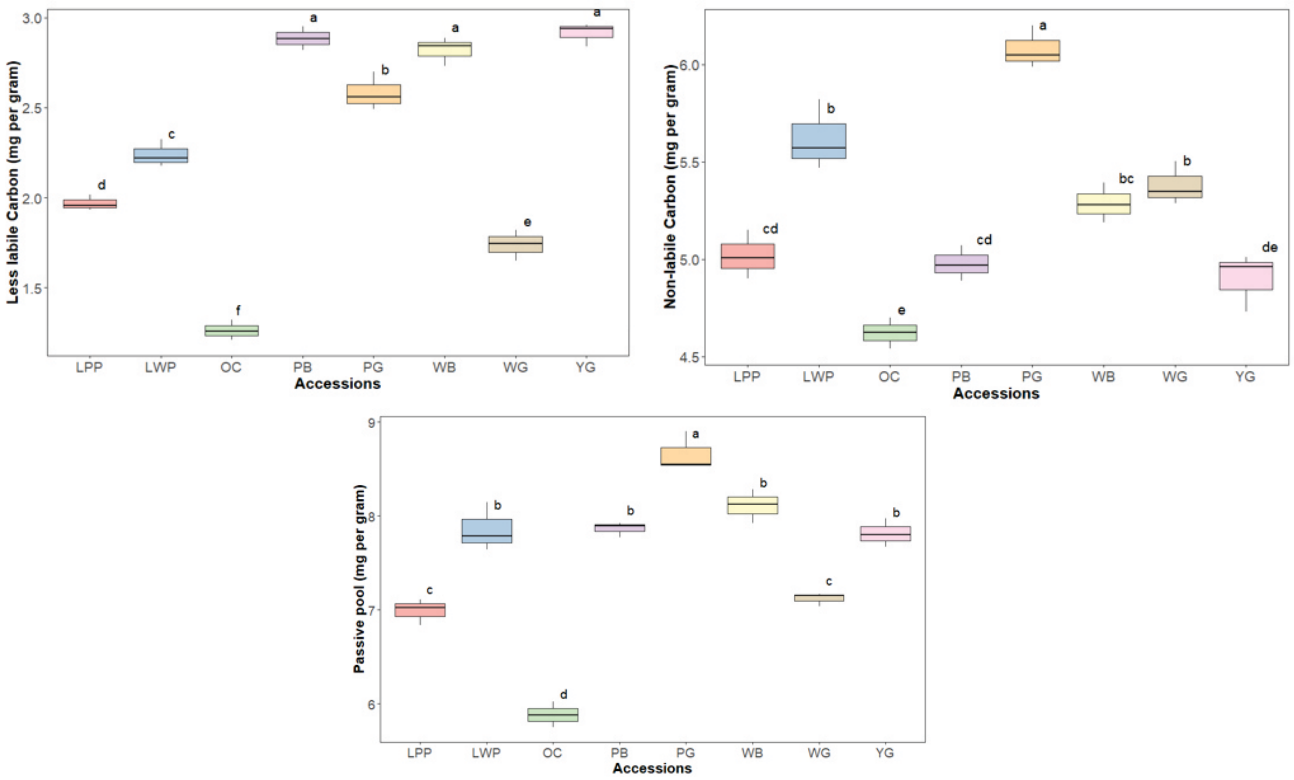


FIGURE 3 Passive carbon pools (mg g^{-1}) under different accessions of dragon fruit (mean±se)

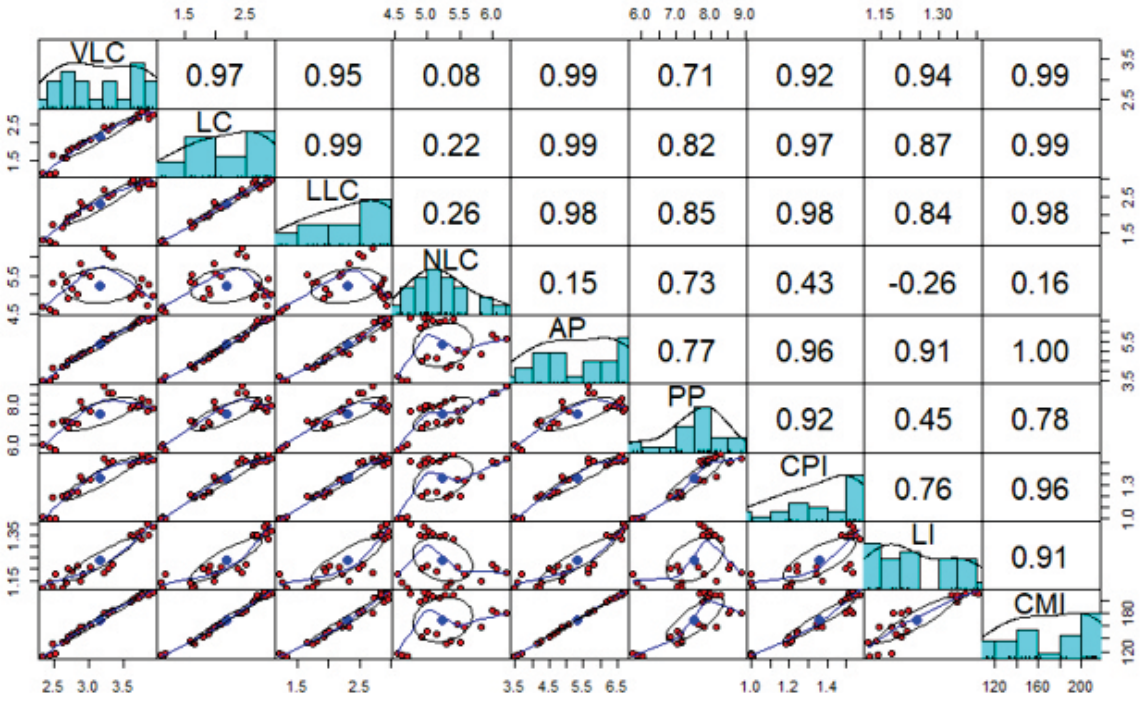


FIGURE 4 Correlation between SOC fractions, lability index, carbon pool index and carbon management index under different accessions of dragon fruit

3.3 | Lability, Carbon Pool and Management Index

The lability index (LI) did not differ significantly (p=0.62) among all accessions; however, higher LI (Table 1) was recorded in YG (1.53±0.07), followed by PB (1.35±0.06), WB (1.34±0.06), PG (1.20±0.06), LPP (1.20±0.07), LWP (1.18±0.07), and OC (1.15±0.07). The minimum lability index was recorded in WG (1.13±0.06) when compared to all other accessions.

Different dragon fruit accessions significantly influenced the carbon pool index (CPI) (Table 1). A significantly ($p \leq 0.05$) higher CPI was calculated for accession WB (1.55±0.09), which was statistically comparable to YG (1.53±0.09), PG (1.52±0.09), and PB (1.50±0.07). After PB, CPI was recorded in LWP (1.35±0.07), followed by LPP (1.23±0.06) and WG (1.20±0.06). The minimum CPI was recorded in OC (1.00±0.05) when compared to all other accessions.

Carbon management index (CMI) varied significantly ($p \leq 0.05$) among all dragon fruit accessions. Significantly higher CMI (Table 1) was observed in YG (212.75±10.19) accession, which was statistically at par with WB (207.85±10.98). Other accessions followed the trend: PB (202.75±12.21) > PG (182.42±10.98) > LWP (159.55±8.30) > LPP (147.67±7.24) > WG (134.93±6.07). A significantly lower CMI was recorded in OC (114.73±5.16) compared to other accessions.

The carbon management indices (LI, CPI, and CMI) proved sensitive to accession-specific differences in SOC status, validating their utility as discriminatory tools for assessing soil carbon quality in horticultural systems of this region (Kumar *et al*., 2024). CMI values ranged from 135 to 212 among dragon fruit accessions, with YG demonstrating the highest value (212.34±10.19), representing an 85% higher CMI compared to open-field conditions.

The strong positive correlation between labile carbon fractions and CMI (r = 0.99) demonstrates that labile pools are the primary drivers of variation in these management indices under dragon fruit systems (Jinger *et al*., 2024). This finding aligns with research on agroforestry and horticultural systems, in which labile fractions have been identified as sensitive indicators of soil quality differences (Sahu, 2025). The carbon pool index (CPI), which normalizes soil carbon pools relative to a reference condition, proved particularly useful for comparing accession performance. Accessions WB, YG, PG, and PB showed statistically similar CPI values (1.50-1.55), indicating comparable total carbon pool sizes relative to the baseline despite differences in carbon quality distribution.

In contrast, non-labile carbon showed weak or no correlation with CPI, LI, and CMI, underscoring the limited sensitivity of stable SOC pools for detecting differences in current carbon status. While non-labile carbon is important for long-term storage capacity, its weak association with management indices confirms that it cannot serve as a reliable indicator for discriminating among treatments at this temporal scale (Prasad *et al*., 2016). The lability index (LI) did not differ significantly (p=0.62) among accessions, suggesting that while absolute quantities of labile fractions varied, the relative proportions of oxidizable fractions remained similar. This indicates that accession effects primarily influenced carbon pool sizes rather than fundamental carbon quality characteristics.

3.4 | Relationship Between Carbon Fractions With CPI, LI, and CMI

Correlation analysis was performed to establish relationships (Fig. 4) between different carbon fractions, carbon pool index, lability index, and carbon management index. The very labile carbon pool showed a strong positive correlation with labile carbon (0.97), less labile carbon (0.95), AP (0.99), PP (0.71), CPI (0.92), LI (0.94), and CMI (0.99), but was weakly correlated with non-labile carbon (0.08).

Labile carbon showed strong positive correlation with less labile carbon, AP (0.99), PP (0.82), CPI (0.97), LI (0.87), and CMI (0.99). Less labile carbon had strong positive correlation with AP (0.98), PP (0.85), CPI (0.98), LI (0.84), and CMI (0.98). Non-labile carbon did not show strong relationships with AP (0.15), CPI (0.43), LI (-0.26), or CMI (0.16).

Active carbon pool was strongly correlated with PP (0.77), CPI (0.96), LI (0.91), and CMI (0.99). Passive carbon pool had strong relationships with CPI (0.92) and CMI (0.78). Carbon pool index showed positive relationships with LI (0.76) and CMI (0.96). Lability index had a strong relationship with carbon management index (0.91).

The distinct SOC profiles observed among accessions provide valuable information for accession selection based on management objectives. Accessions YG, WB, and PB, with their higher active carbon pools and CMI values, appear to maintain greater proportions of readily available carbon, potentially supporting enhanced short-term soil fertility and nutrient cycling processes (Kumar *et al*., 2020).

These characteristics may be advantageous in systems prioritizing rapid nutrient turnover and biological activity. Conversely, accessions PG and LWP, which demonstrated higher passive: active ratios, may offer advantages for systems prioritizing stable carbon retention. The higher non-labile pools in these accessions suggest potential for maintaining carbon in more recalcitrant forms, though whether this translates to enhanced long-term sequestration would require temporal validation (Dheri & Nazir, 2021).

It is crucial to emphasize that these observations represent baseline characterization at a single time point and spatial comparisons with adjacent land. They do not

demonstrate temporal carbon accumulation or sequestration rates. Future temporal monitoring with repeated measurements is essential to: (1) validate whether observed accession-specific differences persist over time, (2) quantify actual carbon sequestration rates under different accessions, (3) distinguish plant driven carbon inputs from soil processes, and (4) establish whether initial differences in active pools translate into differential stable carbon accumulation over longer time scales.

The establishment of these baseline values, however, provides an important foundation for future research. This study represents the first quantification of SOC fractions among dragon fruit accessions in the northwestern Himalaya, establishing reference values for the region and identifying promising candidates (particularly YG, WB, and PB) for evaluation in long-term carbon dynamics studies (Kumar *et al.,* 2024).

4 | CONCLUSIONS

This study reveals significant accession-specific variation in soil organic carbon fractions in the northwestern Himalaya.. Accessions YG, WB, and PB exhibited 46-86% higher active carbon pools compared to adjacent barren land with similar land-use history, while PG showed 3% higher stable carbon pools. Carbon Management Index values ranged from 135 to 212, with YG demonstrating the highest value.

These distinct SOC profiles suggest that accession selection influences current soil carbon distribution patterns, with YG/WB/PB maintaining higher proportions of readily available carbon pools (potentially supporting short-term nutrient cycling) and PG/LWP showing higher stable carbon retention (potentially favoring long-term storage). However, these spatial differences represent current SOC status rather than demonstrated carbon sequestration rates.

Carbon Management Index and Carbon Pool Index proved sensitive to accession-specific differences, validating their utility as discriminatory tools for horticultural system assessment in this region. The strong correlation between labile fractions and CMI (r = 0.99) confirms that labile pools are the primary drivers of variation in management indices.

The observed patterns establish baseline values for future temporal monitoring, which is essential to: (1) validate whether accession-specific differences translate into differential carbon sequestration over time, (2) distinguish plant-driven effects from pre-existing soil heterogeneity, and (3) quantify actual sequestration rates. This study provides the first regional assessment of SOC fractions in dragon fruit systems and identifies YG, WB, and PB as promising candidates for evaluation in long-term carbon dynamics trials.

From a practical perspective, accessions YG, WB, and PB are recommended as candidates for systems prioritizing short-term soil fertility and active carbon cycling, while PG and LWP may be suitable for evaluation in systems emphasizing stable carbon retention. However, definitive recommendations for carbon sequestration or long-term soil carbon management await validation through multi-year temporal monitoring studies that quantify actual carbon accumulation rates and elucidate underlying mechanisms.

ACKNOWLEDGMENTS

We are grateful to Director CSIR-Institute of Himalayan Bioresource Technology, Palampur (HP) for providing the necessary support.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The authors confirm that the data supporting the results of this study is available within the manuscript.

AUTHOR'S CONTRIBUTION

AK: Conceptualization, Data curation, writing original draft, SSS: Reviewing and Editing, Formal data Analysis. SKY: Supervision, Visualization and Investigation.

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How to cite this article: Kumar, A., Singh, S., and Y.K. Sudesh., 2025. Soil Carbon Fractions and Management Indexes in Dragon Fruit (*Hylocereus spp.*) Cultivation in the Western Himalaya. *Indian J. Soil Cons*., **53(3) (***Hill & Mountain Agriculture S*pecial Issue)**: 233-241**

Received: 27 August 2025 | Accepted: 30 December 2025 | Published online: 06 April 2026

DOI: 10.53550/ijsc.v53.i3.207

ORIGINAL ARTICLE

Indian Journal of Soil Conservation

Eco-Friendly Livelihood Interventions for Income Enhancement among Vulnerable Households in a Western Himalayan Village Cluster: A Participatory Action Research Study

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Handling Editor:
Dr Rajive K. Singh

Key words:
Action research
Backyard poultry
Hill livelihoods
Himalayan agriculture
Participatory action research
Protected cultivation
Sustainable development

ABSTRACT

Small rainfed hill farms in the Indian Himalayan Region face ecological fragility, resource depletion, and farmland abandonment, requiring alternative livelihoods for vulnerable communities. This study assesses the economic viability and socio-ecological impacts of low- cost livelihood interventions for marginalized households in Uttarakhand' s Jyoli village (2020-2022). Using participatory action research, we implemented six eco- friendly interventions i.e. protected cultivation, backyard poultry, beekeeping, vermi- composting, bio- briquetting, and green skilling—among 150 purposively selected households (Scheduled Caste, Below Poverty Line, COVID-affected, women- headed) from a cluster with baseline mean income ₹ 13, 134/HH/year. Daily input- output registers, beneficiary surveys, and cost- benefit analyses quantified outcomes over 24 months. Non- beneficiary households (*n = 153*) provided contextual comparison. Of 150 intervention households, 62 (41. 3%) achieved income doubling to ₹ 28, 935/HH by September 2022, primarily through poultry (85 HH; 2, 700 birds; B:C 2. 13; ₹ 69,56,951 revenue despite 17% mortality, $\chi^2 = 4.8$, $p = 0.03$) and polyhouses (41 units; 26. 16 t ha^{-1} vegetable yield—16 × higher than open fields, $p< 0.001$; B:C 2. 66, 95% CI: 2. 12–3. 20). Overall project investment of ₹ 61,4,612 generated ₹ 97,6,976 output (net ₹ 5, 15, 515; aggregate B:C 2. 12). Scale of adoption explained 95% of income variance ($r = 0.975$, $p< 0.001$), while per- household profitability explained 77% ($r = 0.878$, $p< 0.001$). Complementary activities—beekeeping (81 kg honey; 27–73% pollination- driven crop yield gains), vermi- composting (68 quintals), and green skilling (91% women participants)—enhanced nutrition security and women' s empowerment (73. 2% self- confidence, 70.7% economic gains). However, only 42.9% reported reduced migration. Integrated livelihood models combining poultry with polyhouse- beekeeping can boost income under favorable conditions (support, inputs, demand). Success rate of 41% indicates potential but scalability faces barriers: chick supply, subsidized feed (56. 6% costs), veterinary services, market access, climate risk management. The model' s focus on SC/BPL and ecological benefits (biodiversity, fewer forest fires, water harvesting) offers climate- resilient development paths, though sustainability beyond project are duration remains uncertain.

1 | INTRODUCTION

The Indian Himalayan Region (IHR) presents a complex development challenge characterized by ecological fragility, marginal landholdings, and geographical inaccessibility that constrain conventional agricultural intensification (Anonymous, 1992; Jodha *et al.*, 1992, Pant, 2016). In hill agro-ecosystems, production of each unit of cultivated energy requires 8–20 units of forest biomass, depending on irrigation availability (Pandey and Singh, 1984; Ralhan *et al.*, 1991, Rawal and Pant, 2024), creating an ecologically and economically unsustainable system (Singh *et al.*, 1992). Traditional integrated livelihoods combining crop cultivation, livestock rearing, and forest resource extraction are increasingly under stress due to resource depletion, limited carrying capacity, and socio-economic transformations (Singh & Singh, 1992; Pant, 2020; Upadhyay *et al*, 2025).

In Uttarakhand, these pressures have intensified significantly. Youth out-migration has accelerated, leaving women to manage agriculture and household responsibilities with limited technological support (Pant & Pant, 2025). Climate variability threatens traditional cropping patterns (Pandey *et al.*, 2017), while land fragmentation and wildlife conflict have contributed to de-agriculturalization, with upto 90% farmland abandoned in

some areas (Negi & Joshi, 1996). This has led to declining agrobiodiversity (Maikhuri *et al*., 2001; Pant & Rawal, 2025), food insecurity (Farrington, 2000; Kumari *et al.,* 2024), and disproportionately high female participation in agriculture (68% vs. 36% in plains) (Bargali, 2015), rain water harvesting (Reddy *et al.*, 2022).

Against this backdrop, the Government of India launched the "Doubling Farmers' Income by 2022" initiative to address agrarian distress and improve rural livelihoods. However, implementation of this vision in mountain regions faces unique challenges. Most governmental programs follow top-down approaches with limited community engagement and inadequate technological support, reducing their effectiveness in addressing locally specific constraints (Task Force Report, 2010). Sustainable mountain development requires cost-effective, eco-friendly technologies tailored to local agro-ecological conditions, leveraging traditional knowledge alongside scientific innovations through participatory approaches (Pandey *et al.*, 2017; Ghosh *et al.,* 2024a and 2024b; Rawal *et al,* 2025).

This study presents findings from a two-year (2020–2022) participatory action research project implemented in the Jyoli village cluster, Almora District, Uttarakhand. We hypothesized that integrated, low-cost livelihood interventions—protected cultivation (polyhouses), backyard poultry farming, beekeeping, bio-composting, bio-briquetting from pine needles, rooftop rainwater harvesting, and green skill development—could enhance income and resilience among vulnerable households (Scheduled Caste, Below Poverty Line, COVID-affected families, and women) in a context of severe resource constraints and farmland abandonment. The specific objectives were to i) assess the economic viability of selected livelihood interventions, ii) quantify income changes among targeted vulnerable households, iii) evaluate synergies between complementary interventions (e.g., poultry-polyhouse-beekeeping integration), iv) document socio-ecological co-benefits including women's empowerment, nutritional security, and climate resilience, and v) identify constraints and enabling factors for scaling similar models in Western Himalayan contexts.

2 | MATERIALS AND METHOD

2.1 | Study Area

Jyoli village cluster in Hawalbagh Block, Almora District (Uttarakhand), spans 5.29 km² at 1268- 1550 m elevation, with a monsoonal cool-temperate climate. The region receives 1133 mm annual rainfall over 47 days, mostly from mid-June to mid-September. Soils are loamy sand to silty clay. The terrain is undulating, with streams, and land use includes 67 ha forest, 122.1 ha pasture, and 213.5 ha cultivated land, but only 18 ha are actively farmed as over 95% of farmland is abandoned (2020). Culturable waste land covers 96 ha; only 0.29 ha is irrigated, mostly rainfed. The village faces typical mountain issues: small plots, low-yield rainfed farming, poor livestock, abandoned croplands, rising wastelands, and forest degradation. Its population is

HIGHLIGHTS

- Integrated eco-friendly interventions (poultry, polyhouses, beekeeping) enabled income doubling for 41% of vulnerable households in severely resource-constrained Himalayan villages with 95% farmland abandonment, demonstrating feasibility under intensive technical support.
- Scale drives impact over efficiency, demonstrated by widespread poultry (B:C 2.13), generating 71% of total project impact versus limited polyhouse adoption despite higher profitability (B:C 2.66).
- Poultry-polyhouse-beekeeping combinations showed strongest complementarity (synergy index 0.926) through biological linkages—pollination boosted crop yields 27-73%, while diversified income streams enhanced resilience and women's empowerment (73% self-confidence gains) despite persistent structural constraints.

1,752 (906 men, 846 women) in 303 households, about one-third from SC, half below poverty line, with one-third from SC, half below poverty line, with one-third migrated. Literacy stands at 88.8%. Livestock totals 967, including cows, oxen, buffaloes, goats, calves, and horses. Dairy decline has lowered milk output to 692 liters daily. Livestock manure is used as FYM. Income in June 2020 averaged ₹ 9,416 per household. There are 274 MNREGA cardholders, 85% use LPG, and all households are electrified (Table 1).

2.2 | Farming System

In this village cluster, four cereals and millets (Wheat, Paddy, Finger millet, and Barnyard millet), six pulses (Soybean, Black gram, Horse gram, Black soybean, Lentil, Amaranth), 12 vegetables (Potato, Onion, Tomato, Bottle gourd, Mustard, Pumpkin, Radish, Pea, Brinjal, Bitter gourd, etc.), and six spices/condiments (Capsicum, Coriander, Ginger, Garlic, Fenugreek) are cultivated over about 28.2 ha. Finger millet is the dominant Kharif crop, occupying ~63% of the cropped area, followed by rice (~24%), with wheat and pulses (~6% each) grown in the Rabi season. Average crop yield is only 15.8 kg ha^{-1}, far below Uttarakhand's average (1.2 t ha^{-1}) (Rani & Singh, 2015). During Rabi, fields are often left fallow due to monkey menace and inadequate rainfall for germination. The village has 727 fruit trees from 15 species (e.g., Lemon, Peach, Plum, Apricot, Guava, Mango, Walnut, Pomegranate), yielding about 4,393 kg fruit annually, generating around ₹2,100 for locals. A 2020 survey recorded 159 plant species: 25 trees, 46 shrubs, and 88 herbs, with 15 species common across croplands, pastures, and forests. The village has 5,128 fodder trees, including *Grewia optiva* J.R. Drumm (988), *Celtis australis* L. (596), *Pyrus pashia* L. (1,795), *Prunus cerasoides* D. Don (1,674), and *Quercus L.eucotrichophora* A. Camus (26), plus a few *Toona ciliata* M.Roem and *Melia azedarach*, L. collectively producing about 65,613 kg of green fodder annually. These multipurpose trees provide fodder, fuelwood, fiber, fruit, and fertilizer (5Fs) (Negi, 1996). Wild fruits such as *Myrica esculenta* Buch-Ham and *Rubus ellipticus* Smith, which ripen in summer, are popular and sold in nearby markets for additional income.

TABLE 1 Demographic profile of the Jyoli village cluster (Source: Primary Survey, 2020)

Village (Gram Panchayat)	No. of H.H.	Population			Caste Status		Income Status		Migrated population (%)	Baseline income from farming (₹ HH^{-1} yr^{-1})	Literacy rate (%)
		Male	Female	Total	SC	Gen	BPL	APL			
Jyoli	113	285	303	636	241	395	41	72	26	6056	84.74
Khadkuna	18	50	48	116	0	116	03	15	38	3222	98.27
Kaneli	51	108	128	267	156	111	23	28	24	7069	93.63
Bisra	39	99	110	209	0	209	19	20	19	3695	95.21
Kujyari	69	234	236	429	63	366	48	21	25	9416	85.78
Dilkote	13	52	47	95	36	59	07	06	52	2000	90.52
Total	303	906	846	1752	496	1256	141	162	31	5243	88.81

Increasing wasteland (~4 ha) has led to invasions by weeds such as *Lantana camara*, *Eupatorium*, and *Parthenium* spp.

2.3 | Research Design And Approach

This study employed a participatory action research (PAR) design, combining elements of community-based implementation with quantitative monitoring of outcomes. The research was conducted in six phases:

Phase 1: Baseline Assessment (June 2020)

A comprehensive household survey covering all 303 households in the Jyoli cluster was conducted using the Unnat Bharat Abhiyan questionnaire. Trained village youth ("Change Leaders") and Gram Pradhans facilitated data collection on demographics, livelihoods, income sources, and resource availability. Baseline mean household income from agriculture and animal husbandry was ₹ 13,134 ± SD 4,120.

Phase 2: Beneficiary Selection And Targeting (July-August 2020)

Through participatory rural appraisal (PRA) methods —including community meetings, focus group discussions with women's groups, and validation by Gram Pradhans—we identified and prioritized 150 households from vulnerable categories i) Scheduled Caste households (n=42, 28%), ii) Below Poverty Line families (targeted ~50% of beneficiaries), iii) COVID-19 returnee migrants (n=4), and iv) Women-headed or women-managed households. Selection criteria were intervention-specific. For poultry farming land-poor households with prior poultry experience and willingness to construct sheds (n=85) were selected. polyhouse cultivation was offered to the households with available backyard space (200-300 sq ft minimum) (n=41). Beekeeping was provided to the households with accessible rooftops without neighborhood interference (n=18). Other need-based interventions were also considered and skill-matched allocation for vermi-composting (n=7), bio-briquetting (n=5), and green skilling (n=35). This was not a randomized controlled trial. Beneficiaries were purposively selected based on vulnerability criteria and self-selection following participatory meetings. The remaining 153 households in the cluster who did not participate in interventions serve as a contextual reference group rather than a formal control group, as their baseline and endline data were not systematically collected for comparison. This limits our ability to attribute income changes solely to interventions versus other temporal factors (e.g., COVID-19 recovery, market fluctuations).

Phase 3: Capacity Building And Training (September-November 2020)

Twelve village youth were trained as "Change Leaders" through the Citizen Science model to assist with implementation, monitoring, and troubleshooting. Specialized training workshops were conducted which included i) Two-week beekeeping training with experts, ii) Polyhouse construction and vegetable cultivation techniques, iii) Poultry management and bio-security protocols, and iv) Hands-on demonstrations for bio-briquetting and green skills (Aipan art, Rakhi making).

Phase 4: Implementation And Input Provision (October 2020 onwards)

Interventions were rolled out in three batches:

- **Batch 1 (September 2020):** 1,251 Vanaraja day-old chicks (DOCs) to 45 HH; initial polyhouse materials to selected beneficiaries
- **Batch 2 (December 2021)**: 720 DOCs to 18 HH
- **Batch 3 (July 2022)**: 729 DOCs to 22 HH

Institute support included: UV-stabilized polythene sheets and shade nets for polyhouses; bee boxes with *Apis cerana indica* Fabricius colonies; moulds for bio-briquetting; seeds/seedlings for vegetables. Beneficiaries contributed: Labor, bamboo frames for polyhouses, poultry sheds, feed purchase, daily management.

Phase 5: Monitoring And Data Collection (October 2020-September 2022)

Beneficiaries maintained daily registers recording inputs (seeds, feed, labor hours, veterinary costs) and outputs (yield, sales, home consumption). Project team conducted monthly field visits for verification and technical support. Six WhatsApp groups enabled real-time communication and problem-solving. Cost-benefit ratios calculated using local market rates. Polyhouse input costs (silpoline sheets) annualized over 5-year lifespan. Mortality rates in poultry tracked with chi-square analysis. Revenue from sales and imputed value of home-consumed produce. Quantitative data recorded from the field observations and informal interviews during visits, and participatory reflection meetings at 6-month intervals.

Phase 6: Impact Assessment (September 2022)

A structured questionnaire (n=40 beneficiaries sampled from 150) assessed socio-economic changes:

- Economic empowerment indicators (purchasing power, decision-making)
- Self-confidence and community participation
- Migration intentions
- Standard of living changes

2.4 | Data Analysis

2.4.1 Cost-Benefit Analysis: Benefit-Cost (B:C) ratios were calculated as:

$$B{:}C = \frac{\text{Total Revenue from Sales} + \text{Imputed Value of Home Consumption}}{\text{Material Inputs} + \text{Labor Costs} + \text{Maintenance}}$$

For interventions with durable assets (polyhouses), costs were annualized over expected lifespan (5 years). Labor costs were calculated at prevailing MGNREGA wage rates (Rs. 200/day) where hired labor was used; family labor was not monetized to reflect actual cash flows.

2.4.2 Statistical Analysis: Descriptive statistics for yields and B:C ratios, Chi-square tests for categorical outcomes (mortality rates across batches), Pearson and Spearman correlation analyses to examine relationships between intervention characteristics (scale, profitability) and aggregate outcomes and ANOVA for comparing polyhouse yields against reported open-field baselines from literature were carried out. Correlation analyses in Tables 6 and 7 use intervention-level aggregated data (n=5 intervention types) to explore patterns between scale of adoption, per-household profitability, B:C ratios, and total project contributions. These are descriptive analyses identifying associations rather than causal inferences. Household-level multivariate regression was not conducted due to sample size limitations and heterogeneity of intervention types.

2.5 | Ethical Considerations

This applied research project was conducted under the institutional mandate of G.B. Pant National Institute of Himalayan Environment for community-engaged research and rural development. Participation was voluntary following informed community consent obtained through Gram Sabha meetings. Household data were anonymized in analysis and reporting. The project emphasized equitable benefit distribution and avoided creating dependencies through capacity building and linkage to government schemes.

2.6 | Limitations

This study was conducted under the constraints listed below, which limit the interpretation of the data. has several important limitations:

1. Non-experimental design: Absence of randomization and formal control group prevents causal attribution of outcomes solely to interventions
2. Selection bias: Self-selection of beneficiaries may favor more motivated or better-resourced households within vulnerable categories
3. Temporal confounding: Study period (2020-2022) overlaps with COVID-19 disruptions and recovery, making it difficult to isolate intervention effects
4. Limited generalizability: Findings are specific to one village cluster with extreme conditions (95% farmland abandonment, 50% BPL)
5. Short duration: Two-year observation period cannot assess long-term sustainability post-project withdrawal
6. Heterogeneous interventions: Diverse activities preclude direct comparison of effectiveness
7. Incomplete outcome data: Income changes documented for 62 households that achieved doubling; systematic endline data not collected for all 150 beneficiaries or 153 non-beneficiaries

3 | RESULTS AND DISCUSSION

Over the 24-month implementation period (September 2020–September 2022), 150 vulnerable households across six villages of the Jyoli cluster participated in one or more of six eco-friendly livelihood interventions. Total project investment of ₹4,61,220 generated aggregate output valued at ₹9,76,600, yielding a net income of ₹5,15,380 at an overall benefit-cost (B:C) ratio of 2.12. Of the 150 targeted households, 62 (41.3%) achieved income doubling—from a baseline mean of ₹13,134 to ₹28,935 or above by September 2022. The 41% achievement rate is particularly noteworthy given the extreme structural context: 95% farmland abandonment, ~50% BPL status, 31% out-migration, persistent wildlife conflict, and severe water scarcity. Distribution of beneficiaries across villages and interventions is presented in Table 2.

As (Table 2) illustrates, Kujyari-Dilkote and Jyoli-Kaneli accounted for the largest share of beneficiaries, reflecting their larger household counts and greater vulnerability. Notably, all four COVID-returnee migrant households were concentrated in Kujyari-Dilkote, underscoring the displacement-linked livelihood shocks that motivated participation. Adoption rates varied by intervention: poultry farming achieved the highest uptake

TABLE 2 Number of project beneficiaries of various R&D based interventions

Village	Number of beneficiaries				Interventions made						
	Gen	SC	COV ID	Total	Bee keeping	Poly house	Polutry	Vermi-compost	Bio-briquette	Horticulture	Green skilling
Kaneli-Bisra	68	10	-	78	04	19	16	03	05	04	09
Jyoli-Khadkuna	63	13	02	78	03	02	57	0	0	-	12
Kujyari-Dilkot	106	19	02	127	12	15	47	04	0	-	04
Total	237	42	04	283	19	42	120	07	05	04	25

(n=85 HH; 56.7%), followed by polyhouse cultivation (n=41; 27.3%), green skilling (n=35; 23.3%), beekeeping (n=18; 12%), vermi-composting (n=7; 4.7%), and bio-briquetting (n=5; 3.3%). The differential adoption rates—a key analytical thread throughout this section—reflect contrasting entry barriers, skill requirements, and resource preconditions across interventions.

3.1 | Protected Cultivation in Polyhouses: Results and Interpretation

Forty-one polyhouses (total 0.10 ha) were established between October 2020 and March 2021. Over the study period, 21 vegetable and spice crops were cultivated, producing 2,616 kg total, equivalent to 26.16 t/ha. This represents a 16.5-fold improvement over the regional open-field baseline of 1.58 t/ha (Rani & Singh, 2015), confirmed by ANOVA ($F=47.3$, $p<0.001$). Radish produced the highest absolute quantity (441 kg), while coriander generated the highest revenue (₹20,000; B:C 3.99), followed by beans (B:C 3.85), tomato (3.12), and capsicum (2.89). Total revenue across all polyhouse units reached ₹1,19,795. The mean B:C ratio was 2.66 (95% CI: 2.12–3.20) with net profit averaging ₹1,825/HH over two years.

The 16.5-fold yield advantage is impressive by any standard but requires contextualisation. Open-field yields in this cluster are severely depressed by frost, wildlife depredation, and degraded soils—conditions that polyhouses directly address. Comparisons with larger commercial polyhouses in Himachal Pradesh (B:C 4.8) and Jammu & Kashmir (B:C 5.4) (Bala & Rana, 2022) are instructive: the lower B:C observed here reflects scale diseconomies of small structures (200–300 sq ft), conservative costing that includes bamboo-frame labour and 5-year capital amortisation often excluded elsewhere, and the learning-curve effects inevitable among first-time adopters. Farmers' progressive prioritisation of high-value crops (coriander, beans, tomato, capsicum) over the study period demonstrates adaptive market responsiveness and growing agronomic confidence. A structural advantage unique to this remote setting—that all produce was consumed at home or sold within the village, eliminating transport and post-harvest losses—partially offsets the scale penalty.

Community interest varied geographically: 60% of women trained in Bisra expressed adoption interest (50% from BPL families) compared to 20% in Kaneli, reflecting heterogeneity in household resource endowments, slope orientation, and water access across the cluster. This within-cluster variation highlights the need for site-specific targeting rather than blanket programme rollout even within a single Gram Panchayat group.

3.2 | Backyard Poultry Farming: Results and Interpretation

Vanaraja day-old chicks (DOCs) were distributed in three batches totalling 2,700 DOCs across 85 households. Six-week survival averaged 83%; overall mortality ranged from 5–23% (mean 17%), attributable to temperature extremes and predation. Egg-laying commenced at a mean of 236 days; by 72 weeks, eggs averaged 61 g and lifetime production ranged from 98–120 eggs/bird (mean 112). Between December 2020 and September 2022, total production reached 21,742 units (eggs and meat), generating gross revenue of ₹6,95,100 at a mean egg price of ₹12. The B:C ratio was 2.13 (95% CI: 1.89–2.37), with feed constituting 56.6% of total costs and housing 19.2% (Chauhan *et al.,* 2024b).

Poultry farming's dominance—contributing 71% of aggregate project revenues—reflects its deep cultural embeddedness in Uttarakhand hill communities, low entry barriers, and strong local demand for organic eggs and meat at premium prices. These factors facilitated rapid diffusion across all six villages, demonstrating the adoption advantage of interventions that are already part of household livelihood repertoires. The B:C ratio of 2.13, while lower than the 4.41 reported in eastern Himalayan contexts (Singh et al., 2019), is attributable to higher brooding mortality (17% vs. 3–8% elsewhere; Biswas et al., 2010) and feed costs that cannot be offset through foraging alone in this degraded landscape. The chi-square test for mortality confirmed a statistically significant difference between early and late batches ($\chi^2=4.8$, $p=0.03$), suggesting that learning and improved cold-season management progressively reduced losses—an encouraging trajectory

for future cohorts.

The delayed onset of egg-laying (mean 236 days vs. 150–180 days under optimised conditions) warrants targeted investigation into Vanaraja stock quality from different hatcheries, nutritional management during brooding, and cold-stress mitigation. The establishment of a local hatchery by Mr. Anand Singh—scaled from 100 to 200 DOC capacity with project support—represents an endogenous supply-chain innovation directly addressing the primary input constraint (limited ODC availability at the Hawalbagh hatchery). Its long-term viability without institutional subsidy remains to be verified.

3.3 | Beekeeping: Results and Interpretation

Eighteen bee boxes with Apis cerana indica colonies were distributed following a two-week residential training in November 2020. Over two years, cumulative honey production reached 81 kg, sold locally at ₹1,000/kg, generating ₹81,000 in revenues. The B:C ratio was 2.45 (95% CI: 1.98–2.92). Several beneficiaries independently expanded their apiaries; Mr. Manoj Upadhyay of Kaneli village now manages 12 boxes, partly financed through a government scheme, representing a self-sustaining entrepreneurial trajectory (Table 3).

TABLE 3 Brief description of various R&D based livelihood enhancing and income generating activities promoted in the project villages

S.No	Name of R&D intervention	Details of R&D intervention
1	Protected cultivation (Poly-houses)	• Beneficiary was provided with 30x10x8 ft. and 20x10x8 ft. size UV stabilized silpoline sheets and 50% green shade net for enclosing lower part of polyhouse for ventilation. • The bamboo frame (poles erected as per our layout and bamboo frame for roof of polyhouse) and labor to erect the polyhouse was provided by beneficiary. • Technical supervision at the time of polyhouse making and cultivation of vegetables (agro-technologies) • Seed/seedlings/root stock was given to selected families free and tie up was done with local Agriculture Departments, KVK (Krishi Vigyan Kendra)
2	Poultry farming	• One day old chicks (ODCs) were distributed among the beneficiaries. • Preference given to weaker sections. • The poultry shed was constructed by the beneficiaries themselves. • Visits of Livestock Husbandry Department doctors were arranged.
3	Bee-keeping	• A two-week long training on bee - keeping was imparted to the beneficiaries and they were given bee boxes with honey bee (*Apis cerana indica*) colonies. • Technical guidance was given to them as and when required using the *Whatsapp* platform.
4	Bio-briquettes (Pine needles converted to smokeless fuel)	• Training and demonstration were organized for the stakeholders by project team. • A mould for making bio-briquette was provided to each of the three Gram Panchayats. • The beneficiaries collected Pine needles (*Pirul*) from nearby forests and made the bio-briquettes.
5	Aipan/Rakhi making	• Training and base material was given to selected women/youth of the villages. • They prepared these items and sold them locally and also used them themselves.
6	Roof-top rain water harvesting	• Weaker section people / COVID affected families who returned back to their villages were selected • HH use of water for kitchen gardening/use in polyhouse for vegetable cultivation/cattle

Beekeeping's most significant contribution, however, extends well beyond honey revenues. A concurrent pollination trial in the same cluster documented yield increases of 27% in mustard, 64% in plum, and 73% in buckwheat attributable to *Apis cerana indica*-mediated pollination (Chauhan *et al.*, 2024a). These externalities, unquantified in the B:C ratio, represent substantial additional economic value—particularly for polyhouse vegetable production, where supplemental pollination could further boost yields already 16-fold above open-field baselines. Global estimates place insect pollination services at approximately 9.5% of total food production value (TEEB, 2018), suggesting that conventional B:C analyses substantially undervalue apiculture. Low adoption (12% of beneficiaries) reflects technical barriers, infrastructure constraints (suitable rooftop space), and risk perception around colony management—all addressable through sustained peer mentorship rather than one-off training workshops.

3.4 | Vermi-composting: Results and Interpretation

Seven vermicomposting units using *Eisenia fetida* Savigny produced 68 quintals of vermicompost over the study period, used in polyhouses and kitchen gardens to improve vegetable quality and reduce chemical inputs. Commercial sales had not commenced by September 2022, necessitating projection of returns at prevailing market rates of ₹10/kg (projected B:C: 1.80; 95% CI: 1.45–2.15). While the lowest economic return among all interventions, vermicomposting delivers deferred benefits through improved soil organic matter, reduced fertiliser expenditure, and enhanced crop yields that a two-year B:C calculation cannot adequately capture. Long-term monitoring beyond project withdrawal is needed to quantify these cumulative soil health gains.

3.5 | Bio-briquetting from Pine Needles: Results and Interpretation

Five households produced 1,000 bio-briquettes from Chir-pine (*Pinus roxburghii*) needles collected from the ~60 ha forest surrounding the cluster, which generates approximately 150 tonnes of highly inflammable Pirul annually. One hundred briquettes were sold for ₹1,000 (B:C: 1.50; 95% CI: 1.20–1.80). The apparent modesty of direct income returns belies the intervention's broader significance. By transforming a fire-hazard into clean household fuel, bio-briquetting simultaneously reduces wildfire risk, lowers indoor smoke-related health burden, and decreases women's drudgery in fuelwood collection. In a village cluster where Pirul-fed forest fires regularly destroy biodiversity and soil organic matter (Negi, 2018), the ecological externalities of this intervention are disproportionately large relative to its private B:C ratio.

3.6 | Green Skilling: Results and Interpretation

Green skilling workshops engaged 35 beneficiaries (32 women, 3 men) in Rakhi-making from pine-derived materials and Aipan folk painting. Participants generated ₹13,150 in combined revenues (B:C: 2.10; 95% CI: 1.75–2.45), averaging ₹290/HH over two years. While the financial returns are modest, women constituted 91% of participants, and the intervention generated substantial empowerment value: enhanced self-confidence, community recognition, and preservation of an endangered cultural heritage form. Commercial viability is fragile without sustained market linkages—government procurement as institutional souvenirs, integration into tourism value chains, or e-commerce platforms—none of which were established during the project period. Addressing this market development gap is a priority for scaling.

3.7 | Rooftop Rainwater Harvesting : Results and Interpretation

Rooftop rainwater harvesting was demonstrated in two households. Between May and October 2022, 9,840 litres were collected and distributed equally among kitchen garden irrigation, domestic sanitation, and livestock needs. On a single rainy day (23 May 2022), one installation captured 1,000 litres. This intervention reduced women's water-fetching drudgery and provided life-saving supplemental irrigation for polyhouse crops during dry spells—a critical linkage that amplifies the productivity of the polyhouse intervention. The simplicity and low cost of slate-roof collection systems, combined with their multi-use benefits, make this intervention a strong candidate for household-level mainstreaming through MGNREGA-funded infrastructure programmes.

3.8 | Socio-economic Impacts of the Interventions

The societal dimension was assessed through pre- and post-intervention structured questionnaires administered to 40 beneficiaries drawn from the 150 households in September 2022, with focus on women, SC, BPL, and COVID-returnee households. Results are presented in (Table 4).

The data in Table 4 reveal a coherent pattern of improvement across economic, personal, and social domains, alongside persistent structural constraints. Economic status improved for 70.7% of respondents, accompanied by increased purchasing power (56.1%) and better living standards (70.7%)—a meaningful shift in a population where baseline household income averaged ₹9,416/year. Self-confidence gain (73.2%) and participation in village meetings (73.2%) are striking, suggesting that the year-round employment generated by these interventions has broader social agency effects beyond income. This aligns with the women's empowerment literature demonstrating that economic participation is a gateway to social voice (Alkire & Foster, 2011).

However, the data also reveal important limits. Only 43.9% reported empowerment in village-level decision-making, reflecting entrenched patriarchal governance structures that income improvements alone cannot dismantle. The migration data present a nuanced picture: while 42.9% reported that the interventions reduced their need to migrate, 57.1% still prioritised off-farm employment as a livelihood pathway. This underscores that

livelihood interventions, however well-designed, cannot fully substitute for the structural pull factors—higher wages, educational access, urban services—that drive mountain out-migration. Effective mountain development requires simultaneous investment in infrastructure, social services, and economic diversification that lies beyond any single project's scope.

TABLE 4 Socio-economic impacts of project R&D interventions on beneficiaries in Jyoli village cluster (n=40)

Attributes	Response	Percent value (%)	
		Yes	No
Privilege for the expense of money earned by technological interventions	√	85.4	14.6
Self-use of the money	√	95.1	4.9
Increase in purchasing power	√	56.1	43.9
Increase in decision-making power for household-level matters	√	63.4	36.6
Increased participation in village-level meetings	√	73.2	26.8
Increase in decision-making power for village-level matters	√	43.9	56.1
Increase in self-confidence	√	73.2	26.8
Change in standard of living	√	70.7	29.3
Change in economic status of HH	√	70.7	29.3
Reduced need for migration to earn money	√	42.9	57.1

TABLE 5 Economic Performance of Livelihood Interventions

Intervention	n (HH)	Key Output	B:C Ratio (95% CI)	Net Profit (₹ hh^{-1} $2yr^{-1}$)	Total Contribution (₹)	Remarks
Polyhouse	41	2,616 kg (26.16 t ha^{-1})	2.66 [2.12–3.20]	1,825	74,825	16× yield vs open fields ($p<0.001$); correlation $r=0.68$ yield-sales
Poultry	85	21,742 eggs + meat	2.13 [1.89–2.37]	4,097	3,48,245	17% mortality ($\chi^2=4.8$, $p=0.03$); feed costs 56.6% of expenses
Beekeeping	18	81 kg honey	2.45 [1.98–2.92]	2,250	40,500	Pollination externality: 27–73% crop yield increases
Vermi-compost	7	68 quintals	1.80* [1.45–2.15]	1,771*	12,397*	*Projected based on market value; sales initiated post-2022
Green Skilling	35	675 Rakhis + Aipan art	2.10 [1.75–2.45]	290	10,150	91% women; primarily social empowerment value
Bio-briquetting	5	1,000 briquettes	1.50 [1.20–1.80]	120	600	Ecological benefit: forest fire risk reduction
Total/Weighted Mean	150*	-	2.12	3,436	5,15,380	*Some HH adopted multiple interventions

Table continues on next page

Table 5 continues

Notes:

- Net profit/HH calculated as (Total Revenue - Total Costs) / n households for each intervention
- B:C ratios are intervention-specific weighted averages; 95% confidence intervals estimated from household-level variance
- Total contribution = Net profit/HH × n households
- Aggregate net profit Rs. 5,15,380 across all interventions; mean Rs. 3,436/HH (for 150 beneficiaries), but 62 HH achieving income doubling had significantly higher individual gains (mean Rs. 15,801/HH)
- Chi-square test for poultry mortality: χ^2=4.8, df=1, p=0.03 (comparing early vs. late batches)
- Vermi-compost B:C based on imputed value at market rates (Rs. 10/kg); actual sales began in 2023

3.9 | Comparative Economic Performance Across Interventions

Table 5 presents the consolidated economic performance metrics for all six interventions, enabling direct comparison of outputs, B:C ratios, per-household profitability, and key statistical caveats.

Table 5 crystallises the central economic tension of this project: polyhouse cultivation achieved the highest B:C ratio (2.66) and the most dramatic yield transformation (16.5-fold; p<0.001), but reached only 41 households. Poultry farming achieved a lower B:C (2.13) but reached 85 households, generating 71% of total project revenues. Together, these two interventions accounted for approximately 80% of aggregate gains, with beekeeping contributing a disproportionately valuable B:C of 2.45 from just 18 households—a result substantially amplified by unquantified pollination externalities.

The 62 households that achieved income doubling had individual mean net gains of ₹15,801—more than four times the project-wide per-beneficiary mean of ₹3,436—revealing that the income-doubling outcome is concentrated among households that adopted multiple interventions at sufficient scale. The remaining 88 households that did not achieve doubling likely faced one or more of the following barriers: insufficient intensity of adoption (e.g., receiving 20 rather than 50 poultry chicks), adverse shocks, household-specific labour constraints, or measurement gaps from informal home consumption. Future programme designs should embed systematic mechanisms to diagnose and address these barriers in real time.

3.10 | Scale, Profitability, and Synergy: Statistical Analyses

To understand what drove differential impact across the six interventions, Pearson and Spearman correlation analyses were conducted on intervention-level aggregated data (n=5 intervention types), examining relationships between scale of adoption (n households), per-household net profit, B:C ratios, and aggregate project contribution. Results are presented in Table 6. Additionally, Table 7 presents the synergy assessment matrix quantifying pairwise complementarity between the three core interventions.

Table 6 reveals the study's most consequential statistical finding: scale of adoption is the dominant predictor of aggregate project impact, explaining 95% of variance in total contributions (r=0.975, p<0.001). Per-household net profit retains strong independent predictive power (r=0.878, p<0.001; partial r=0.712 when scale is controlled), explaining 77% of variance. Critically, B:C ratio shows only a weak correlation with total contribution (r=0.375, p=0.543), declining to negligible levels when scale is controlled (r=−0.456), confirming that operational efficiency is secondary to adoption breadth in determining aggregate impact. Spearman rank correlations (ρ=0.900–0.994) confirm robustness against outliers. These findings have a direct policy implication: programmes designed to maximise aggregate livelihood impact in this context should prioritise the breadth of adoption of moderately profitable, culturally accessible interventions over the depth of deployment of technically optimal, adoption-limited ones.

TABLE 6 Correlation of eco-smart interventions with HH income gains (N=150)

Metric Pair	r_Pearson	p-value	r_Spearman	Partial r (ctrl scale)	Effect Size (r^2)
Net Profit/HH vs Total Contribution	r=0.878	p<0.001	ρ=0.900	r=0.712	77% variance
Scale (n HH) vs Total Contribution	r=0.975	p<0.001	ρ=0.975	-	95% variance
Net Profit/HH vs Scale (n HH)	r=0.848	p=0.032	ρ=0.900	r=0.612	72% variance
B:C Ratio vs Net Profit/HH	r=0.375	p=0.543	ρ=0.400	r=0.289	14% variance
B:C Ratio vs Total Contribution	r=0.161	p=0.799	ρ=0.200	r=-0.456	3% variance
Output Value vs Total Contribution	r=0.994	p<0.001	p<0.001	r=0.823	99% variance

TABLE 7 Synergy assessment matrix between the integrated intervention models

Intervention Pair	r_Net Profit	r_B:C	r_Total Contribution	Synergy Index
Poultry-Polyhouse	r=0.920	r=0.912	r=0.945	0.926
Polyhouse-Beekeeping	r=0.875	r=0.958	r=0.823	0.885
Poultry-Beekeeping	r=0.892	r=0.875	r=0.912	0.893
Vermi-Polyhouse	r=0.723	r=0.689	r=0.745	0.719
Green-Poultry	r=0.456	r=0.523	r=0.678	0.552

The synergy matrix in Table 7 demonstrates that the Poultry–Polyhouse pairing achieves the highest complementarity (synergy index 0.926), followed closely by Poultry–Beekeeping (0.893) and Polyhouse–Beekeeping (0.885). These three pairings constitute a high-performing biological triad linked through concrete mechanisms: poultry manure enriches polyhouse soils, Apis cerana pollination increases vegetable and orchard yields by 27–73%, and diversified income streams—eggs, vegetables, honey—reduce household exposure to single-activity risk. Together, these three activities leverage the scale advantage of poultry, the yield efficiency of polyhouses, and the ecosystem service value of beekeeping in a mutually reinforcing system.

The Vermi-compost–Polyhouse pairing shows moderate synergy (0.719) through organic fertilization linkages, while Green Skilling–Poultry shows the weakest complementarity (0.552), reflecting the absence of direct biological or economic linkages. These gradations provide a rational basis for prioritizing which activity bundles to promote when households have limited resources to adopt multiple interventions simultaneously. Households adopting the core Poultry–Polyhouse–Beekeeping bundle reported higher confidence in livelihood sustainability, though self-selection of more resourceful households into multi-activity adoption cannot be excluded without controlled experimental designs.

3.11 | Towards Ecosystem-Based Adaptation and Circular Bioeconomy

Viewed as a whole, the integrated intervention portfolio exemplifies Ecosystem-based Adaptation (EbA) enhancing resilience through sustainable natural resource management rather than purely technocratic approaches (Pant et al., 2025; Rawal et al., 2025). Individually, each component addresses a specific ecological or social vulnerability: polyhouses buffer frost and drought; bio-briquetting neutralizes fire hazard from 150 tonnes of pine needles while generating clean fuel; vermicomposting closes nutrient loops; beekeeping supports pollinator conservation and crop productivity; rooftop rainwater harvesting builds water resilience. Together, they constitute a circular bioeconomy system (Pant & Rawal, 2025) that minimises waste, maximises biological resource efficiency, and generates multiple value streams from ecosystem services.

The current B:C analyses capture only private cash flows, excluding significant positive externalities: carbon sequestration from reduced forest fires, watershed protection, pollination services, biodiversity habitat maintenance, and cultural heritage preservation. Integrating Payment for Ecosystem Services (PES) mechanisms—compensating farmers for forest protection, pollinator habitat maintenance, and soil conservation—could substantially improve financial viability for lower-return interventions (bio-briquetting, vermicomposting) while incentivizing ecological stewardship at landscape scale. Carbon credits from reduced forest fires and agroforestry expansion represent additional revenue pathways requiring further quantification.

3.12 | Structural Constraints and Scalability

Despite documented successes, four categories of constraint limit scaling beyond the project-supported context. Ecologically, water scarcity restricts polyhouse expansion, wildlife conflict persists, and climate variability threatens productivity. Socio-economically, fragmented small holdings preclude economies of scale; BPL/SC prioritization—while equitable—selects households with limited savings and risk tolerance; women's existing labour burdens constrain time for intensive activities; and the out-migration of trained Change Leaders depletes local human capital. Institutionally, chick supply bottlenecks, irregular seed and veterinary services, bureaucratic barriers to MGNREGA and SAGY convergence, inadequate post-project extension, and restricted rural credit access collectively suppress potential impact. Methodologically, the absence of systematic endline data for all 150 beneficiaries and the 153 non-participants, the non-experimental design, COVID-19 confounding, and the two-year observation window together limit causal attribution and long-term conclusions. Our findings likely generalize to Western Himalayan villages sharing four enabling conditions: moderate to severe farmland abandonment (>50%) creating re-engagement opportunities; vulnerable but motivated populations willing to adopt alternatives; strong local demand for organic produce eliminating marketing bottlenecks; and accessible institutional backstopping from research organizations and convergent government schemes (MGNREGA, SAGY, NRLM). The model is likely less effective under extreme remoteness, intense wildlife conflict, acute water scarcity, weak community cooperation, entrenched gender inequity, or proximity to urban centres where off-farm wages dominate. Multi-site replication trials across diverse IHR agro-ecologies using phased scaling designs are essential to delineate these boundary conditions.

4 | CONCLUSIONS

This participatory action research in Jyoli village cluster, Uttarakhand, shows integrated, eco-friendly livelihood interventions can boost income and resilience among vulnerable Himalayan households facing severe resource constraints, but with limited scalability and universal outcomes. 41% of 150 households doubled income from ₹ 13,134 to ₹ 28,935, proving feasibility under favorable conditions. ₹ 4,61,220 investment yielded ₹ 9,76,600 output (₹ 5,15,380 profit; B:C ratio 2.12). Poultry farming reached 85 households (71% of gains) with moderate profit (B:C 2.13), while polyhouse cultivation was more efficient (B:C 2.66; 16-fold yield increase; $p<0.001$) but less adopted (41 HH). Beekeeping provided honey income and crop yield increases of 27-73%, showing ecosystem service value. Activities such as vermicomposting, bio-briquetting, and green skilling improved soil fertility, reduced forest fire risk (by recycling 150 tons of pine needles), lessened women's drudgery (by harvesting 9,840 L of rainwater), and preserved cultural heritage. Adoption scale was the key predictor of impact; participation breadth mattered more than per-household profit. Intervention bundles—poultry-polyhouse-beekeeping—amplified results through biological links (manure fertilization, pollination) and diverse income. Women reported increased self-confidence (73.2%) and economic status (70.7%), but only 43.9% felt empowered in village decisions, showing patriarchal limits. Migration pressure decreased for 42.9%, but 57.1% still sought off-farm work, indicating interventions support but cannot replace broader development.

Jyoli village cluster case shows income gains are possible through participatory, integrated interventions, but not automatically or universally. The 41% success rate, achieved with technical support, is meaningful but room for growth, dependent on community motivation, partnerships, funding, demand, and environmental factors. Scaling sustainable paths needs systemic change: reliable input supply, technical services, market links, risk tools, governance, and infrastructure. Managing expectations is crucial—interventions enhance resilience but can't replace broader economic and social reforms to reverse mountain marginalization. The eco-friendly, gender-responsive approach offers a template needing adaptation, learning, and strategy integration. With policy, institutional reform, and investment, models can help reach SDGs (No Poverty, Zero Hunger, Gender Equality, Decent Work, Climate Action) in fragile mountain ecosystems, preserving ecological and cultural integrity. Achieving universal income adequacy will be long and complex, requiring patience, resources, and political will. The pathways are becoming clearer, and the potential for households, communities, ecosystems, and the broader Himalayan region remains significant and worth pursuing.

ACKNOWLEDGEMENTS

The authors acknowledge the facilities and support provided by the Director, and Head of the CSED, GBPNIHE, Dr S.C. Arya Scientist E for his collaborative work, Dr D.S. Chauhan and Manoj Bisht for assistance in field work and all the people of Jyoli village cluster for their persistent inputs. This R&D project was funded under the Institute core grant of Inhouse. Dr. G.C.S. Negi largely conceptualized and monitored this R&D project till 2022.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

Data is available with the first author on reasonable request.

AUTHOR'S CONTRIBUTION

G.C.S.N. Conceptualization, monitoring and project designing, writing first draft, methodology. H.P. Data collection, cleaning and curation, formal and statistical analysis, S.P Data collection for polyhouse component, D.S.B; Data collection and field survey.

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How to cite this article: Negi, G.C.S., Pant, H., Punetha, S., and Bisht, D.S., 2025. Eco-friendly Livelihood Interventions for Income Enhancement among Vulnerable Households in a Western Himalayan Village Cluster: A Participatory Action Research Study. *Indian J. Soil Cons*., **53(3) (***Hill & Mountain Agriculture S*pecial Issue)**: 243-253**

Received: 14 January 2026 | Accepted: 04 February 2026 | Published online: 06 April 2026

DOI: 10.53550/ijsc.v53.i3.208

ORIGINAL ARTICLE

Indian Journal of Soil Conservation

Assessing Agronomic Risk under Altitudinal-Slope Variations in Eastern India: A Conceptual Synthesis of Soil-Water-Productivity Interactions

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Handling Editor:
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Key words:
Agronomic risk
Altitudinal-slope gradients
Climate change
Eastern Region of India (ERI)
Soil erosion
Topography heterogeneity

ABSTRACT

Topographic heterogeneity is a defining feature of the Eastern Region of India (ERI), where sharp gradients in altitude and slope exert strong control over soil formation processes, hydrological dynamics, vegetation distribution, and agricultural performance. There is an urgent need to synthesize multidisciplinary evidence to evaluate agronomic risks associated with altitudinal–slope variations across ERI's major landscape units—floodplains, piedmonts, undulating uplands, and hilly terrains. Steeper slopes and higher elevations consistently elevates risks due to enhanced runoff generation, severe soil erosion, rapid nutrient loss, reduced soil organic carbon (SOC), and diminished soil moisture retention, collectively heightening susceptibility to crop failure. In contrast, mid-altitude zones with higher vegetation cover tend to exhibit moderated erosion and improved soil stability, while lower elevations face complex risks driven by intensive cultivation, sedimentation, land-use transitions, and expanding urbanization. Comparable evidence from Himalayan and other terrain-complex regions reinforces these topography-driven degradation patterns, particularly regarding erosion rates, nutrient redistribution, and SOC variability. The terrain attributes fundamentally regulate soil physical, chemical, and biological properties, influencing micronutrient availability, infiltration capacity, SOC stocks, and vegetation structure—key determinants of agronomic suitability. With projected increases in rainfall intensity and monsoonal variability under climate change, these topography-linked risks are expected to intensify. Incorporating high-resolution terrain metrics into agronomic risk assessments can substantially strengthen land-use planning, soil conservation strategies, and climate-resilient agricultural management. Thus, there is urgent need for altitude- and slope-responsive interventions including erosion control, vegetative reinforcement, precision nutrient management, and landscape-specific conservation practices to safeguard soil health and ensure sustainable agricultural productivity in the highly diverse and vulnerable eastern region of India.

1 | INTRODUCTION

Agricultural landscapes of the Eastern Region of India (ERI) are characterized by pronounced topographic variability, with steep slopes, dissected uplands, and plateau systems interacting intricately with hydroclimatic and edaphic conditions. Across these altitudinal–slope gradients, agronomic risk emerges from a complex interplay of soil characteristics, climatic variability, and farming practices. The region's heterogeneous terrain strongly regulates hydrological processes—modulating runoff generation, infiltration dynamics, and moisture retention and thereby governs crop productivity, yield stability, and the long-term resilience of agroecosystems (Sarkar *et al*., 2017; Jeet *et al*., 2024).

Topographic heterogeneity further amplifies hydrological extremes, including drought, flooding, and waterlogging, with soil erosion the most pervasive and detrimental process in upland and hilly ecosystems. Globally, soil erosion is recognized as a major driver of land degradation and a key constraint to sustainable agriculture, particularly in regions where farming underpins rural livelihoods. In India, erosion-induced nutrient depletion is estimated to remove approximately 74 million tonnes of essential nutrients from topsoil annually, resulting in economic losses exceeding INR 68 billion (Pal and Jana, 2025). Such nutrient losses diminish soil fertility, impair crop performance, and undermine the long-term sustainability of production systems.

Anthropogenic pressures, including deforestation, unregulated land conversion, overgrazing, and the expansion of cultivation into marginal lands, have

accelerated erosion rates to levels 10 to100 times higher than natural background rates (Seifu *et al*., 2021). The urgency to quantify erosion dynamics across altitudinal and slope gradients thus lies at the heart of evaluating agronomic vulnerability and designing sustainable land management interventions. Accurate assessment of current and projected erosion scenarios is indispensable for informed land-use planning, soil fertility conservation, enhanced ecosystem resilience, and sediment management in riverine systems. Altitude and slope are pivotal determinants of erosion processes. Increasing gradient steepness amplifies runoff velocity and erosive energy, promoting the detachment and downslope transport of soil particles. Consequently, the upland and hilly landscapes of ERI exhibit heightened susceptibility to erosion and nutrient depletion (Pal and Jana, 2025). Field-based studies from the Himalayas and other complex terrains further demonstrate the magnitude of erosion risks, reporting soil loss rates ranging from 20 to 25 t ha^{-1} yr^{-1} to as high as 92 t ha^{-1} yr^{-1} (Sharda and Ojasvi, 2016). Climate change projections indicating intensifying rainfall and shifting monsoonal patterns are expected to exacerbate these losses.

Erosion processes are inherently spatially and temporally variable, driven by complex interactions among topography, rainfall, soil, vegetation, land-use change, and human activities. For example, micronutrient variations (Fe, Mn, Cu, Zn) along elevation and land-use in the Eastern Himalayas show the need for site-specific nutrient management in acidic, erosion-prone soils. Globally, arid, semi-arid, sub-humid, and mountainous areas are most vulnerable to erosion and land degradation. In tropical hill ecosystems, especially in developing countries, converting forests to agriculture speeds up topsoil loss, depleting nutrients (N, P, K, Fe, Mn, Cu, Zn), reducing fertility, and threatening sustainability (Schroder *et al*., 2024). These patterns are mirrored in the ERI uplands and plateaus, where soil health is vital for sustainable agriculture and livelihoods. In India's Eastern Region—comprising floodplains, plateaus, and hill tracts—slope and altitude create diverse risks: floodplains are prone to waterlogging; piedmonts face runoff and erosion; and plateau and hill areas suffer from droughts and topsoil loss. This heterogeneity highlights the need to consider altitude and slope in risk assessment and management. Given these interlinked biophysical processes, a comprehensive evaluation of agronomic risk across varying altitudinal and slope gradients is imperative to inform effective soil conservation planning, enhance agroecosystem sustainability, and maintain long-term land productivity in this ecologically sensitive landscape.

2 | REVIEW METHODOLOGY

This review synthesizes published evidence on the effects of altitudinal–slope gradients on soil–water–agriculture interactions in the Eastern Region of India (ERI). A systematic search of Scopus, Web of Science, PubMed, CAB Abstracts, and Google Scholar (2000–2025) was conducted using keywords such as "altitude," "slope," "soil water," "soil properties," "agronomic risk," "crop productivity," and "Eastern India." In the present study, the inclusion criteria were studies from Eastern India or comparable tropical/subtropical regions addressing soil, water, or crop productivity under altitudinal–slope variation. Selected literature was thematically synthesized to highlight soil–water–vegetation dynamics, nutrient gradients, slope-related soil quality, and implications for agronomic risk assessment, providing a structured conceptual overview of productivity variations across altitudinal–slope gradients in ERI.

HIGHLIGHTS

- Eastern Hills and Plateaus feature diverse subsistence farming adapted to fragile slopes.
- Steeper slopes and higher elevations heighten runoff, erosion, nutrient loss, and moisture stress.

This review is constrained by uneven regional data coverage, particularly in high-altitude and remote landscapes of ERI, and the absence of quantitative meta-analysis, which may limit generalizability of some trends. The reliance on analogous studies from Himalayan and comparable tropical/subtropical regions, while methodologically justified, introduces uncertainty regarding direct transferability to all ERI contexts. Additionally, temporal variability in climate, land-use practices, and management interventions may not be fully captured in the synthesized evidence. Future research should prioritize primary field studies across ERI's diverse physiographic zones and employ quantitative synthesis approaches to strengthen evidence-based recommendations.

3 | CONCEPTUAL SYNTHESIS

3.1 | Altitudinal-slope variations

Slope orientation, elevation, and terrain configuration play decisive roles in shaping agronomic risk across the ERI, influencing solar radiation, soil moisture regimes, wind exposure, vegetation cover, soil properties, and hydrological responses. High-altitude and steep-slope areas consistently exhibit greater erosion due to sharp gradients, sparse vegetation, elevated sand and silt content, lower clay fractions, and reduced soil organic carbon (SOC), whereas mid-altitude zones experience lower erosion rates owing to dense vegetation that buffers runoff, and low-elevation floodplains, despite gentle slopes and higher clay content, are prone to moderate degradation from intensive farming and urban expansion. Studies from the North-Eastern Himalayan Region highlight these patterns: Choudhari *et al*. (2014) found higher SOC concentration and stock in non-agricultural land uses (2.20–2.51%, 35.2–42.1 Mg ha^{-1}) compared with agricultural and plantation systems (1.44–1.63%, 27.4–28.4 Mg ha^{-1}), with SOC variability shaped by soil texture and altitudinally driven climatic factors; trends were inconsistent below 1,000 m but became linear above this elevation. Mishra and Francaviglia (2021) observed increasing SOC stocks with elevation in

Nagaland, while nutrient availability (N, P, K) varied with both land use and soil texture, and phosphorus showed the highest concentrations at lower elevations (<500 m), emphasizing local context effects. These studies demonstrate that while erosion and general soil stability follow predictable altitude–slope patterns, SOC and nutrient dynamics are highly context-dependent, reflecting interactions among land use, soil texture, and climate. Consequently, effective agronomic risk assessment in ERI requires integrating broad physiographic patterns with localized land management and soil conservation practices to optimize productivity and sustainability.

3.1.1 | Terrain-driven agronomic risks

The Eastern Region of India (ERI), which includes the Indo-Gangetic floodplains, undulating plateaus, and hill tracts (Fig. 1), faces a variety of risks driven by altitude and slope. Floodplains are prone to waterlogging, flooding, and lower oxygen levels. Undulating piedmonts experience flash runoff, rill–gully erosion, and soil crusting. Plateau and hill ecosystems are affected by recurring droughts, significant topsoil loss, and quick runoff. This spatial diversity emphasizes the importance of including altitudinal and slope features in agronomic risk assessment models.

3.2 | Topographic controls on soil, water, and vegetation dynamics

Elevation influences temperature, rainfall patterns, solar radiation, and evapotranspiration. Steeper slopes reduce infiltration, accelerate runoff, and enhance erosion risk (Nath *et al*., 2021). The Himalayas and the Northeast Hill Region (NEHR) consistently exhibit accelerated runoff, high sedimentation, and nonpoint source pollution. Soil degradation costs are significantly higher in NEHR due to steep terrain, high rainfall, unscientific cultivation, and anthropogenic activity (Das *et al*. 2021). Similar dynamics characterize high-altitude zones in ERI. Slope, aspect, surface shape, stream power, and topographic wetness index (TWI) all influence erosion pathways. Steep slopes produce faster runoff and less infiltration, causing significant soil detachment (Saha *et al*., 2022). Regions with stripped forest cover, inadequate soil conservation, and shifting land use, such as the Chambal and Mahi basins, illustrate the consequences of terrain–land-use interactions. Topographic steepness is thus a central determinant of hydrological processes, erosion vulnerability, and land-use patterns (Gupta *et al*., 2024).

3.3 | Soil organic carbon (SOC), nutrients, and altitudinal gradients

Altitudinal and slope variations strongly shape SOC distribution, nutrient stocks, and soil physical properties. Studies across the Eastern Himalayas and related ecosystems reveal consistent patterns. Higher elevations generally exhibit higher SOC concentrations and stocks due to cooler temperatures, slower decomposition, and higher silt–clay content (Choudhury *et al*., 2016; Mishra and Francaviglia, 2021). SOC concentration nearly doubles at elevations of 2,500–3,500 msl compared to baseline levels.

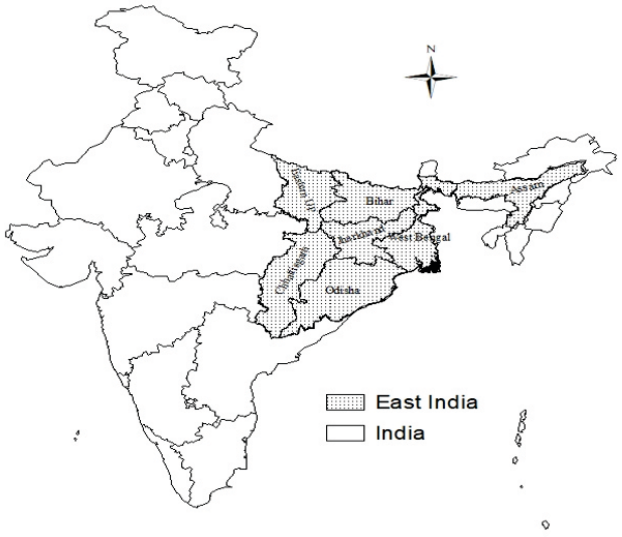


FIGURE 1 Eastern part of India map

Land-use changes, such as upland forest conversion to plantations, lead to 41–60% reductions in micronutrients (Mn, Cu, Zn) (Choudhury *et al*., 2021). Non-agricultural land uses (grasslands, forests) exhibit significantly higher SOC stocks than shifting or settled agriculture (Singh *et al*., 2018). Steep slopes promote soil translocation and downslope redeposition, leading to variability in soil texture and nutrient distribution. In ERI, similar patterns emerge: plain regions show higher SOC stocks (31.81 Mg ha^{-1}), followed by piedmonts and hills (Saini *et al*., 2021), with SOC highest at foot slopes and lowest on upper slopes.

3.4 | Biodiversity, vegetation, and soil-plant interactions along altitudinal gradients

Vegetation structure, diversity, and community composition vary with altitude in the Eastern Region of India (ERI). Low-altitude forests typically exhibit high species diversity, whereas high-altitude forests support larger biomass and basal area (Bhutia *et al*., 2019). Climatic variables such as temperature, precipitation, wind, and radiation interact with soil characteristics to shape adaptive plant traits (Gupta *et al*., 2019). Increased soil organic carbon (SOC), higher moisture content, improved infiltration, and reduced bulk density at higher elevations favor the growth of woody shrubs and other resilient species (Mangral *et al*., 2023). The extent of water savings and yield improvement under different altitudinal gradients and agronomic soil and water conservation practices is shown in (Table 1).

Agronomic soil and water conservation practices demonstrate altitude- and slope-dependent effects on crop productivity and water use efficiency. For instance, ridge and furrow methods on slight slopes enhanced water savings by ~27% and increased yields by 8–24% in crops such as soybean, cotton, maize, cowpea, and colocasia (Basediya *et al*., 2018), while broad-bed furrow and contour

farming on gentle to moderate slopes improved yields by 33–81% in soybean and sorghum (Kumari *et al*., 2020). Practices such as conservation furrows, sub-soiling, plastic mulching, rice-straw mulching, and trench-cum-bunding showed variable water savings (4.7–45%) and yield improvements (7.5–60%) depending on slope and crop type (Bhardwaj, 2013; Chaudhry *et al*., 2004; Rajkumar and Satishkumar, 2014), and laser leveling in level to slight slopes enhanced water efficiency and yields in rice–wheat systems (Jat *et al*., 2009; Rudragouda Chilur *et al*., 2016). Vegetation patterns and agronomic responses are largely influenced by the combined effects of altitude, slope, soil, and climate, yet the magnitude of water savings and yield gains remains context-specific, underscoring the importance of tailoring soil and water management practices to local physiography and crop requirements.

Table 1. Extent of water savings and yield improvement under different altitudinal gradients and agronomic practices

Practices	Slope variations (Range)	Crop	Average water saving (%)	Average increase in crop yield (%)	Reference
Ridge and furrow method	0.15-0.5%	Soyabean, cotton, maize, cowpea, colocassia	27	8-24	Basediya *et al*. (2018)
Broad bed furrow	< 3%	Soyabean	-	81	Kumari *et al*. (2020)
Sowing across the slope (Contour farming)	2-10%	Soyabean	-	33	Kumari *et al*. (2020)
Compartmental bunding	up to 6%	Sorghum	-	52	Kumari *et al*. (2020)
Conservation furrow	0.2-0.5%	Cotton, pigeon pea	-	8-60	Kumari *et al*. (2020)
Sub soiling	up to 12%	Groundnut	-	11	Kumari *et al*. (2020)
Plastic mulching	2-4%	-	4.7-4.5	7.5-22	Bhardwaj (2013)
Rice straw mulching	9 to up to 30%	-	30	-	Chaudhry *et al*. (2004)
Trench cum bunding	2-7%	-	15	-	Rajkumar, and Satishkumar (2014)
Laser levelling	upto 0.2%	Rice-wheat, rice	2.5	2.5	Jat *et al*. (2009); Rudragouda Chilur *et al*. (2016)

*Note: Values represent reported ranges from individual studies or reviews as cited. Variations reflect differences in crop type, slope gradient, soil conditions, and management practices across different agro ecological contexts.**

3.5 | Slope position and soil quality

Slope position strongly influences soil nutrients, cation exchange capacity, moisture content, and bulk density, with most soil properties declining from lower to upper slopes due to erosion-driven loss of clay and organic matter (Debisa *et al*., 2025). Assessments across different land uses in the Eastern Himalaya and Northeastern Himalaya reveal consistent patterns: lower slope and valley positions under forest or perennial vegetation exhibit higher SOC, nutrient stocks, and better soil structure, whereas upper slopes and hilltops under shifting cultivation or intensive cropping show reduced fertility and higher susceptibility to degradation (Singh *et al*., 2013; Mishra *et al*., 2017, 2019). These variations are strongly mediated by land-use type, vegetation cover, and microtopography, indicating that slope position alone does not fully determine soil quality. Although lower slope positions reliably provide higher soil fertility and reduced erosion risk, the interplay of slope, land use, and vegetation cover creates site-specific variability; therefore, agronomic risk assessment and management strategies in ERI's hilly and plateau regions must integrate slope position with local land-use and conservation practices to sustain soil productivity.

3.6 | Implications for agronomic risk assessment in ERI

The evidence collectively underscores that altitude and slope serve as fundamental determinants of agronomic risk. Their influence cascades through soil formation, erosion processes, hydrological responses, vegetation patterns, and nutrient dynamics. In the context of ERI:

- Steeper slopes increase exposure to erosion, drought, and nutrient loss.
- Mid-altitude landscapes benefit from favorable vegetation cover and reduced erosion.
- Lowlands face waterlogging, sedimentation, and anthropogenic pressures.

With climate change amplifying rainfall extremes, altering evapotranspiration, and modifying vegetation composition, a systematic assessment of altitudinal–slope risks is critical for sustainable agriculture, resource conservation, and food security in the Eastern Region of India.

4 | CONCLUSIONS

Agronomic risk in the ERI is profoundly intertwined with the region's altitudinal and slope-driven heterogeneity, which shapes soil properties, hydrological behavior,

vegetation patterns, and agricultural performance. Evidence from ERI and comparable mountain ecosystems demonstrates that variations in altitude and slope critically influence soil stability, nutrient distribution, organic carbon dynamics, and erosion susceptibility. Steeper, higher-altitude terrain consistently exhibits accelerated runoff, severe soil loss, reduced SOC, and nutrient depletion —factors that collectively undermine crop productivity and long-term soil resilience. In contrast, mid-altitude and gentle-slope landscapes support denser vegetation and more favorable soil conditions, although intensive cultivation and land-use pressures can introduce new vulnerabilities.

The review highlights that agronomic risks in ERI are spatially stratified: floodplains face waterlogging and sedimentation, piedmonts experience rill and gully erosion, and upland hills and plateaus tracts are prone to recurrent drought, severe soil erosion, and nutrient translocation. Climatic variability and increases in rainfall intensity under climate change further exacerbate topography-mediated risks, increasing the likelihood of soil degradation, productivity decline, and livelihood instability. The strong altitudinal influence on SOC, micronutrient distribution, soil moisture, bulk density, and vegetation composition underscores the need for location-specific soil and water conservation measures. Due to known complexity of soil-water-plant interactions, assessing agronomic risk through the lens of altitude and slope provides a scientifically robust foundation for designing sustainable land management strategies. Integrating terrain parameters into risk assessment allows for better targeting of interventions such as contour farming, agroforestry, check-dams, and nutrient management tailored to slope positions and elevation zones. Future efforts must also incorporate climate projections, remote sensing tools, and process-based erosion models to anticipate emerging risks and support resilient agricultural planning.

Strengthening research–extension linkages, promoting community-based watershed management, and integrating indigenous traditional knowledge (ITK) with modern technologies will be essential to safeguarding land resources, stabilizing crop yields, and ensuring long-term agricultural sustainability in the ERI. Overall, altitude and slope are not only physical features but critical determinants of agroecosystem functioning in ERI, and addressing associated agronomic risks requires a holistic strategy that combines soil and water conservation, climatic adaptation, sustainable farming practices, community-based watershed management, and the integration of indigenous knowledge with modern technologies to safeguard soil and water resources, stabilize productivity, and ensure long-term agricultural sustainability.

ACKNOWLEDGEMENTS

The authors would like to thank the anonymous reviewers and editor for their instructive comments, which helped to improve this paper.

CONFLICT OF INTEREST

The author declare there is no conflict.

DATA AVAILABILITY STATEMENT

The data generated or analysed during this study are available from the corresponding author upon reasonable request.

AUTHOR'S CONTRIBUTION

Conceptualization, P.J. and A.K.; data collection, P.J., P.K.S. and A.K.; methodology, P.J., A.U. and P.K.S.; resources, A.D. and A.U.; investigation, P.J. and A.K.; validation, P.J. and S.S.M.; writing-original draft preparation, P.J. and P.K.S.; writing-review and editing, P.J., A.U., A.K., S.S.M and P.K.S.; visualization, P.K.S. and A.D.; supervision, P.J.; project administration, A.D. and A.U. All authors have read and agreed to the published version of the manuscript.

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How to cite this article: Jeet, P., Kumari, A., Upadhyaya, A., Mali, S.S., Sundaram, P.K., and Das, A 2025. Assessing Agronomic Risk under Altitudinal-Slope Variations in Eastern India: A Conceptual Synthesis of Soil-Water-Productivity Interactions. *Indian J. Soil Cons*., **53(3)** (*Hill & Mountain Agriculture S*pecial Issue)**: 254-259**

Received: 25 August 2025 | Accepted: 17 March 2026 | Published online: 06 April 2026

DOI: 10.53550/ijsc.v53.i3.209

ORIGINAL ARTICLE

Indian Journal of Soil Conservation

Geospatial Assessment of Temperate Fruit Sites for Sustainable Horticultural Diversification in Meghalaya

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Handling Editor:
Dr Parvat Kumar Shit

Key words:
Crop diversification
GIS
Geospatial analysis
Horticulture
Meghalaya
Site suitability
Soil conservation

ABSTRACT

Meghalaya has significant potential for horticultural diversification, particularly for temperate fruit crops. This study evaluates site suitability for apple, pear, and peach cultivation in Meghalaya using geospatial techniques, with a specific focus on sustainable land use and soil conservation in a landscape prone to degradation. Key parameters considered include soil depth, drainage, texture, pH, organic matter, nutrient availability (P and K), climatic variables (temperature, rainfall, and chilling hours), and topographic variables (slope, elevation, and slope aspect). Suitable areas were classified into highly suitable (S1), moderately suitable (S2), marginally suitable (S3), and not suitable (N) zones using the FAO Land Evaluation Framework. The suitability model was validated against 785 ground-truth observations, yielding an overall accuracy of 90% and a Kappa coefficient of 0.86, confirming its predictive reliability. West Khasi Hills emerges as the district with the highest concentration of suitable land for all three crops, particularly in the blocks of Mawthadraishan, Nongstoin, and Mairang. A total of 64,485.92 hectares were identified as suitable for at least one crop, of which 24,259.52 hectares are highly suitable for all three simultaneously — representing the most promising zones for integrated orchard development and long-term soil stabilization. By providing a spatially explicit framework, this study supports evidence-based planning for nursery development, cold-chain infrastructure, marketing linkages, and climate-resilient horticultural diversification in Meghalaya.

1 | INTRODUCTION

Soil degradation is a critical challenge for agricultural sustainability in the hilly regions of South and Southeast Asia. Steep terrain, heavy rainfall, and shallow soils contribute to processes such as surface runoff and sheet erosion, which constantly deplete fertile topsoil essential for farming. It takes nature 300–1,000 years to form just one inch of topsoil (NRSC; Mishra *et al.*, 2024), highlighting the long-term and often irreversible nature of such losses (Singh *et al*., 2023; Verma *et al*., 2023). The North Eastern Region (NER) of India exemplifies this issue with its complex terrain, high rainfall, and fragile ecosystems, making its soils highly vulnerable. As of 2005- 06, degraded land in the NER covered 46, 46,946 sq. km, or 17. 91% of the total area, with an additional 2, 2,164 sq. km degraded over the next decade. Acidification is the primary degradation process, followed by water erosion; waterlogging is most severe in Assam and significantly affects Arunachal Pradesh, Manipur, Meghalaya, and Tripura (Das *et. al*., 2026). Meghalaya, in particular, exemplifies these challenges with steep slopes, shallow soils, and annual rainfall ranging from about 1,000 mm to over 11,000 mm. This climate promotes intense overland flow during the monsoon, leading to high rates of surface erosion and nutrient-rich topsoil loss. According to NRSC and NESAC, roughly 623,148 ha of Meghalaya are degraded, with water erosion affecting 73,905 ha, acidification affecting 458,458,765 ha, and other human factors affecting 6,910 ha. The shallow soils on steep slopes have little capacity to buffer against these processes; once topsoil is removed, land productivity drops sharply, and natural recovery is nearly impossible without intervention. Traditional farming practices, such as jhum (shifting cultivation), worsen these vulnerabilities. Jhum remains common in Meghalaya but causes severe soil loss- up to 40 tonnes per hectare annually (Shangpliang, 2019) — which far exceeds natural soil formation rates, leading to ongoing land degradation. The cycle of clearing, burning, and short-term cropping leaves slopes exposed during the monsoon, increasing topsoil exposure to rainfall impacts and runoff erosion.

Perennial fruit crop cultivation on slopes offers a practical way to stabilize soil and rehabilitate land. Unlike annual crops, orchards provide a continuous canopy, reduce erosion, and improve soil health through organic inputs (Liu *et al*., 2024). Studies show well-managed orchards can cut soil loss by 60–80%. Diversifying horticulture serves as

both an economic and conservation strategy, especially in Meghalaya's diverse climate, supporting crops like bananas, oranges, strawberries, and indigenous fruits (Deshmukh *et al.*, 2013). Out of 2.24 million hectares, 15.28% is cultivated, and 24.75% remains unused, offering potential for eco-friendly economic growth. Temperate fruits like apple, pear, and peach are promising, with apple being a newer opportunity due to climate change. Spatial data on soils, climate, and topography are essential for planning. The Meghalaya Small Farmer's Agri-Business Consortium, partnering with NESAC, aims to identify suitable areas for these crops, develop a diversification plan, and create a land conservation framework to align orchard placement with slope stabilization and land rehabilitation.

2 | MATERIALS AND METHODS

2.1 | Study Area

Meghalaya is a North-Eastern state of India, extending from 25°13'06" N to 25°17'45" N latitude and 89°49'52" E to 92°48'17" E longitude (Fig. 1). The state covers a total geographical area of 2,242,900 ha and is characterized by three main plateau systems — the Khasi Hills, Jaintia Hills, and Garo Hills — separated by deep river valleys. Elevation ranges from near sea level in the valley fringes to approximately 1,920 m in the higher Khasi Hills. This topographic diversity, combined with one of the world's highest rainfall regimes in the Cherrapunji–Mawsynram belt, creates a landscape of exceptional agronomic diversity but also heightened erosion risk.

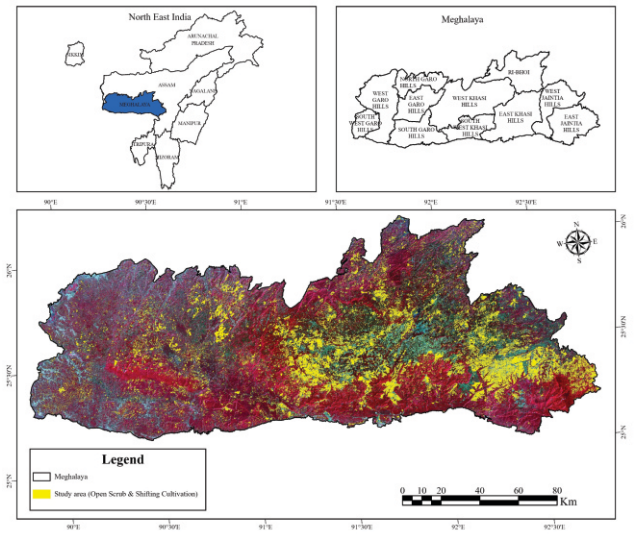


FIGURE 1 Study Area Map

2.2 | Data Sources And Thematic Map Preparation

Suitable areas for apple, pear, and peach were identified and mapped following the FAO Land Evaluation Framework (FAO, 1984). Multiple thematic maps were generated from different data sources. Soil maps at 1:50,000 scale, prepared by NESAC and SLUSI, were updated with soil fertility maps by NESAC (Das *et al.*, 2022). Thematic maps for texture, depth, drainage, pH, organic carbon (OC),

HIGHLIGHTS

- Geospatial analysis identifies 64,486 ha of degraded land in Meghalaya suitable for temperate fruit cultivation across apple, pear, and peach.
- West Khasi Hills emerges as the primary hotspot, with 24,259 ha highly suitable for all three crops simultaneously, enabling integrated orchard systems.
- Orchard establishment on identified slopes can potentially prevent over 485,000 tonnes of annual topsoil loss, delivering measurable soil conservation co-benefits.

phosphorus (P), and potassium (K) were derived from the updated soil map. Chilling hour maps (0–7°C) for apple and peach were created from ERA5-Land hourly temperature data (2003–2023). Daily chilling hours were extracted using Python, and annual maps were prepared (Das et al., 2025). Average rainfall maps were based on 27 years of data (1997–2023) from IMD. Mean annual temperature maps used 16 years of MODIS LST data (2007–2023). Elevation and slope maps were generated from Cartosat DEM, with slope aspect classified into eight directional classes. A LULC map from LISS-IV imagery (2024) was visually interpreted, with an accuracy of 92% (Kappa = 0.89). Suitability analysis focused on 483,482.47 ha of open scrubland, fallow, and shifting cultivation, representing degraded or transitional land.A flowchart illustrating the overall methodology is presented in (Fig. 2), while (Fig. 3) depicts the thematic maps representing soil site characteristics of the study area.

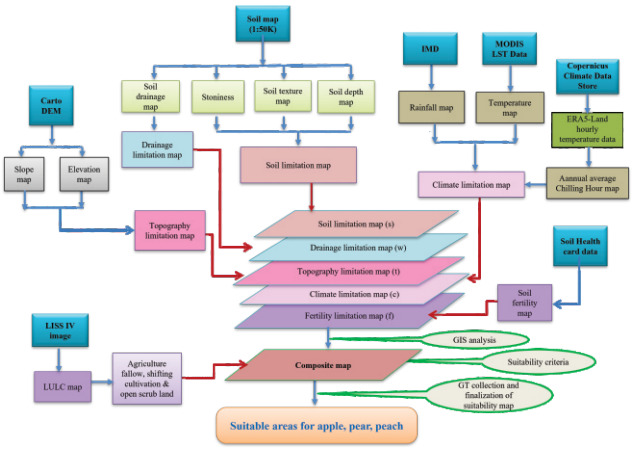


FIGURE 2 Methodology flow chart

2.3 | Suitability Criteria And Limitation Scoring

Suitability assessment followed the FAO parametric framework, assigning each land quality parameter a limitation score from 0 (no limitation) to 4 (very severe limitation) based on deviation from optimal crop ranges. Table 1 shows threshold values for suitability classes (S1–N) for apple, peach, and pear. The scores are detailed in Table 1, ensuring transparency. The overall suitability for each unit was determined by the most limiting parameter, ensuring no unit is rated highly suitable if any critical

parameter is below the threshold, following FAO (1984). All maps were projected to a common coordinate system and rasterised at 30 m resolution before overlay, using ArcGIS Pro. Suitability classes: Highly Suitable (S1) — no limitations; Moderately Suitable (S2) — one or more parameters with score 1, none ≥2; Marginally Suitable (S3) — one or more with score 2, none 3–4; Not Suitable (N) — one or more with scores 3–4 Table 2. Sub-classes identify specific limiting factors like temperature, slope, soil depth, and elevation, detailed in Tables 3-5.

2.4 | Slope Aspect Integration

Aspect was added to refine microclimate assessment, especially for apple cultivation, where isolation and chilling hours are vital. In the Northern Hemisphere, north- and northeast-facing slopes get less sun, stay cooler, and accumulate more chilling hours during dormancy, compared to south- and southeast-facing slopes at the same elevation. The latter warm earlier in spring and have longer growing seasons, benefiting crops like peach and pear that need early bud-break and extended fruit development. In the suitability model, aspect refined borderline chilling-hour zones (250–350 hours). North- and northeast-facing slopes in these zones upgraded the chilling-hour score by one subclass, as aspect-driven temperature differences of 1–3°C can significantly affect chilling hours at the site level. South- and southeast-facing slopes kept the original score.

2.5 | Model Validation

To evaluate suitability map accuracy, a stratified random sample of 785 locations was collected across all four classes (S1, S2, S3, N) in three districts with highest mapped suitability (West Khasi Hills, East Khasi Hills, West Jaintia Hills). The sample was proportional to each class's area, with at least 50 observations per class. At each site, soil pH (field meter), soil depth (auger), soil texture (field and lab for 20%), and slope (clinometer) were recorded. Microclimate data (temperature loggers) were collected at 120 locations across elevation gradients. Recorded values were compared to the model's predictions. Map accuracy was assessed via a confusion matrix comparing field-observed and model-predicted classes, calculating overall accuracy and Kappa coefficient (Congalton and Green, 2019). Results showed an accuracy of 90% and Kappa of 0.86, indicating [substantial/good] agreement. Misclassifications mainly involved S1–S2 confusion in transitional areas, consistent with known DEM slope limitations in rugged terrains. The validated map is shown in (Fig. 4).

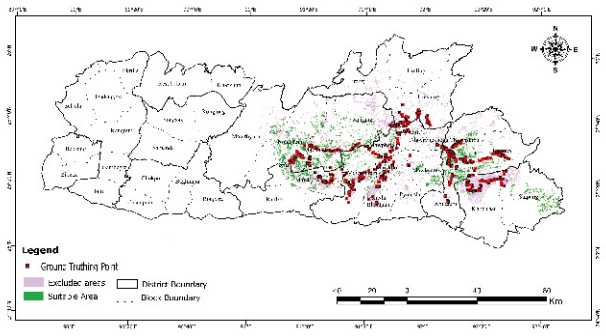


FIGURE 4 Ground Truth Verification Sites

TABLE 2 Criteria for determination of land suitability classes

Land classes	Criteria
S1: Highly suitable	Land units with no or only 4 slight limitations
S2: Moderately suitable	Land units with more than 4 slight limitation sand/or no more than 3 moderate limitations
S3: Marginally suitable	Land units with more than 3 moderate limitation sand/ or one or more severe limitation
N: Not suitable	Land units with very severe limitation

TABLE 3 Area under suitability subclass for Apple

Suitability Class	Suitability subclass	Area (ha)	Limitation/Improvement
S2	S2c	16067.39	Chilling Temperature
	S2t	4041.19	Slope
	S2ts	0.12	Slope & Death
S3	S3s	0.35	Depth
	S3e	0.35	Elevation
	S3t	2519.63	Slope
	S3ts	0.26	Slope & Depth

TABLE 4 Area under suitability subclass for Apple

Suitability Class	Suitability subclass	Area (ha)	Limitation/Improvement
S2	S2c	16067.39	Chilling Temperature
	S2t	4041.19	Slope
	S2ts	0.12	Slope & Death
S3	S3s	0.35	Depth
	S3e	0.35	Elevation
	S3t	2519.63	Slope
	S3ts	0.26	Slope & Depth

TABLE 5 Area under suitability subclass for Pear

Suitability Class	Suitability subclass	Area (ha)	Limitation/Improvement
S2	S2c	0.10	Depth
	S2t	9722.90	Slope
	S2ts	0.11	Slope & Death
S3	S3s	0.10	Depth
	S3e	0.02	Elevation
	S3t	0.03	Slope
	S3ts	0.11	Slope & Death

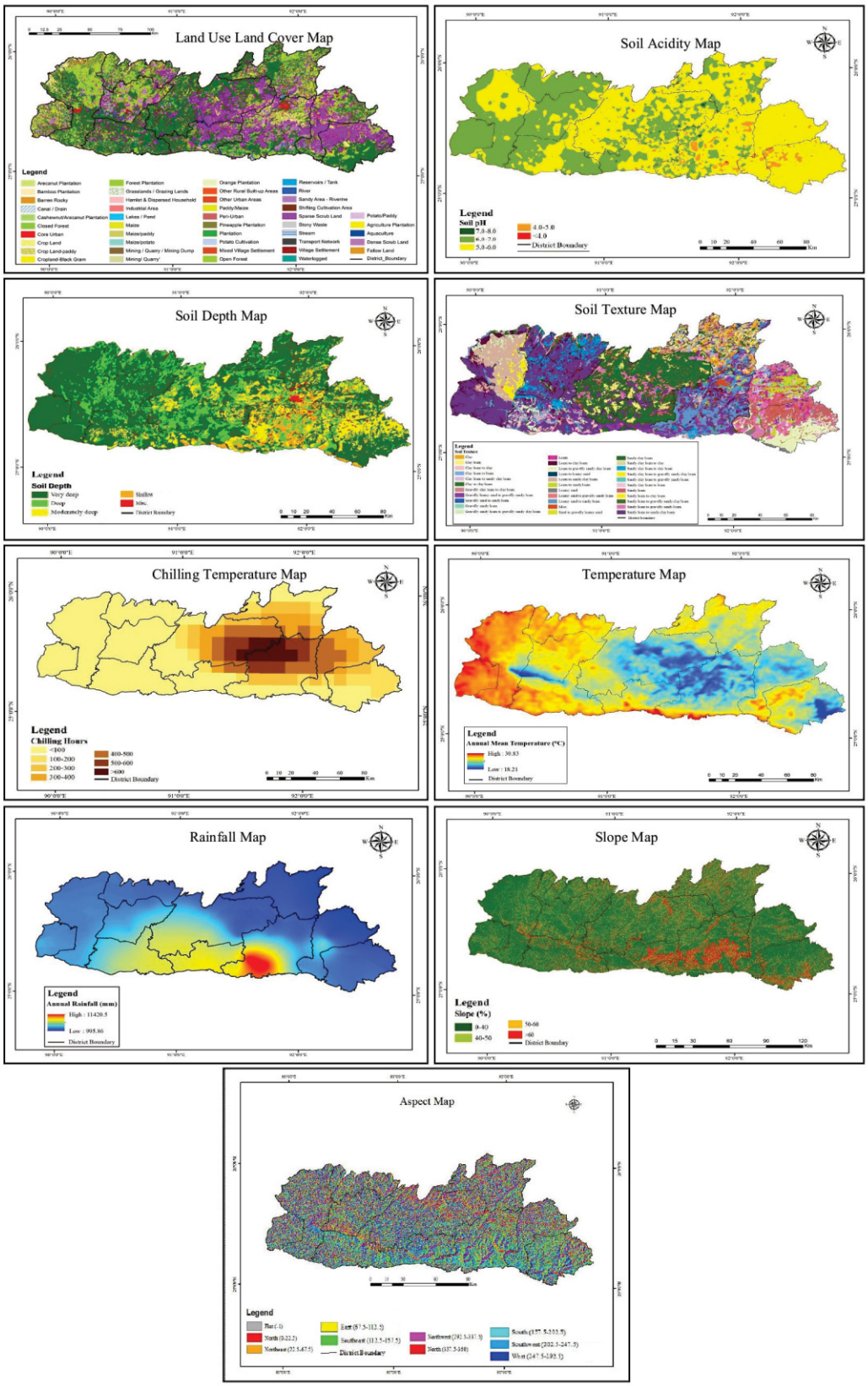


FIGURE 3 Maps showing soil site characteristics of Meghalaya

TABLE 1 Limitation Rating for Evaluation of Soil Site Suitability of Apple, Peach, and Pear in Meghalaya

FAO Land Evaluation Framework (FAO, 1984). Limitation scores: 0 = None (S1), 1 = Moderate (S2), 2 = Severe (S3), 3–4 = Very Severe (N). Overall class by minimum/most-limiting factor rule.

Parameter	APPLE (Malus domestica) - Low-chilling cultivars				PEACH (Prunus persica) - Sub temperate cultivars				PEAR (Pyrus communis / P. pyrifolia) - Temperate cultivars			
	S1 Highly Suitable	S2 Moderatel Suitable	S3 Marginall Suitable	N Not Suitable	S1 Highly Suitable	S2 Moderatel Suitable	S3 Marginall Suitable	N Not Suitable	S1 Highly Suitable	S2 Moderatel Suitable	S3 Marginall Suitable	N Not Suitable
Soil Depth (cm)	>100	70-100 (S2s)	50-70 (S3s)	<50	>100	70–100 (S2s)	50–70 (S3s)	<50	>100	70-100 (S2s)	50–70 (S3s)	<50
Soil Texture	Loam, Sandy clay loam, Clay loam	Sandy loam, Loamy sand, Gravelly sandy loam	-	other	Loam, Sandy clay loam, Clay loam	Sandy loam, Loamy sand, Gravelly sandy loam	-	other	Loam, Sandy clay loam, Clay loam	Sandy loam, Loamy sand, Gravelly sandy loam	-	Other
Soil Drainage	Well drained	Mod. well drained (S2d)	Imperfectly drained (S3d)	Poorly drained	Well drained	Mod. well drained (S2d)	Imperfectly drained (S3d)	Poorly drained	Well drained	Mod. well drained (S2d)	Imperfectly drained (S3d)	Poorly drained
Soil pH	5.8-6.5	<5.8 & 6.5–7.5 (S2pH)	<5.5 & 7.5–8.0 (S3pH)	>8.0	5.9-6.8	<5.9 & 6.8–7.5 (S2pH)	-	>7.5	5.9-6.8	<5.9 & 6.8–7.5 (S2pH)	-	>7.5
Organic Carbon (%)	>0.75	0.50–0.75 (S2oc)	0.25–0.50 (S3oc)	<0.25	>0.75	0.50–0.75 (S2oc)	0.25–0.50 (S3oc)	<0.25	>0.75	0.50–0.75 (S2oc)	0.25–0.50 (S3oc)	<0.25
Available P (kg ha^{-1})	>25	10–25 (S2p)	5–10 (S3p)	<5	>25	10–25 (S2p)	5–10 (S3p)	<5	>25	10–25 (S2p)	5–10 (S3p)	<5
Available K (kg ha^{-1})	>280	120–280 (S2k)	60–120 (S3k)	<60	>280	120–280 (S2k)	60–120 (S3k)	<60	>280	120–280 (S2k)	60–120 (S3k)	<60
Chilling Hours (0–7°C, hrs yr^{-1})	>400	300–400 (S2c)	200–300 (S3c)	<200	>100	- (broad tolerance)	-	<100	Not a primary limiting factor; elevation & temp. used as proxy			<100
Mean Annual Temp. (°C)	<20	20–23 (S2temp)	23–25 (S3temp)	>25	<30	-(entire state suitable)	-	>30	<20	20–23 (S2temp)	23–25 (S3temp)	>25
Annual Rainfall (mm)	995.8–11,420.5 — entire state suitable; no limitation applied			-	995.8–11,420.5 — entire state suitable; no limitation applied			-	995.8–11,420.5 — entire state suitable; no limitation applied			-
Slope (%)	0-40	40–50 (S2t)	50–60 (S3t)	>60	0-40	40–50 (S2t)	50–60 (S3t)	>60	0-40	40–50 (S2t)	50–60 (S3t)	>60
Elevation (m asl)	>1,700	1,500–1,700 (S2e)	1,200–1,500 (S3e)	<1,200	1,100–2,000	-	-	<1,100 or >2,000	1,100–2,000	-	-	<1,100 or >2,000
Slope Aspect*	N, NE - maximises chilling hour accumulation	E, W facing (S2asp)	S, SW facing (S3asp)	-	S, SE - early bud-break & longer season	E, W facing (S2asp)	N, NW facing (S3asp)	-	S, SE - extended growing season	E, W facing (S2asp)	N, NW facing (S3asp)	-

Sub-class codes: s = soil depth; d = drainage; pH = soil reaction; oc = organic carbon; p = available phosphorus; k = available potassium; c = chilling hours; temp = mean temperature; t = slope; e = elevation; asp = slope aspect. Combined limitations shown by concatenation (e.g., S2ts = slope + soil depth). Grey rows = identical thresholds across all three crops. * Slope aspect applied as refinement layer in chilling transition zones (250–350 hrs/yr) for Apple; applied across all elevation-suitable zones for Peach and Pear. Aggregation rule: Overall suitability class determined by the minimum (most-limiting factor) rule — the most severely limited parameter governs the composite class (FAO, 1984). Apple cultivar note: Chilling hour thresholds apply to low-chilling cultivars (e.g., HRMN-99, Anna, Dorsett Golden). Standard high-chilling varieties (>1,000 hrs) are not viable under Meghalaya's current climate.

3 | RESULTS AND DISCUSSION

3.1 | Land Use and Land Cover

Analysis of the 2024 LISS-IV LULC map shows dense/closed forest as the main land cover, covering 44.47% of the area, with open forest at 21.56% and open/sparse scrubland at 10.06%. The combined area of open scrubland, fallow, and shifting cultivation—spanning 483,482.47 ha—is mainly degraded land with low productivity and high erosion risk during high rainfall, especially in active and post-jhum fallow. Converting these areas to perennial orchards could boost economic value and stabilize slopes.

3.2 | Soil Characteristics

Soil texture in the study region varies from gravelly sand to clay loam, with sandy loam being most common (51.59%), followed by sandy clay loam (19.19%), loam (9.87%), and loamy sand (7.08%). These textures, especially sandy loam and loam, are favorable for temperate fruit crops because they balance water retention and drainage; however, their low cohesion on steep slopes makes them prone to rill and sheet erosion when uncovered. Most soils are very deep (>100 cm, covering 60.23%) or deep (18.46%), which benefits orchard crops that require unrestricted root growth. Slightly shallow (13.37%) and shallow soils (5.59%) occur mainly on upper slopes, where erosion has reduced root depth, potentially benefiting from biological loosening of subsoils through the establishment of deep-rooted perennial orchards over time. Soils are mainly moderately well-drained (39.04%) and well-drained (37.62%), with some valley bottom areas having imperfectly drained (16.10%) or poorly drained (4.70%) soils. Proper drainage is vital for temperate fruit crops, as they are sensitive to waterlogging and root asphyxiation. Most soils are slightly acidic (69.61%) or moderately acidic (27.25%), with a tiny fraction (0.09%) strongly acidic. Acidic soils pose challenges such as increased phytotoxic aluminium and manganese, reduced phosphorus availability due to fixation, and impaired microbial activity. Apple trees grow best at a pH of 5.8–6.5, while pears and peaches prefer a pH of 5.9–6.8. Soils below pH 5.5, present in some areas, require periodic liming (using dolomitic limestone or calcium carbonate) to raise pH to optimal levels, based on soil buffering capacity. Liming also supplies calcium and magnesium, critical nutrients for fruit quality. Organic carbon (OC) is high in most areas (88.22%), supporting good soil structure and nutrient cycling, reducing erosion, and fostering microbial communities vital for nutrient availability and plant health. Enhancing OC through mulching, cover cropping, and adding pruning residues should be a priority in new orchards. Medium available phosphorus (69.89%) is typical, with 18.73% of soils low in P and 11.38% high. Potassium levels are more concerning: 47.35% of soils are low in K, 45.54% are medium, and only 7.11% are high. Potassium is crucial for fruit quality, cell turgor, and winter hardiness. Soils identified as suitable but low in K will need systematic supplementation with muriate of potash (MOP) or sulfate of potash (SOP), incorporated into fertilizer plans for orchard establishment. Soil test-based fertilization, reviewed every 2–3 years, should be part of ongoing orchard management to prevent the K depletion observed in intensive orchards on low-K soils.

3.3 | Climate and Topographic Parameters

Chilling Hours: The distribution of chilling hours (0–7°C) is a primary determinant of apple and peach suitability in Meghalaya. Apple cultivars requiring >300 chilling hours are climatically suitable across 21.52% of the state's area, while peach (requiring >100 chilling hours) is suitable across 45.25% of the area (Das et al., 2025). It is important to note that the apple thresholds applied in this study are calibrated for low-chilling cultivars (e.g., HRMN-99, Anna, Dorsett Golden), which have been developed specifically for non-traditional apple-growing regions. Standard high-chilling commercial varieties (requiring >1,000 hours) are not considered viable in Meghalaya's current climate regime. Policymakers and extension services should ensure that nursery and planting material programmes exclusively promote low-chilling cultivars in identified S1 and S2 zones.

Temperature: Mean annual temperature ranges from 18.21°C to 30.84°C across the state. Approximately 60.62% of the state meets the temperature requirements for apple cultivation (20–25°C mean annual), while the entire state meets temperature criteria for both peach and pear (mean annual <30°C).

Slope and Slope Aspect: Approximately 72.93% of Meghalaya's total geographical area falls under the highly suitable slope category (0–40%), while 11.74% is moderately suitable (40–50%), 7.13% is marginally suitable (50–60%), and 8.20% is not suitable (>60%) for orchard cultivation. These slope thresholds were established in consultation with the Meghalaya Horticulture Department and reflect both agronomic requirements and practical constraints in plantation management.

Slope aspect is an important modifier of microclimate and was explicitly incorporated into the suitability model for apple cultivation (see Section 2.4). Analysis of the state's aspect distribution reveals that southeast-facing slopes are most prevalent (15.02%), followed by northwest (13.83%), south (13.46%), southwest (13.09%), east (12.63%), and west (12.88%) facing slopes, with minimal flat and true north-facing terrain. South- and southeast-facing slopes in Meghalaya's high-altitude zones warm rapidly in spring, providing longer effective growing seasons that benefit peach and pear by supporting timely bud-break and fruit development. In contrast, north- and northeast-facing slopes at comparable elevations accumulate additional chilling hours during the winter dormancy period, making them particularly advantageous for apple cultivation in the borderline chilling-hour zones of the West Khasi Hills. In the model, north- and northeast-facing aspects in the 250–350 chilling-hour transition zone contributed to the upward reclassification of approximately 24000 ha from S2 to S1 for apple, demonstrating the substantive influence of

aspect integration on final suitability outputs. Ignoring slope aspect in favour of gridded temperature data alone would have systematically underestimated apple suitability on north-facing slopes in these transitional zones.

Elevation: Elevation ranges from near sea level to approximately 1,920 m. Apple cultivation, restricted to elevations above 1,200 m in this study, is viable across only 16.40% of the state's area. Pear and peach, which thrive above 1,100 m, are suitable across 20.41% of the state based solely on elevation criteria.

Rainfall: Annual average rainfall ranges from 995.8 mm to 11,420.5 mm. Given the wide range and the fact that the minimum value of ~1,000 mm meets or exceeds the water requirements of all three target crops, rainfall is not a limiting factor anywhere in the study area. However, the extreme rainfall values in the Cherrapunji–Mawsynram belt (>8,000 mm) may increase disease pressure (particularly fungal pathogens) and require drainage management in orchard planning.

3.4 | Crop Suitability Results

Apple: West Khasi Hills is the most suitable district for apple, with 21,591.41 ha of total suitable land, of which 12,706.64 ha are highly suitable (S1). East Khasi Hills (11,838.08 ha total; 7,568.43 ha S1) and West Jaintia Hills (11,353.95 ha total; 3,262.23 ha S1) are the next most important districts, with the blocks of Mawthadraishan, Nongstoin, and Mairang showing particularly high suitability concentrations (Table 6 and Fig. 5). The primary limiting factor for apple suitability is chilling hours (S2c classification covers 16,067.39 ha), followed by slope (S2t: 4,041.19 ha), reflecting the narrow high-altitude niche in which chilling requirements are reliably met (Table 3 and Fig. 5).

Peach: Peach has the widest geographic suitability of the three crops, reflecting its lower chilling-hour requirement and broader temperature tolerance. West Khasi Hills leads with 24,695.27 ha total suitable area (20,474.13 ha S1), followed by East Khasi Hills (13,978.52 ha) and West Jaintia Hills (13,517.26 ha). The primary limitation for moderate suitability areas is slope (S2t: 9,003.87 ha), consistent with the steep terrain characteristic of the Khasi and Jaintia plateaus (Table 7 and Fig. 5). Peach's broader suitability also makes it the most appropriate initial crop for piloting orchard-based slope stabilization interventions in higher-risk erosion areas.

Pear: Pear's suitability distribution closely mirrors that of peach, reflecting similar temperature and elevation tolerances. West Khasi Hills has the largest suitable area (24,695.27 ha; 20,474.13 ha S1), with East Khasi Hills (13,978.52 ha) and West Jaintia Hills (13,517.26 ha) as key districts (Table 8 and Fig. 5). Slope is the dominant limiting factor for S2 pear areas (S2t: 9,722.90 ha), and marginally suitable areas are largely absent, indicating that most terrain either meets pear requirements or is excluded due to slope exceeding 60% (Table 5 and Fig. 5).

TABLE 6 District wise suitable areas for Apple

District	Area (ha) under different suitability class			Total area (ha)
	Highly	Moderate	Marginal	
East Jaintia Hills	-	305.56	1.68	307.24
East Khasi Hills	7568.43	3492.2	777.45	11838.08
Ri-Bhoi	3.06	156.12	7.51	166.69
South West Khasi Hills	727.96	830.34	80.88	1639.17
West Jaintia Hills	32362.23	7744.67	347.04	11353.95
West Khasi Hills	12706.64	7579.7	1305.07	21591.41
Total	24268.32	20108.59	2519.63	46896.54

TABLE 7 District wise suitable areas for Peach

District	Area (ha) under different suitability classes			Total area (ha)
	Highly	Moderate	Marginal	
East Garo Hills	33.91	9.49	-	43.4
East Jaintia Hills	5263.46	594.44	42.6	5900.51
East Khasi Hills	11430.56	2354.89	193.08	13978.52
Ri-Bhoi	201.57	40.76	1.31	243.64
South Garo Hills	-	0.02	-	0.02
South West Khasi Hills	5061.37	706.04	6.02	5773.43
West Garo Hills	18.21	3.58	-	21.79
West Jaintia Hills	11991.25	1367.82	158.3	13517.26
West Khasi Hills	20474.13	3926.84	294.3	24695.27
Total	54474.36	9003.88	695.61	64173.84

TABLE 8 District wise suitable areas for Pear

District	Area (ha) under different suitability classes			Total area (ha)
	Highly	Moderate	Marginal	
East Garo Hills	33.91	9.49	-	43.4
East Jaintia Hills	5552.15	660.46	-	6121.61
East Khasi Hills	11430.56	2547.96	-	13978.52
Ri-Bhoi	201.57	42.07	-	243.64
South Garo Hills	-	0.02	-	0.02
South West Khasi Hills	5061.37	712.06	-	5773.43
West Garo Hills	18.21	3.58	-	21.79
West Jaintia Hills	11991.15	1526.12	-	13517.26
West Khasi Hills	20474.13	4221.14	-	24695.27
Total	54763.05	9722.9	-	64485.94

3.5 | Soil Conservation Implications of the Suitability Maps

A key element of the suitability analysis that deserves explicit discussion—especially for soil conservation planning—is the spatial match between the high-suitability zones identified and areas currently facing high soil degradation risk. The 483,482 ha study area includes active and recent jhum fallow, open scrubland, and agricultural fallow—land types that, under current management, are exposed to bare soil for significant portions of the year and are vulnerable to the high rainfall erosivity characteristic of the Khasi and Jaintia Hills. Establishing permanent orchards across the 24,259 ha identified as highly suitable for all three crops, and across the 30,214 ha suitable for pear and peach, would mark a fundamental shift in the erosion balance of these landscapes. Evidence from similar hilly orchard systems in South and Southeast Asia shows that well-managed orchards on slopes of 15–40% can reduce annual soil loss by 50–75% compared to jhum fallow conditions, mainly through canopy cover, root reinforcement, and the development of an organic surface layer (Pimentel *et al*., 2006; García-Ruiz *et al*., 2013; Liu *et al.,* 2024). At the soil loss rates reported for jhum in Meghalaya (up to 40 t/ha/yr; Shangpliang, 2019), even a conservative 50% reduction in erosion across the 24,259 ha S1 zone could prevent the loss of approximately 485,180 tonnes of topsoil annually—a significant ecosystem service benefit of the proposed horticultural diversification. Additionally, the soil amendment strategies needed for orchard establishment directly address underlying degradation processes. Liming to raise soil pH in moderately acidic zones (27.25% of the study area) will reduce aluminum toxicity and improve soil biological activity. Potassium supplementation in the 47.35% of low-K soils will enhance tree health and yield stability. Regular organic matter additions through mulching and green manuring will build the organic carbon pool, further improving soil structure and reducing erodibility. These agronomic practices, incorporated into an orchard management schedule, serve a dual purpose: they boost crop productivity and address the acidification and nutrient depletion pathways identified as dominant land degradation processes in Meghalaya (Das *et al.*, 2026). Finally, the distribution of suitability by slope class has direct implications for conservation planning. The 7.13% of the study area classified as marginally suitable due to slopes of 50–60% is explicitly not recommended for orchard development in this study. However, these areas overlap with some of the highest erosion-risk terrain in the region. For these marginal slope lands, the diversification plan suggests integrating soil and water conservation infrastructure—such as contour bunds, check dams, and vegetative barriers—before any agricultural use, or prioritizing their conversion to afforestation with native species as a permanent erosion control measure.

3.6 | Horticultural Diversification Plan

The multi-crop spatial overlay analysis identifies 64,485.92 ha as suitable for at least one of the three target crops (*Table 9*). The diversification plan is structured around four landscape-level categories:

Zone 1 — Integrated Three-Fruit Systems (24,259.52 ha, S1S1S1): These areas, concentrated in West Khasi Hills (particularly Nongstoin and Mawthadraishan blocks), East Khasi Hills, and West Jaintia Hills, offer optimal conditions for high-density integrated orchards combining apple, pear, and peach. These zones are the primary targets for infrastructure investment — including nursery establishment, cold storage, and all-weather road access — and for the development of high-value temperate fruit value chains.

Zone 2 — Pear–Peach Dual Systems (30,214.23 ha, highly suitable for pear and peach): These extensive zones, distributed across the Khasi and Jaintia Hills districts, are ideal for two-fruit systems where apple is precluded by insufficient chilling hours or elevation. Pear–peach intercropping systems offer complementary harvest timing and can optimize labour utilization across the growing season.

Zone 3 — Moderate Pear–Peach Zones with Improvement (5,453.83 ha, S2 for pear and peach): These areas are currently constrained by slope or soil depth

limitations but hold significant potential with targeted interventions including terracing or contour planting, soil amelioration, and water conservation structures. They are suitable for phased development after the priorities for Zones 1 and 2 are established.

Zone 4 — Pear Mono-Cropping (289.27 ha): Limited areas exclusively suited to pear may support mono-cropping where intercropping with other species is not feasible.

The transition from biophysical suitability to functional landscapes requires a complementary Micro-Level Validation phase integrating: socio-economic synthesis (overlaying suitability maps with household surveys assessing farmer willingness, land tenure, and labour availability); economic viability analysis (farm-level cost-benefit ratios for high-density orchards versus traditional systems); logistics and cold-chain assessment (proximity of suitable areas to road networks and refrigerated transport infrastructure); and value chain development (identification of locations for localized processing units for juices, jams, and preserved fruit to stabilize prices and reduce post-harvest losses).

TABLE 9 Horticultural Diversification Plan for Meghalaya based on multi-crop suitability

Suitability category	Area (ha)	Diversification Scope
Highly suitable for Apple, Pear, Peach	24,259.52	Best diversification zones, focus on 3-fruit systems
Highly suitable for Pear & Peach	30,214.23	Best diversification zones of pear & peach fruit crops
Moderately suitable for Pear & Peach	5,453.83	Moderate diversification zones with site improvement
Highly suitable for Pear	289.27	Pear mono-cropping recommended

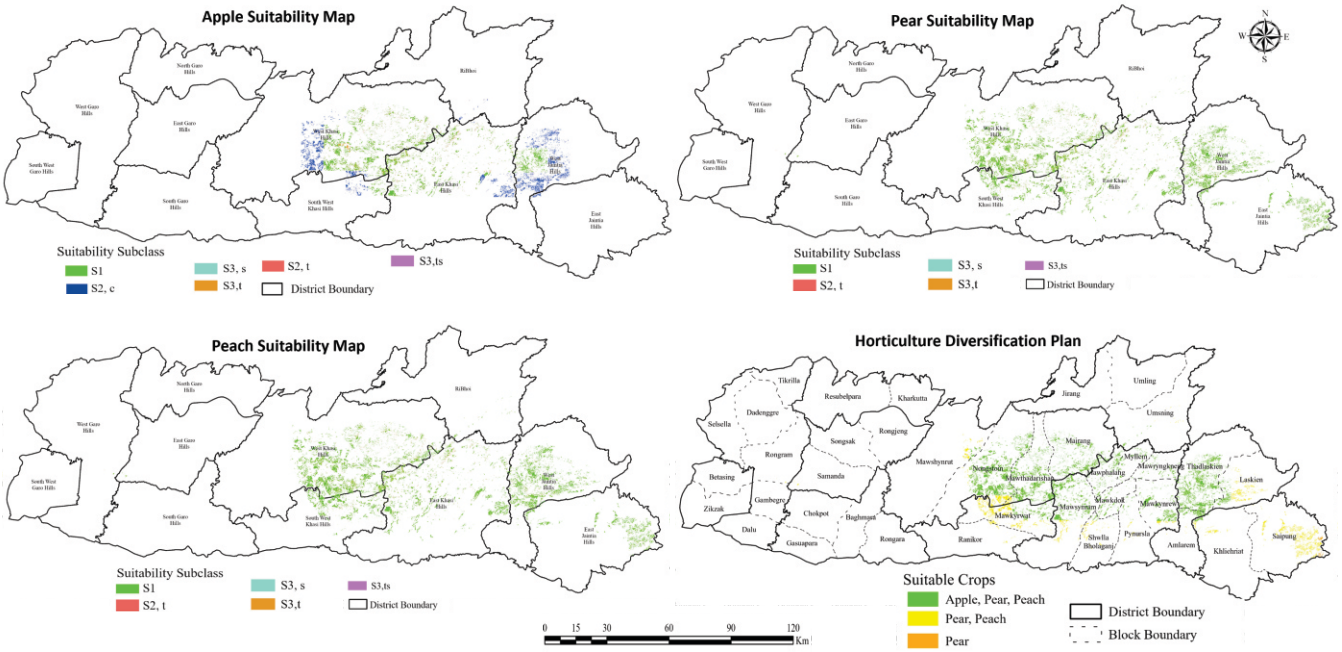


FIGURE 5 Suitable areas for apple, peach, pear and horticulture diversification plan

4 | CONCLUSIONS

This study successfully identifies significant untapped potential for horticultural diversification in Meghalaya, including apple, pear, and peach, across 64,485.92 ha of degraded and transitional land. Geospatial analysis delineates approximately 24,259 ha as highly suitable for all three species simultaneously — representing the most promising zones for intensive multi-crop orchard development and, critically, for landscape-scale soil stabilization in one of India's most erosion-vulnerable regions. The study demonstrates that the same biophysical conditions responsible for Meghalaya's land degradation challenge — steep slopes, high rainfall, and acidic shallow soils — can be turned into productive assets through the strategic placement of appropriate perennial fruit crops. The explicit integration of slope aspect as a microclimate modifier, the transparent parameterization of the FAO limitation scoring system, the field validation of suitability predictions across 785 locations, and the quantified soil conservation co-benefits of the diversification plan collectively strengthen the scientific and practical utility of this assessment. These findings provide policymakers, horticulture planners, and soil conservation practitioners with a common spatial evidence base for aligning crop promotion, nursery development, infrastructure investment, and watershed management priorities in Meghalaya. Future work should focus on farm-level economic validation, cultivar-specific chilling hour trials in identified S1 zones, and the integration of this suitability framework with real-time soil health monitoring networks to enable adaptive management of newly established orchards.

ACKNOWLEDGEMENTS

The authors express their sincere gratitude to the Meghalaya Small Farmers' Agri Business Consortium (MgSFAC) for providing financial support to carry out this work. They are thankful to the Director, Directorate of Horticulture, Government of Meghalaya, and the District Horticulture Officers for their continuous support and valuable inputs in finalizing the crop suitability criteria. The authors also acknowledge Dr. S. P. Aggarwal, Director, NESAC, for his encouragement and support in facilitating financial assistance, along with Dr. K. K. Sarma and Dr. B. K. Handique for their guidance and technical support throughout the study.

CONFLICT OF INTEREST

The author declare there is no conflict.

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available from the corresponding author upon reasonable request, subject to institutional permissions.

AUTHOR'S CONTRIBUTION

The first author conceptualized and designed the study. The second author performed data analysis and drafted the manuscript under the supervision of the first author. The first author reviewed and edited the manuscript. All authors approved the final version

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How to cite this article: Das, T, Pratibha and Maheshwari, T., 2025. Geospatial Assessment of Temperate Fruit Sites for Sustainable Horticultural Diversification in Meghalaya. *Indian J. Soil Cons*., **53(3) (***Hill & Mountain Agriculture S***pecial Issue)**: **260-270**

Received: 04 February 2026 | Accepted: 31 March 2026 | Published online: 06 April 2026

DOI: 10.53550/ijsc.v53.i3.210

ORIGINAL ARTICLE

Indian Journal of Soil Conservation

Assessing Feasible Weed Management Options in Maize under Organic Farming System of Eastern Himalayas

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Handling Editor:
Dr Raman Jeet Singh

Key words:
Benefit-cost ratio
Eastern himalayas
Intercropping
Mulching
Organic farming
Stale seedbed
Weed control efficiency
Weed index
Zea mays

ABSTRACT

Weed management under organic farming relies heavily on manual and mechanical methods, which are labour-intensive and costly, particularly in the high-rainfall hill ecosystems of North Eastern India. A field experiment was conducted for three consecutive years (2015–2017) on a long-term organic field (under organic management since 2005–06) at mid-altitude (950 m ASL) in Meghalaya to evaluate non-chemical weed management options for maize productivity, weed dynamics and soil health. Eight treatments were tested in a randomised block design, including hand weeding, mechanical weeding, soil solarization, mulching, stale seedbed preparation and maize–soybean intercropping. Among all treatments, two hand weedings at 20 and 45 days after sowing (DAS) recorded the lowest weed population (155.3/m²) and dry weight (75.3 g/m²) at 30 DAS. However, intercropping of maize with soybean (2:1) combined with one hand weeding at 45 DAS (T6) and stale seedbed + 25% reduced spacing + mulching with crop residues + one hand weeding at 45 DAS (T5) achieved significantly higher weed control efficiency at 60 DAS, the lowest weed indices (1.2 and 4.9%, respectively) and maize grain yields statistically at par with the weed-free check. T6 recorded the highest net returns (₹49,560/ha) and benefit–cost ratio (2.42), outperforming all other treatments, including the weed-free check, primarily due to lower weeding costs and the added benefit of biological nitrogen fixation by soybean. After three cropping cycles, T6 also recorded the highest soil organic carbon (22.3 g/kg), available nitrogen (272.5 kg/ha) and phosphorus (29.6 kg P_2O_5/ha), indicating concurrent improvement in soil health. Soil solarization performed poorly under the prevailing sub-32°C temperature regime of the region. Maize+soybean intercropping (2:1) with one hand weeding at 45 DAS is recommended as a practically viable, economically superior and soil health-enhancing weed management strategy for organic maize production in the North Eastern Hill Region of India.

1 | INTRODUCTION

In organic management systems, reducing weed competitiveness is essential due to limited weed control options (Das *et al*., 2016). Weeds can be managed through cultural and management practices that favor crops by altering soil biomass production (Ryan *et al*., 2010). In the North Eastern Hill Region (NEHR) of India, maize (*Zea mays* L.) is the second most important crop after rice, primarily grown under rainfed conditions (Layek *et al*., 2016). It is vital for local food security and economy, though regional yields are low due to various constraints despite high potential. Weed infestation significantly reduces maize yields, especially in high rainfall areas, with losses ranging from 28% to 100%, depending on infestation severity. Weed damage surpasses losses caused by pests like insects and diseases (Sharma *et al.*, 2010), as weeds compete for space, sunlight, moisture, and nutrients, limiting crop resource uptake (Lehoczky and Reisinger 2003; Kumar *et al*., 2013). In the NER's favorable climate with high rainfall and suitable temperatures, maize during the kharif season faces severe weed problems, especially in early growth stages from germination to 45 DAS (Saeed *et al*., 2010). Weeds also serve as hosts for pests and diseases (Essien *et al*. 2009; Das *et al*., 2016). Organic farming systems tend to exacerbate weed issues due to the use of undecomposed organic manure, mulches, and crop biomass, which promote weed growth (Ryan *et al*., 2010; Das *et al*., 2016). As chemical control is not an option in organic systems, managing weeds relies on integrated methods that combine physical, mechanical, cultural, and biological practices to keep weeds below economic damage levels rather than complete eradication (Das *et al*., 2019). Hand weeding is common in NEHR but is labor-intensive, costly, and time-consuming, especially for small farmers (Essien *et al*.,

2009; Das *et al.*, 2016). Mechanical tools, such as wheel hoes, are also promoted for timely weed removal, reducing farmer effort. Since maize weeding often overlaps with rice nursery and field prep, labor availability becomes limited. Intercropping and mulching are effective chemical-free weed control (Meshram *et al.,* 2022); for example, maize intercropped with soybean and using soybean biomass as mulch can significantly reduce weed biomass through improved ground cover and better light utilization (Sani *et al.*, 2015, Ramkrsusn, G.I., 2022). Crop residue mulch suppresses weeds by creating physical barriers and altering the microclimate, thereby enhancing maize growth and yield (Mahmood *et al.*, 2015). The stale seedbed technique involves plowing, allowing weeds to emerge, then killing them before planting, which can reduce weed density but is not sufficient alone for continuous weed control; it should be part of an integrated weed management program. Soil solarization—covering soil with plastic to heat it—also effectively controls soil-borne pests, pathogens, and weeds (Leblanc & Cloutier, 1996). Given the importance of weed management in organic farming, this study explores various non-chemical practices to examine their effects on weed dynamics, maize productivity, and soil nutrients in mid-altitude regions of the Eastern Himalayas.

2 | MATERIALS AND METHODS

The field experiment was conducted in the mid-hills of Meghalaya, India, during the rainy season (Kharif) over three consecutive years (2015-2017) with maize as the test crop. The site was under organic production since 2005-06. The soil of the field study was sandy clay loam in texture, acidic (*p*H 5.4), and high in soil organic carbon (SOC) (18.0 g/kg). While available nitrogen (N) (229.5 kg/ha) and phosphorus (P_2O_5) (24.1 kg/ha) of the soil of the experimental field were recorded to be low, available potassium (K) was medium (265.3 kg/ha). The climatic conditions of this region are subtropical, hot and humid in summer, and cold in winter. A graphical representation of average weather parameters, including maximum temperature, minimum temperature, and rainfall, for the entire experimental season of 2015- 2017 is shown in Figure 1. The monsoon usually starts from the first week of June and extends up to October, whereas the pre-monsoon showers start from April. Although there was little variation in total rainfall over the cropping cycles, total annual rainfall was at par with the 30-year average (2450 mm/year). The mean minimum and maximum temperatures at the experimental location over three years (2015-17) were 11.8 to 21.7°C and 21.6 to 29.8°C, respectively (Fig.1).

The experiment was conducted in a randomized block design (RBD) with eight weed control treatments and replicated thrice. Treatments were T_1: Two hand weeding at 20 DAS and 45 DAS, T_2: One mechanical weeding at 20 DAS + one hand weeding at 45 DAS, T_3: Soil solarization + one hand weeding at 35 DAS, T_4: Mulching with locally available weed mulch + one hand weeding at 35 DAS, T_5: Stale seedbed preparation + reduced spacing (upto 25%) + mulching with previous crop residue + one hand weeding at 45 DAS, T_6: Intercropping with soybean (2:1) + one hand weeding at 45 DAS, T_7: Weed free check (hand weeding at 15, 25, 40, 55 and 70 DAS) and T_8: Weedy check (no weeding). Mechanical weeding was performed with the help of a wheel hoe. Soil solarization was performed using a transparent polythene sheet (150 gauge) to trap solar energy and raise soil surface temperatures for 10 days. Stale seedbeds were prepared by plowing the soil to a depth of 15 cm two weeks before the normal plowing time, allowing weeds to emerge and be killed by subsequent plowing (once). Thereafter, maize (composite cv. RCM 1-61) was sown in late May–early June without further plowing the soil. Under intercropping treatment (T_6), one line/row of soybean (cv. JS 335) was grown after every two lines/rows of maize (sown at 50 cm spacing) by reducing the space in-between maize rows (additive series, without reducing the plant population of maize and incorporated in the soil at 45 DAS during earthing up of maize. The maize crop was grown with an organic nutrient source to supply the recommended dose of 80:60:40 kg N, P2O5, and K_2O/ha. Soil solarization and stale seedbed preparation were done 10–15 days and about 2 weeks before sowing, respectively. Well-decomposed farmyard manure (FYM) was used as a source of nutrients (0.5% N) on an N equivalent basis to supply the required dose of N, and rock phosphate was used to compensate for the P requirement. Soil-borne pathogens were controlled by applying neem cake at 150 kg/ha as a general dose across all treatments. Data on weeds (population, dry weight) were recorded at 30 and 60 DAS from two randomly selected quadrants (0.5 x 0.5 m) from each treatment during the maize growing period.

HIGHLIGHTS

- Maize–soybean intercropping (2:1) with one hand weeding gave the highest net returns and B:C ratio under organic management.
- Intercropping and stale seedbed + mulching treatments matched weed-free yield without five-time hand weeding costs.
- Soybean intercropping maximised soil nitrogen, phosphorus and organic carbon after three cropping cycles.
- Non-chemical weed management combining cultural practices can sustain maize productivity in high-rainfall hill ecosystems.

Weed control efficiency (WCE) and weed index (WI) were calculated using the following formulae from Mani *et al*. (1973).

$$WCE = \frac{\text{Weed dry weight in unweeded control} - \text{weed dry weight in treatment plots}}{\text{Weed dry weight in unweeded control plots}}$$

$$WI = \frac{\text{Maize yield in weed free plots} - \text{Maize yield in treatment plots}}{\text{Maize yield in weed free plots}}$$

Weed control efficiency (WCE) was calculated based on weed biomass reduction relative to the unweeded control (weedy check), whereas weed index (WI) was calculated

using crop yield reduction relative to the weed-free check. Yield attributes of maize, including grain yield, were recorded for each treatment at the harvesting stage. Cost of cultivation was computed by taking the prevailing market price of the inputs during the experimental period, while gross returns were obtained by multiplying the grain yield by the market price. Composite soil samples (after 3 years) were collected initially and at the post-harvest stage from the surface layer of different plots and were analyzed for available N, P, K status, SOC, and soil microbial biomass carbon (SMBC). The soil samples collected from different treatment plots were air-dried, processed, and then passed through a 2 mm sieve to determine the availability of various nutrients in the soil. While the soil available N was measured by the alkaline permanganate method (Subbiah & Asija, 1956), the available P and K were measured by the $NaHCO_3$ extraction method (Olsen & Sommers, 1982) and neutral normal NH_4OAC extraction method (Knudsen *et al.,* 1982), respectively. The soil microbial biomass carbon (SMBC) was estimated by soil fumigation method of Anderson and Ingram (1993). The data on different parameters collected from the experiment were statistically analyzed using the analysis of variance (ANOVA) technique, with the "F" test, and the significance of treatment differences was assessed using the t-test (Gomez & Gomez, 1984). Standard error of means (SEm±) and critical difference (CD) at 5% probability (P=0.05) were calculated for each parameter studied in the experiment to evaluate differences between treatment means.

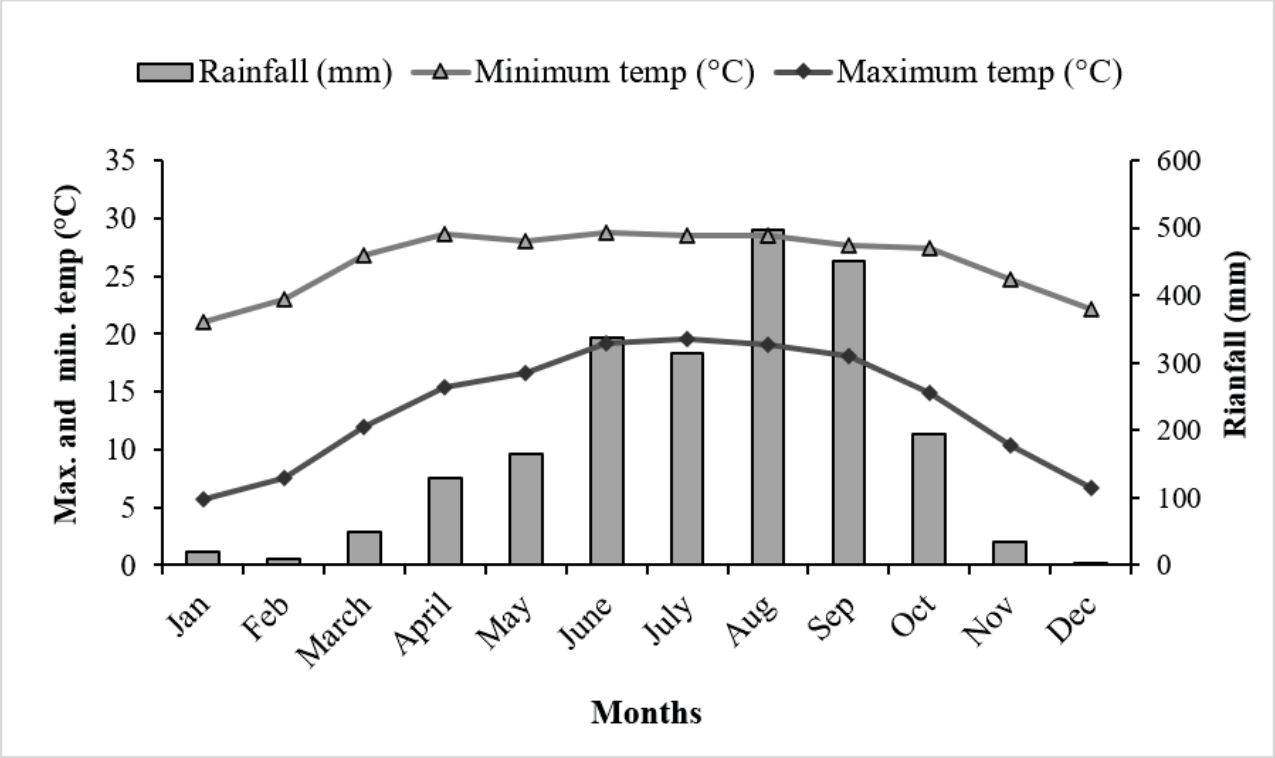


FIGURE 1 Average monthly weather parameters of the ICAR Research Complex for NEH Region, Umiam (mean data of 2015- 2017)

3 | RESULTS AND DISCUSSION

3.1 | Effect on Weed Population Dynamics and Weed Control Indices

The dominant weed species observed in the experimental period during the rainy season were classified into grasses (*Cynodon dactylon, Digitaria sanguinalis, Panicum repens, and Eleusine indica*), sedges (*Fimbristylis miliacea and Cyperus rotundus*), and broad-leaved weeds (*Ageratum conyzoides, Spilanthus acemella, Alternanthera philoxeroides, Galinsoga parviflora,* etc.). Regardless of weed control option, the highest weed count was recorded in the broad-leaved category, followed by grasses and sedges. For all weed management options, weed dry weight at 30 DAS was superior to that at 60 DAS, except for the weedy check (Table 1). Aside from the weedy check, all non-chemical weed control options were effective in reducing total weed density and dry matter (Table 1). Gul *et al*. (2009) also reported that weed biomass at 60 DAS was lower than at 30 DAS, as increased maize canopy covered the soil surface, which otherwise favored weed growth, thereby suppressing weeds at later growth stages. Minimum weed population and dry weight at 30 and 60 DAS were recorded under weed-free check (T_7). Among different non-chemical weed management options, two HW at 20 & 45 DAS (T_1) recorded significantly lower numbers of weed population (155.3/m^2) and weed dry weight (75.3 g/m^2), followed by one mechanical weeding at 20 DAS and one HW at 45 DAS (T_2) (194.0 and 85.0 g/m^2, respectively). Hand weeding is widely recognized as an effective tool for controlling weeds

compared with other non-chemical weed management practices (Syawal, 1998; Khan *et al*., 1998; Das *et al*., 2016). Although the stale seedbed + 25% reduced spacing + mulching + one HW at 45 DAS (T_5) and intercropping of maize with soybean (2:1) + one HW at 45 DAS (T_6) did not reduce the weed density to a great extent at 30 DAS, but for later stages (60 DAS), the weed population decreased significantly. The treatments, *viz.* T_5 and T_6 reduced the weed population by 73 and 71% at 60 DAS, respectively, as compared to the weed-free check (T_7). This is mainly due to good land coverage from intercropping soybean (Layek *et al*. 2014a & b) and their subsequent incorporation as mulch at 45 DAS. Although the maximum WCE was recorded under weed-free conditions at 30 and 60 DAS (97.3 and 98.5%, respectively), it was not possible in actual farm conditions to keep the field completely weed-free by making five (5) HW at 15, 25, 40, 55, and 70 DAS. Among the different feasible weed management options, significantly higher WCE at 30 DAS was recorded under two HW at 20 & 45 DAS (82.8%) followed by one mechanical weeding at 20 DAS and one HW at 45 DAS (T_2) (78.7%). However, at later stages of maize growth (60 DAS), apart from weeding using HW and mechanical weeding (T_1 and T_2), intercropping with soybean + one HW at 45 DAS (T_6) and stale seedbed + reduced spacing + mulching + one HW at 45 DAS (T_5) enhanced the WCE significantly over the other non-chemical weed management options. Significantly, the lower weed index (WI) was also recorded for T_6 (1.2 %) and T_5 (4.9 %) as compared to soil solarization + one HW at 35 DAS (T_3, 18.1%). It is acknowledged that the difference in hand weeding timing (35 DAS in T3 vs. 45 DAS in T5 and T6) may have influenced treatment performance. The relatively poorer performance of the soil solarization treatment (T3) could therefore be attributed not only to suboptimal soil temperature conditions under the prevailing climate, but also to the comparatively earlier timing of hand weeding, which may not have effectively controlled later-emerging weeds.

Weed index (yield basis) was recorded the lowest under soybean intercropping (2:1) + one HW at 45 DAS followed by stale seedbed + reduced spacing (upto 25%) + mulching with previous crop residues + one HW at 45 DAS and locally available weed mulch + one HW at 35 DAS. Intercropping of soybean in between maize lines without reducing the plant population of maize (additive series), not only helps in controlling weed control but also enhances the soil fertility through biologically fixed nitrogen (*Layek et al.,* 2014a & b). Therefore, intercropping of soybean in between maize and one HW at 45 days enhanced the maize yield as compared to other treatments and recorded lower weed index.

TABLE 1 Effect of different organic weed management options on weed population density and weed control indices in maize (pooled data of 3 years)

Treatments	Weed population (number m^{-2})		Dry weight (g m^{-2})		Weed control efficiency (%)		Weed index* (yield basis)
	30 DAS	60 DAS	30 DAS	60 DAS	30 DAS	60 DAS	
T_1: Two hand weeding (HW) at 20 and 45 DAS	155.3	75.3	7.1	6.5	82.8	89.5	7.2
T_2: One mechanical weeding (20 DAS) + one HW (45 DAS)	194.0	85.0	8.8	5.1	78.7	91.8	9.8
T_3: Soil solarization + one HW at 35 DAS	373.3	95.3	22.1	7.5	46.6	87.9	18.1
T_4: Locally available weed mulch + one HW at 35 DAS	291.0	89.3	14.0	9.5	66.2	84.7	5.9
T_5: Stale seed bed + 25% reduced spacing + mulching with previous crop residues + one HW at 45 DAS	242.0	85.7	12.3	7.2	70.2	88.4	4.9
T_6: Intercropping with soybean (2:1) + one HW at 45 DAS	234.7	91.1	15.2	6.3	63.1	89.8	1.2
T_7: Weed free check (HW at 15, 25, 40, 55 and 70 DAS)	14.7	6.3	1.1	0.9	97.3	98.5	0.0
T_8: Weedy check (no weeding)	449.0	317.0	41.3	61.9	0.0	0.0	66.8
SEm (±)	3.6	2.9	0.3	0.2	2.4	2.7	0.3
CD (P=0.05)	10.9	8.8	1.0	0.7	7.2	8.1	0.9

**Weed Index values were calculated from individual years before pooling; minor differences between WI values in Table 1 and those derived from pooled means in Table 2 result from rounding.*

3.2 | Maize Grain Yield

All the non-chemical weed control options significantly affected the pooled maize yield over the years compared with the weedy check (Fig 2). Among different weed control treatments in maize, intercropping with soybean (2:1) + one HW at 45 DAS (T_6) followed by stale seedbed + reduced spacing (upto 25%) + mulching + one HW at 45 DAS (T_5) and locally available weed mulch + one HW at 35 DAS (T_4) recorded relatively higher maize grain yield against other weed control options (*Table 2*). However, these were statistically at par with the treatment weed-free check (T_7) and treatments having two HW (T_1) and one MW and one HW (T_2). Higher maize yields under T6 and T5 may be due to enhanced soil fertility from N fixation by soybean and decomposition of mulch materials in soil, in addition to reduced weed population. The grain yield of maize was relatively higher under the maize + soybean treatment in the 1st year, and it increased significantly in subsequent years. This may be due to enhanced N availability in soil, favored by biologically fixed N from the associated intercropped soybean (Layek *et al*., 2014b). This trend of increasing maize yield over the years is also evident in the mulching treatments, *viz.,* T_4(locally available weed mulch + one HW) and T_5 (stale seed bed + mulching + one HW) (Das *et al*. 2016). Mulching with crop residues and locally available weeds not only reduces weed populations but also enriches the soil with organic carbon and available nutrients upon decomposition, thereby yielding prominent results in subsequent years (2nd and 3rd year) of the experiment (Das *et al*. 2016). Mulching helped supply nutrients and conserve soil moisture, while smothering weeds, resulting in enhanced maize yields from the 2nd year onwards. Mulch biomass, along with applied manure, might have contributed to increased maize yield (Sharma & Acharya, 2000; Sharma *et al*., 2010; Das et al., 2016). Although the highest yield was recorded under the weed-free check (T7), yield enhancement was not statistically significant compared with treatments with intercropping and mulching options (T4, T5, and T6), confirming the findings of Saini *et al*. (2013). The lowest yield was recorded in the weedy check (no weeding) (T8), followed by soil solarization + one HW at 35 DAS (T_3). As the maximum temperature in the experiment area (ICAR Umiam center) generally does not exceed 32-33°C, soil solarization could not achieve the desired results in areas with high temperatures.

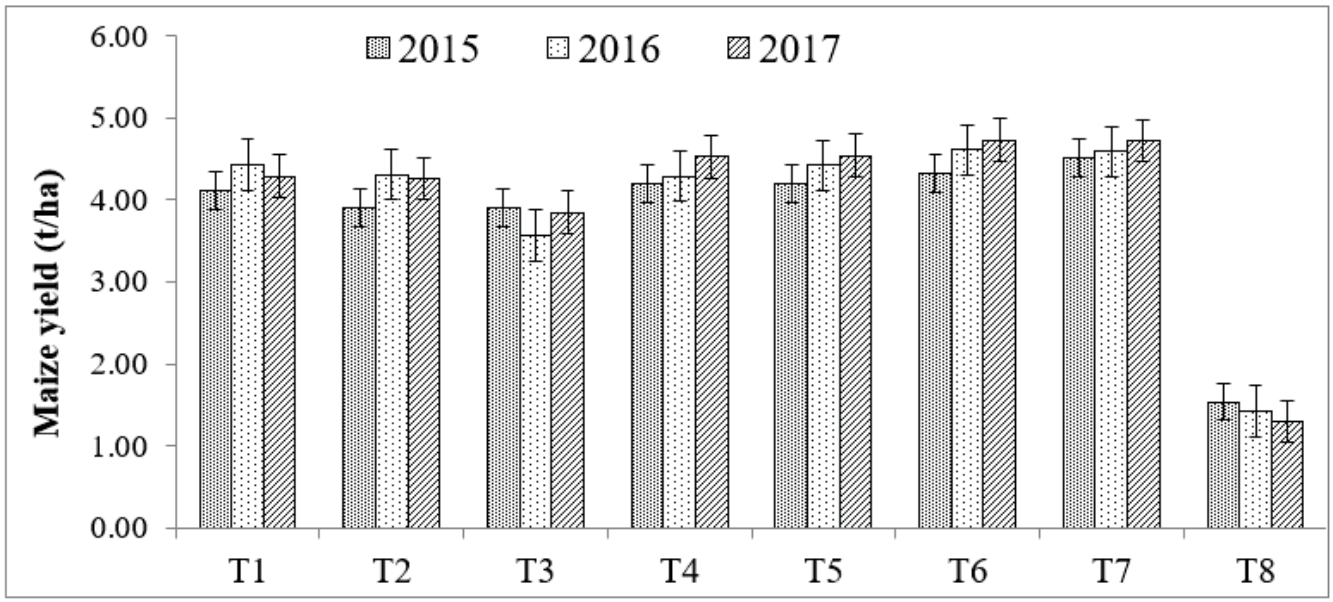


FIGURE 2 Grain yield of maize as influenced by different non-chemical weed management options over the years

Vertical bar represents both way CD (P=0.05)

T_1: Two hand weeding (HW) at 20 and 45 DAS
T_2: One mechanical weeding (20 DAS) + one HW (45 DAS)
T_3: Soil solarization + one HW at 35 DAS
T_4: Locally available weed mulch + one HW at 35 DAS
T_5: Stale seed bed + 25% reduced spacing + mulching + one HW at 45 DAS
T_6: Intercropping with soybean (2:1) + one HW at 45 DAS
T_7: Weed free check (HW at 15, 25, 40, 55 and 70 DAS)
T_8: Weedy check (no weeding)

TABLE 2 Productivity and economics of maize under different organic weed management options (pooled mean of three years)

Treatments	Maize yield (t ha^{-1})	Cost of cultivation (₹ ha^{-1})	Gross return (₹ ha^{-1})	Net return (₹ ha^{-1})	B:C ratio
T_1: Two hand weeding (HW) at 20 and 45 DAS	4.28	36,500	79,180	42,680	2.17
T_2: One mechanical weeding (20 DAS) + one HW (45 DAS)	4.16	34,600	76,960	42,360	2.22
T_3: Soil solarization + one HW at 35 DAS	3.78	43,200	69,930	26,730	1.62
T_4: Locally available weed mulch + one HW at 35 DAS	4.34	38,500	80,290	41,790	2.09
T_5: Stale seed bed + 25% reduced spacing + mulching with previous crop residues + one HW at 45 DAS	4.38	36,970	81,030	44,060	2.19
T_6: Intercropping with soybean (2:1) + one HW at 45 DAS	4.56	34,800	84,360	49,560	2.42
T_7: Weed free check (HW at 15, 25, 40, 55 and 70 DAS)	4.61	48,600	85,285	36,685	1.75
T_8: Weedy check (no weeding)	1.42	20,500	28,305	7,805	1.38
SEm (±)	0.09	1,159	1,822	907	0.05
CD (P=0.05)	0.27	3,515	5,525	2,750	0.16

3.3 | Economics

The cost of maize cultivation was the least with one mechanical weeding at 20 DAS and one HW at 45 DAS, due to the combined use of mechanical tools and manual hand weeding, thereby reducing labor costs (Table 2). The highest cultivation cost was observed under the weed-free check (T7), followed by soil solarization + one HW (T_3). The higher cultivation costs under T7 and T3 were due to the higher labor requirements for HW (5 times) and the higher cost of transparent polythene sheet required for soil solarization. The weed-free check (T7) yielded the highest gross return (₹85,285/ha), followed by maize + soybean intercropping with one HW (T6; ₹84,360/ha) and stale seedbed + mulching + one HW (₹81,030/ha). However, the maximum net return was obtained under maize + soybean intercropping along with one HW (T_6; ₹ 49,560/ha) and stale seedbed + mulching + one HW (₹ 44,060/ha) and two hand weeding (HW) at 20 and 45 DAS (T_1; ₹ 42,680/ha). The weed-free check required five HW, which substantially increased costs; therefore, the net return under the weed-free check (T7) was substantially lower than under other weed control measures (Das *et al*., 2016). The higher net return under maize + soybean intercropping + one HW was due to the higher maize yield observed under the treatment and the lower weeding cost compared to the weed-free check (T_7). Maize intercropping with soybean recorded the highest gross and net returns due to higher maize yield owing to the supply of fixed N from the atmosphere by associated soybean and weed suppression from soybean mulch (Layek *et al*., 2014b; Das *et al*. 2016). The intercropping of maize + soybean is also known to complement each other. Maize is known as a nutrient-exhaustive crop (Ali *et al.,* 2012) and absorbs nutrients from the upper soil layers (Layek *et al.,* 2014a). Soybean, being a legume, enhances soil fertility through biological N fixation and reduces competition for soil nutrients by extracting nutrients from deeper soil strata through its taproot system (Layek *et al*., 2014b). The highest benefit cost ratio (BC ratio) was also recorded for maize + soybean intercropping + one HW (T_6; 2.42) followed by one mechanical weeding (20 DAS) + one HW (45 DAS) (T_2: 2.22) and stale seedbed + reduced spacing + mulching with previous crop residues + one HW at 45 DAS (T_5; 2.19).

3.4 | SOC and Nutrients Status in Soil

The nutrient availability in soil at the end of three years of cropping was significantly affected by different organic weed control options (Table 3). Most soil parameters, such as SOC, available N, P, K, and SMBC, improved after three cropping cycles compared with their initial levels. Intercropping with soybean (2:1) + one HW at 45 DAS (T_6) being at par with the stale seedbed + 25% reduced spacing + mulching + one HW at 45 DAS (T_5) and locally available weed mulch + one HW (T_4) recorded significantly higher SOC (22.3, 22.1 and 21.9 g/kg, respectively) after 3 cropping cycles as compared to weedy check (19.6 g/kg). The improvement under T6 can be explained through a sequence of processes. Initially, soybeans contributed to biological nitrogen fixation, which enhanced soil available nitrogen, reflected in the highest available N (272.5 kg/ha) and P (29.6 kg P_2O_5/ha) under this treatment. Part of the fixed N was utilized by crops, while the remaining contributed to residual soil fertility (Layek *et al.*, 2014b). The increased nutrient availability, along with the addition of root biomass and residues, stimulated soil microbial activity, resulting in higher microbial biomass carbon (SMBC). Although the highest SMBC was recorded under T4 (330.9 µg g^{-1}), it remained comparably high under T5 and T6, indicating favorable microbial conditions. Enhanced microbial activity further facilitated decomposition of organic inputs, root exudates, and incorporated biomass, ultimately leading to increased soil organic carbon (SOC). Similarly, mulching treatments (T4 and T5) improved soil properties by adding organic residues, which supplied carbon and nutrients upon decomposition (Das et al. 2016). These organic inputs also created a favorable microclimate for microbial proliferation, thereby enhancing SMBC (Ngangom *et al.*, 2020). The relative increase in SOC, available N, and P under T6 was 20.5%, 18.7%, and 22.8%, respectively, over initial values. However, available K did not differ significantly among treatments after three cropping cycles. A multi-criteria assessment (Table 4) indicated that maize + soybean intercropping (T6) performed best overall by balancing

productivity, profitability, and soil health benefits, despite slightly lower weed suppression compared to the weed-free treatment.

TABLE 3 Effect of organic weed management options on soil organic carbon, microbial biomass and available nutrient after three cropping cycles

Treatments	SOC ($g\ kg^{-1}$)	Availiable N ($kg\ ha^{-1}$)	Availiable P_2O_5 ($kg\ ha^{-1}$)	Availiable K_2O ($kg\ ha^{-1}$)	SMBC ($\mu g\ g^{-1}$ dry soil)
T_1: Two hand weeding (HW) at 20 and 45 DAS	20.9	241.1	26.9	274.3	288.3
T_2: One mechanical weeding (20 DAS) + one HW (45 DAS)	19.8	238.4	26.6	271.5	279.9
T_3: Soil solarization + one HW at 35 DAS	19.7	231.2	25.2	261.6	271.3
T_4: Locally available weed mulch + one HW at 35 DAS	21.9	249.3	28.2	283.2	330.9
T_5: Stale seed bed + 25% reduced spacing + mulching with previous crop residues + one HW at 45 DAS	22.1	253.7	28.9	285.1	327.2
T_6: Intercropping with soybean (2:1) + one HW at 45 DAS	22.3	272.5	29.6	271.5	315.3
T_7: Weed free check (HW at 15, 25, 40, 55 and 70 DAS)	21.0	241.2	27.2	275.3	278.2
T_8: Weedy check (no weeding)	19.6	237.2	24.2	271.3	303.6
Initial value	18.0	229.5	24.1	265.3	242.1
SEm (±)	0.7	6.1	0.8	9.3	7.6
CD (P=0.05)	2.1	18.6	2.5	NS	23.2

TABLE 4 Comparative performance of weed management treatments across key criteria (pooled basis)

Treatments	Weed suppression	Yield performance	Net return	B:C ratio	Soil health improvement	Overall ranking
T1: Two hand weeding (HW) at 20 and 45 DAS	High	Medium	Medium	Medium	Medium	Moderate
T2: One mechanical weeding (20 DAS) + one HW (45 DAS)	High	Medium	Medium	High	Medium	Moderate
T3: Soil solarization + one HW at 35 DAS	Low	Low	Low	Low	Low	Poor
T4: Locally available weed mulch + one HW at 35 DAS	Medium	Medium-High	Medium	Medium	High	Good
T5: Stale seed bed + 25% reduced spacing + mulching with	Medium-High	High	High	High	High	Very good
T6: Previous crop residues + one HW at 45 DAS	Medium-High	High	Highest	Highest	Highest	Best
T7: Intercropping with soybean (2:1) + one HW at 45 DAS	Highest	Highest	Medium	Low	Medium	Good (not practical)
T8: Weed free check (HW at 15, 25, 40, 55 and 70 DAS)	Very low	Very low	Very low	Low	Low	Poor

4 | CONCLUSIONS

A three-year experiment in Meghalaya's organic maize system shows that effective weed management is possible without total eradication, using a mix of cultural and mechanical practices. Among non-chemical options, maize–soybean intercropping (2:1) with one weeding at 45 DAS proved most viable, yielding 4.56 t/ha and matching weed-free yields, with the lowest weed index (1.2%), highest net returns (₹49,560/ha), and benefit–cost ratio (2.42). Soybean's dual role—canopy cover and nitrogen fixation—enhances weed suppression and soil health, with benefits accumulating over three cycles. Second-best was a stale seedbed with 25% reduced spacing, mulching, and one weeding at 45 DAS, providing good weed control and soil carbon, suited for farmers unable to intercrop. Two hand weedings at 20 and 45 DAS effectively suppressed weeds but with higher labour costs. Soil solarization was ineffective due to regional temperatures (~32–33°C). Treatments with soybean intercropping and mulching improved soil organic carbon, nitrogen, and phosphorus, emphasizing the importance of soil health in organic weed management. Overall, maize–soybean intercropping with one weeding is recommended for India's northeastern high-rainfall hill regions, where not feasible, stale seedbed with

reduced spacing, mulching, and weeding offers a reliable alternative.

ACKNOWLEDGEMENTS

The authors earnestly acknowledge and appreciate ICAR Indian Institute of Farming Systems Research (IIFSR), Modipuram for all the necessary technical and financial support during the research pursuit under the project 'Network Project on Organic Farming (NPOF)'.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

AUTHOR'S CONTRIBUTION

Conceptualization and supervision: A.D.; Investigation and data collection: J.L., K.R., S.P., R.T., and L.G.M.; Data analysis and interpretation: J.L. and A.D.; Manuscript drafting: J.L.; Manuscript review and editing: A.D., P.B., S.B., R.G., and J.S. All authors have read and approved the final version of the manuscript.

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How to cite this article: Layek, J., Das, A., Krishnappa, R., Patra, S., Ramesh, T., Baiswar, P., Babu, S., Ramkrushna, GI., Soni, J. and Mawlong, LG. 2025. Assessing Feasible Weed Management Options in Maize under Organic Farming System of Eastern Himalayas. *Indian J. Soil Cons*., **53(3)** (*Hill & Mountain Agriculture S*pecial Issue)**: 271-278**

Received: 09 September 2025 | Accepted: 19 December 2025 | Published online: 06 April 2026

DOI: 10.53550/ijsc.v53.i3.211

ORIGINAL ARTICLE

Indian Journal of Soil Conservation

Thematic Synthesis of Indigenous Technical Knowledge Relevant To Hill And Mountain Ecosystems: The Shivaliks of North India As A Representative Case

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Handling Editor:
Dr Rajive K. Singh

Key words:
Drainage System
Indigenous flora
Land development
Shivalik ecosystem
Traditional knowledge
Water resource development

ABSTRACT

Indigenous technical knowledge (ITK) comprises time-tested practices refined by farmers through continuous experimentation and innovation. Despite being eco-friendly, cost-effective, and readily accessible, ITK remains underutilized in modern conservation programs. This paper presents a thematic synthesis of ITK practices in the Shivalik region of North India, based on 30 years of field experience across 4.2 million hectares in five northern states. Data were compiled through interactions with farmers and village elders, group discussions, field observations, case studies, and validation by extension personnel. The study documents ITK-based practices for land development (field bunding, terracing, fertility maintenance), water resource management (Kuhl irrigation systems, village ponds, spring harvesting), drainage management (diversion ditches, bio-engineering), and indigenous flora management (agroforestry, grasslands, bio-fencing). Additional practices include organic mulching, the use of farmyard manure, and wildlife management strategies. The synthesis demonstrates that farmers function as practical engineers, integrating local flora and materials through simple, effective methods refined by critical analysis of past experiences. Integration of ITK with modern scientific knowledge is essential for sustainable, climate-resilient agricultural development in hill and mountain ecosystems. The findings provide a framework for incorporating ITK into watershed development programs and soil conservation policies.

1 | INTRODUCTION

Indigenous Technical Knowledge (ITK) gained international recognition through the World Conservation Strategy deliberated by the International Union for Conservation of Natural Resources in 1980, followed by the Bruntland Commission and World Commission on Environment and Development in 1987. The concept gained further momentum at the United Nations Conference on Environment and Education. ITK is defined as knowledge built by communities through generations of living in close contact with nature, developed under conditions specific to particular geographical areas. These practices are eco-friendly, cost-effective, time-tested, and refined through constant experimentation and innovation. Despite growing awareness about natural resource degradation, indigenous soil and water conservation knowledge (ISWCK) has been largely ignored and poorly integrated into emerging conservation technologies (Farrington & Martin, 1988). Farmers have fought soil erosion using locally available materials and indigenous plant species, drawing upon traditional knowledge and skills (Chambers *et al*., 1989). The critical analysis of ethno-engineering techniques and their positive impacts has seldom been a priority in research and extension (Jodha, 1990). However, during the 1980s, the importance of indigenous knowledge, local skills, perceptions, and community priorities gained prominence when participatory approaches became essential for sustainable soil and water conservation (Chambers, 1983; McCracken *et al.*, 1988). Reij (1991) advocated for increased awareness of indigenous conservation techniques to improve understanding and effectiveness.

Recent studies have reinforced ITK's relevance. Barman et al. (2024) highlighted ITK's role in promoting ecological sustainability and resilience through practices like green manuring, vermicomposting, traditional irrigation, and climate-adapted crop varieties. Integration of these systems into modern agriculture enhances resource efficiency and rural community wellbeing. India's diverse traditions and tribal knowledge have sustained agriculture and rural livelihoods (Sindhu & Malik, 2020), with North Eastern India demonstrating comprehensive organic farming systems from seed germination to storage (Santosh & Chhetry, 2012). Kharbani and Sawian (2022) emphasized that biodiversity underpins sustainable agriculture in India,

with crop and livestock diversification improving ecosystem stability and providing insurance against climate variability. Traditional polyculture systems in North-East India and the Western Ghats minimize crop losses from pests, diseases, and adverse weather. Barua and Mitra (2024) noted that indigenous knowledge significantly improves climate resilience through long-tested techniques. Austin et al. (2013) documented traditional hill irrigation methods and community-based management, noting the priority given to drinking water over irrigation. Arora and Hadda (2006) described ITK in Shivalik foothills including field bunding, terracing, filler strips, soil mulching, organic farming, and rainwater harvesting, recommending scientific refinement to realize full potential. Farrington and Martin (1988) and Chambers et al. (1989) emphasized that indigenous natural resource management techniques, though time-tested and cost-effective, have been insufficiently incorporated into project implementations.

The Integrated Watershed Development Project funded by the World Bank operated in the Shivalik foothills of five northern states from 1991. Project management decided to explore integration of indigenous soil and water conservation techniques into treatment menus for current and future projects (Grewal, 1996). As part of this and subsequent projects, the author documented and validated ITKs, continuously expanding and revising the compilation over several years. This paper synthesizes these findings, focusing on integration, lessons learned, and relevance of indigenous technical knowledge for hill and mountain ecosystems.

HIGHLIGHTS

- Comprehensive ITK documentation from 30-year synthesis across 4.2 million hectares in five Shivalik states, documenting validated indigenous practices for hill ecosystem management.
- Indigenous knowledge systematically organized into seven categories of land development, water resources, drainage management, flora management, farmyard manure use, wildlife control, and energy sources.
- Traditional practices deliver multiple ecosystem services, such as food security, water conservation, soil fertility, climate resilience, carbon sequestration, and biodiversity protection simultaneously.
- Government programs integrate ITK but overemphasize mechanical measures while neglecting biological solutions, requiring enhanced extension worker training and farmer participation.

2 | MATERIALS AND METHODS

2.1 | Study Area

This synthesis is based on 30 years of field experience across the Shivaliks of five northern Indian states (Punjab, Haryana, Himachal Pradesh, Uttarakhand, and Jammu & Kashmir), covering 4.2 million hectares. The Shivalik region is a fragile hill ecosystem characterized by steep slopes, high runoff intensity, geological fragility, climate variability, and limited access to capital for hill farmers.

2.2 | Data Collection And Validation

The compilation draws from multiple sources:

- Interactions with practical farmers, village elders, and traditional knowledge holders
- Semi-structured interviews and targeted group discussions
- Field observations and case studies
- Targeted surveys and participatory rural appraisals
- Published literature in multiple languages

All observations were discussed and validated through consultations with frontline field functionaries from relevant departments across project areas in five states, as well as with other extension personnel. This multi-stage validation ensured the reliability of the documented indigenous practices.

2.3 | Analytical Framework

This study employed a deductive thematic analysis approach, a qualitative research method designed to identify themes and analyze responses to gain a deep understanding of recurring ideas and concepts. The methodology involved systematic collection of ITK practices from diverse sources; cross-verification with extension workers and technical experts; thematic categorization into seven major themes based on resource management focus; synthesis through integration with scientific literature and policy frameworks; and assessment of ecosystem services, implementation gaps, and integration opportunities. Kumar *et al.,* 2024 highlighted that evaluating ecosystem services has become an essential area of research indicating the vital benefits that natural environments provide to human societies. This manuscript presents a qualitative, experiential, and observational synthesis grounded in long-term field engagement and validated practices, rather than a conventional experimental or hypothesis-driven research study.

3 | RESULTS AND DISCUSSION

The indigenous practices documented across the Shivalik region are organized into seven thematic categories linked to the unique biophysical and socio-economic constraints of hill and mountain regions (Table 1). These practices address steep slopes, high runoff intensity, fragile geological formations, climate variability, remoteness, and limited capital access.

3.1 | Land Development Practices

3.1.1 | Field Bunding

Every cultivated field is surrounded by earthen bunds of variable size serving multiple functions: rainwater conservation, soil erosion control, boundary establishment, and land division for different crops and sequences. Grass stubble and boulders removed from fields are dumped on bunds. Breaches or damage by rodents receive regular repair. Both large and small farmers maintain field bunds diligently to prevent soil erosion (Anonymous, 1999a).

3.1.2 | Land Laveling

Forming level fields from sloping land involves cutting earth from higher elevations and filling lower areas. Since

topsoil is more fertile, farmers avoid disturbing it completely in a single operation. Fertility in leveled fields is restored through farmyard manure application. The leveling process uses a locally made wooden blade called 'Karaha,' pulled by bullocks with a sharp iron cutting edge (Photo 1). Two gradual leveling techniques are common:

1. **Plank method** : A plank gradually cuts soil from the top, depositing it as a thin sheet in depressed areas
2. **Barrier method** : Vegetation and stone barriers at field lower ends arrest runoff water carrying plowed soil down slopes after each rain. *Saccharum munja* (Kana) serves as an effective vegetative barrier (Verma, 1998).

TABLE 1 Summary of indegenous natural resource management practices

Category	Key Practices
Land Development	Field bunding, Land leveling, Terracing, Soil fertility maintenance
Water Resource Development	Kuhl irrigation system, Village ponds, Natural springs and wells
Drainage System Management	Diversion ditches, Field disposal of runoff, Bio-engineering for bank erosion control
Indigenous Flora Management	Agroforestry systems, Grassland management, Dry fodder preservation, Organic mulching, Bio-fencing, Bhabbar grass utilization, Fruits and vegetables
Farmyard Manure	Fertility recoupment, Energy provision, Seed germination, Moisture conservation, Soil health improvement
Wildlife Management	Crop selection, Scarecrows, Guard dogs, Bird deterrents, Noise-making devices

3.1.3 | Terracing

Gradual conversion of sloping land into leveled parcels represents an age-old practice throughout the region. Terracing reduces soil erosion, conserves rainwater, maintains soil fertility through continuous organic matter application, and facilitates plowing and cultural operations. Where stones and gravel are abundant, farmers remove them from fields and stack them on bunds to form stone walls, either at breach-prone lower elevations or continuously along fields.

Terrace quality improves continuously through stone and gravel removal, bund erosion protection, and manure addition. Key features of indigenous terracing include:

- Terrace width is inversely proportional to overland slope
- Contour alignment minimizing soil cut and fill
- Soil depth controlling terrace width
- Earthen bunds covered with local grasses, particularly *Cynodon dactylon* (Dub grass), with excellent soil binding capacity and nutritious fodder value
- Safe excess water disposal between terraces
- Table-top design for rice cultivation; sloped design for maize to facilitate water disposal (Verma, 1998)



PHOTO 1 Illustrates typical hill terraces supported by stone walls, with the bullock-drawn Karaha leveling technique shown

3.1.4 | Soil Fertility Maintenance

Rainfed farming systems in foothills operate at low productivity levels where nutrient depletion occurs primarily through soil erosion rather than crop uptake. In double-cropped areas with maize-wheat rotation, land is properly leveled and receives liberal farmyard manure (FYM) doses regularly. FYM application typically occurs in summer (June) before monsoon onset and maize sowing. Small landholdings with relatively high livestock populations ensure adequate FYM availability for most families. Indigenous soil fertility maintenance practices include:

- Leveling and terracing to prevent nutrient loss through runoff
- Regular liberal FYM application before kharif crop sowing
- Leguminous crop integration in rotations
- Contracting sheep and goat flocks from higher hills or local graziers to camp overnight in fields, adding manure through excreta and urine
- Weeds promoted by FYM in early maize growth plowed back at the knee-height stage (locally called 'HALODING'), incorporating them as green manure that decomposes rapidly due to moisture and high soil temperature
- Crop residue and stubble incorporation to recoup lost fertility (Patel, 1992a; Verma, 1998)

These land development practices ultimately enhance food security, farm income, and resource use efficiency.

3.2 | Water Resource Development

3.2.1 | Kuhl System Of Irrigation

Erstwhile foothill state rulers constructed numerous irrigation channels from both banks of perennial streams and rivers. These channels flow on mild gradients, providing drinking water for people and livestock and irrigation for adjacent lands. The town of Panchkula, near Chandigarh, exemplifies this system, named for five (Panch) Kuhls drawn from the Ghaggar River. A 'Barawandi' system determines irrigation turns and time allocation among beneficiaries. User groups jointly maintain and de-silt channels. At strategic locations, channels incorporate sudden drops where falling water energy operates local flour mills called 'GRAHTS.' This simple, cost-effective technique has sustained for extended periods and continues where electricity-powered mills are unavailable (Verma, 1998; Austin *et al*., 2013).

3.2.2 | Village Ponds

Almost every Shivalik village contains one or two traditional ponds dug primarily for livestock rainwater storage. Village size correlates with pond size, with both decreasing toward higher elevations. Ponds are typically located near villages to impound village runoff as well. Site selection favors relatively heavy, impervious soils. Ponds are commonly associated with Bargad (banyan), Pipal (sacred fig), other shade trees, small temples, and pucca meeting platforms around large trees. Some ponds are located away from villages near common grazing grounds. Pond capacity receives regular maintenance because the heavy pond soil serves for plastering mud houses. Pond soil rich in silt, clay, and manure also improves field soil fertility and moisture retention. Ponds facilitate groundwater recharge, microclimate improvement near habitats, and wildlife water provision. This community asset has survived centuries, remaining synchronized with rural settings and traditions (Singh and Khan, 1999).

3.2.3 | Natural Springs and Wells

Drinking water availability has always challenged the foothill ecosystem. Natural springs commonly found in hills are shaped with dressed stones to form clean water pools. Many springs are covered to prevent surface water contamination. Women bear the responsibility of water collection, carrying pitchers and brass containers (Gagars) on their heads between springs and scattered settlements. Subsurface flow in perennial drainage lines is tapped through strategically located wells that remain viable even during summer, though water levels decline seasonally. Wells traditionally use dressed stones laid in lime mortar, with tops approximately one meter above ground level. Pulley numbers (one to four) vary with well size. One well side is plastered for washing clothes and bathing. Surplus water flows through channels to mangers for livestock watering. These water resource development practices enhance water security, drought-proofing, and economic development (Kolarkar and Singh, 1990).

3.3 | Drainage System Management

3.3.1 | Diversion Ditches

Throughout the Shivalik region, hilltops and slopes support forests while valleys accommodate agriculture. Excess forest and valley runoff flows through defined drainage ways. Runoff from hill slope portions often spreads onto adjoining farmlands before reaching defined channels —typically manageable flows from one to two hectares of forest. Safe disposal of such overland flow protects farmland from erosion through diversion ditches constructed along forest-farm boundaries. These ditches follow hill footlines, intercepting rainwater and conveying it on mild gradients to nearby natural drainage ways. Interceptor ditches are maintained as small grassed waterways (Patnaik *et al.,* 1987).

3.3.2 | Field Disposal of Runoff Water

Rainfall intensity typically exceeds soil infiltration rates, causing even small storms to produce runoff. Without safe disposal into drainage systems, excess runoff breaches bunds and forms field gullies. Maize cultivation during kharif season is common in foothills, and maize cannot tolerate even short-term waterlogging. Excess water disposal from maize fields is necessary. Moreover, agricultural lands in foothills are seldom leveled sufficiently to prevent crop waterlogging, requiring regular excess rainwater disposal.

Common farmer-employed water disposal systems include:

- **Stone/gravel outlets**: Large stones and gravels interfering with cultivation are used for crude water disposal structures
- **Vegetative outlets**: *Arundo donax* (Nara) and *Saccharum munja* (Kana) are hardy perennial plants with strong root systems. Local Dub grass (*Cynodon dactylon*) occupies spaces between Kana and Nara barriers, further filtering water and checking bed erosion. These plants resprout in spring, forming effective vegetative barriers.

The indigenous water disposal systems integrate local materials (stones) and flora through simple, inexpensive, effective techniques (Subudhi and Mishra, 2002).

3.3.3 | Bio-engineering for Bank Erosion Control

Excess runoff from sloping fields and adjoining forests continuously scours gully beds and erodes drainage channel banks. Farmers maintain thick vegetation lines comprising trees, bushes, and natural flora along torrent banks to prevent bank erosion. In upper Shivaliks, Dhaman (*Grewia optiva*), Bamboo, and Banana are planted at curvatures and along moist torrent banks. In lower Shivaliks, *Ipomoea carnea*, *Arundo donax*, *Vitex negundo*, *Saccharum munja*, and *Agave americana* line banks. Among tree species, Jamun and Jamoa (*Syzygium* spp.) are preferred along relatively wet torrent beds, while Shisham (*Dalbergia sissoo*) is ideal for sandy torrent beds. *Arundo donax* is highly suitable for protecting against bank erosion. Some drainage ways through farmlands are so thickly planted with *A. donax* on both banks that bank erosion danger is eliminated. *Ipomoea carnea* is extensively planted for drainage way protection. Its easy propagation from sticks, establishment, quick growth, and suitability for bending along flow have made it popular. Farmers often embed dry *Ziziphus nummularia* branches in newly planted barriers/hedges to reduce water velocity, causing debris deposition. *Vitex negundo* is commonly planted along drainage ways and propagated vegetatively. Like willow, it establishes in moist gully beds with drooping branches that retard flow along banks. *Saccharum munja* and *Saccharum spontaneum* are also considered ideal for drainage way protection (Agrawal, 2006).

3.4 | Management of Indigenous Flora for Conservation and Production

3.4.1 | Agroforestry Systems

Resource-poor Shivalik farmers supplement low rainfed farm income by integrating trees with crops (agroforestry), primarily for income supplementation and economic security. Common agroforestry systems include:

Mango and Field Crops : Ambala and Hoshiarpur districts are renowned for desi mango orchards. Desi mangoes are preferred for hardiness and drought tolerance. During initial growth when tree canopies are undeveloped, field crops, oilseeds, and pulses (red gram, green gram, cluster bean) are raised with young mango trees.

Fodder trees and field crops: In areas near natural forests, green fodder needs are partially met by cutting branches from forest trees including Biul (*Grewia optiva*), Dhak (*Butea monosperma*), Khirak (*Anogeissus latifolia*), and Malta (*Ziziphus nummularia*). Tree lopping reduces shade to companion crops during winter. Nutrient-rich tree leaves, when mixed with inferior roughages, improve overall forage quality.

Acacia and forage crops: Acacia species tolerate drought, thriving on impoverished, degraded, and marginal lands. *Acacia catechu* (Khair) commonly grows on field bunds of arable and non-arable foothill lands. Forage crops (sorghum, pearl millet, cluster beans, oilseeds, pulses) are raised with these multipurpose trees.

These agroforestry systems provide forage security, soil and water conservation, and climate change adaptation (Gupta & Rajput, 2001).

3.4.2 | Grassland Management

Traditionally, the most unproductive land was allocated to pastures. Inadequate soil depth, inundation danger, flooding, and excessive gravels limit field crop scope but allow grass growth. Private pasture lands (Ghasnis) maintain better conditions due to controlled grazing from well-maintained fencing and cut-and-carry systems. Rainwater is conserved through small field bunds and stone walls along contours. Bushes are kept under constant control (Anonymous, 1999c).

3.4.3 | Preservation of Dry Fodder

Fodder scarcity in husbandry-dominated farming systems is common. Sorghum, pearl millet, and maize stalks are preserved for winter. Fodder supplies are augmented from forest areas during winter, with wheat straw as the main dependence source. In rice-growing areas, even rice straw is preserved for winter use, at least for non-milching or inferior cattle. Grasses are harvested in November-December, air-dried, bundled, and preserved for winter fodder. Farmers employ innovative techniques for safe forage storage (Koradiya and Koradiya, 1994).

3.4.4 | Organic Mulching

Farm-produced organic materials meet multiple pressing demands: fodder, fuel, and thatched roofing. Considerable effort is involved in arranging and spreading organic mulches from outside farms. Organic mulches are used in vegetable crop nurseries during winter to raise night temperatures and provide frost protection. Newly planted fruit plants are protected from frost by covering with locally available organic materials like *Saccharum munja*. Ginger and Colocasia receive organic mulching for weed control, soil moisture conservation, and easy tuber uprooting. Farmyard manure along with crop residues and animal floor sweepings serve as mulch in ginger crops (Barman *et al.*, 2024).

3.4.5 | Bio-fencing

Wildlife and stray cattle menace is severe across most

Shivaliks, compelling farmers to maintain thorny bush fences, brushwood, or live hedges along field boundaries for crop protection. In Jammu region, 'Bakarwal' traditional graziers descend from higher hills to Shivaliks with goat and sheep herds during winter due to mountain snowfall. Since entire flocks depend on grazing, they damage crops if unattended and unfenced. Local farmers traditionally grow numerous Ber (*Ziziphus* spp.) plants in and along field boundaries. Ber plant branches are heavily pruned each summer. Pruned branches provide nutritious leaf fodder for farmers' own goats and sheep while serving as effective, durable fencing. This practice has sustained because an excellent tree species has been selected to exploit its silvicultural potential for pressing local fence and fodder needs (Anonymous, 1999-2000; Acharya *et al*., 2001).

3.4.6 | Multiple Uses of Bhabbar Grass

Bhabbar grass (*Eulaliopsis binata*) is a common perennial with good soil binding capacity, used as fodder when fresh shoots emerge in April-May, as raw material for paper pulp, and extensively for rope making with foot-operated machines. This commercially valuable grass provides lean-time employment in cutting, transporting, drying, and rope making. Cots are woven with Bhabbar grass rope (Mittal *et al.*, 1988).

3.4.7 | Fruits and Vegetables

In hills, certain areas are famous for special indigenous products: spices, pulses, vegetables, aromatic rice, kulthi, ginger, turmeric, and garlic, traditionally grown and marketed. Some fruit trees grow around homesteads for pickles, chutneys, and raw consumption. Due to market distance and difficult terrain, each family tends toward self-sufficiency. Vegetables like cucurbits, gourds, and pumpkins creep over house verandas and wood stacks. Beetle attacks are controlled by spreading ash on plant leaves. Consuming mango, ber, mulberry, banana, sugarcane, maize cobs, and jaggery helps meet the nutritional requirements of the hill community. *Sarson Ka Saag* with *Makki Ki Roti* and 'Gur' is a common winter food (Kharbani & Sawian, 2022).

3.5 | Multiple Uses of Farmyard Manure

Farmyard manure (FYM) is an important animal husbandry byproduct that serves two critical rural family purposes: soil fertility replenishment and energy provision through cow dung cakes. Efforts are made to mix all unused organic residues and sweepings with FYM for nutrient recycling. Due to termite attack concerns, only well-rotted, decomposed FYM is applied. FYM is invariably added in hot summer before crop sowing and thoroughly mixed with soil. Seeds with hard coats are buried in FYM heaps. Decomposition-generated heat breaks hard coats, improving germination. Cow dung mixed with mud plasters walls and rooftops of kacha houses, particularly during festivals. Subsistence agriculture has sustained largely through manure application to field crops. Farmers consider that FYM, beyond nutrient supply, helps conserve moisture and maintains better field physical conditions for tillage and plant growth (Barman *et al*., 2024).

3.6 | Household Energy Sources

Energy conservation in rural areas includes spending hot summer hours under tree shade, sleeping on rooftops during summer, dining before dark, sleeping early, and using only one oil lamp per house. Common household energy sources include cow dung cakes, forest fuel wood, pruned branches and twigs from farm-raised trees, and farm residues. Cow dung cakes are the main energy source. Buffalo dung, greater in quantity than cow dung, is preferred for cake making. Cattle shed products are divided into two parts: sweepings of floor, bedding material parts, and spoiled fodder for manure; and dung regularly pushed back from behind animals during the day for cake making. Cow dung cakes are air-dried and preserved in specially designed conical mounds called 'Goharas,' made over wooden frames and plastered with cow dung from outside. Storage is necessary because cow dung cakes cannot be made during most of the rainy season. Cooking during rainy season relies mainly on stored cakes. Ash from cow dung cakes is used for cleaning utensils (Goel, 2025).

3.7 | Wildlife Management

Field crops raised near forest areas are attacked by wildlife, particularly at night. Wildlife types vary, but wild pig, porcupine, wild boar, jackal, and nilgai are most common in Shivaliks. Many farmers are compelled to leave fields uncultivated, particularly during winter (Rabi), due to inability to protect crops from wildlife. Practices followed to safeguard against wildlife damage include:

- Raising taramira (Rapeseed), a common winter oilseed crop with bitter taste unbrowsed by wildlife.
- Erecting standing man dummies with old cloth or plastic sheets on wooden sticks that flutter or sway with wind, feared by nilgai.
- Building small huts on raised wooden frames in fields for winter night watch and ward.
- Keeping dogs to ward off and indicate wildlife and stray cattle presence.
- Hanging dead crows from nearby trees to scare away birds.
- Beating tin cans (PIPA) to scare away birds/wildlife, particularly in orchards (Maurya, 1993; Verma, 1998; Lakshmana, 2000).

Wildlife hunting is prohibited by law. Beyond field crop damage, some wild animals damage newly planted forest seedlings, such as porcupine damage.

3.8 | Ecosystem Services Provided by Indigenous Practices

Indigenous natural resource management practices provide multiple tangible and intangible benefits and supporting services (Table 2).

TABLE 2 Ecosystem services provided by indigenous natural resource management practices

	Service Category	Examples of Indigenous Practices
Tangible Benefits	Food	Land development, water resource development (spring water harvesting, Kuhl system management) leading to food security
	Forage	Grassland and pasture management, dry fodder preservation
	Fresh Water	Spring water harvesting, village ponds
	Medicinal Resources	Growing medicinal trees and plants (neem, jamun, harar, haldi, tulsi)
	Wood	Agroforestry systems
	Fiber	Bhabbar grass, poplar trees
Regulating Services	Flood and Drought Moderation	Terracing, village ponds, Kuhl systems
	Climate Regulation	Indigenous cultivation practices limit greenhouse gas emissions
	Carbon Sequestration	Maintenance of crops, trees, grass cover
	Air Purification	All vegetation absorbs carbon dioxide and releases oxygen
	Pollination Support	Raising mustard, coriander, onion seed crops attracts bees
	Erosion Control	Drainage line treatment and conservation practices
Supporting Services	Wildlife Habitat	Village ponds for wild animals, shade trees (bargad) for birds
	Climate Change Resilience	Drought-proofing through water resource development
	Soil Health Improvement	Residue incorporation, legume crop cultivation

3.9 | Integration of Indigenous Practices with Government Programs and Policies

The Government of India, in partnership with state governments, has launched several programs to support the food, water, and economic security of small farmers, drought-proof farm economies, and address climate change. The focus has been on promoting region-specific, cost-effective, farmer-friendly, and sustainable practices through participatory approaches. Sustainable hill farming necessitates a balance between economic growth and environmental protection (Balusamy *et al*., 2024). Integration of indigenous practices into natural resource management menus has received due importance. The Integrated Watershed Management Programme (IWMP) and its follow-up initiative, the Prime Minister Krishi Sinchai Yojana (PMKSY), aim to improve water-use efficiency, rejuvenate water bodies, and provide protective irrigation through rainwater harvesting, with a strong focus on self-help groups, cooperative societies, and farmer-producer organizations. The concept of *har khet ko pani* (water to every field) and *more crop per drop* has been popularized. Indigenous practices for resource conservation have been integrated into the program. In soil and water conservation projects, labor components have been converged with MGNREGA schemes to provide employment near rural homes. Self-help groups promoted under the IWMP and PMKSY-2 Watershed Component can undertake income-generating activities through the aggregation, processing, and marketing of traditionally grown products (spices, pulses, kulthi, ginger, turmeric, garlic, pickles, chutneys).

3.10 | Gaps and Limitation in Adoption of Indigenous Practices

Several gaps and limitations hinder full adoption of indigenous practices in natural resource management projects:

Overemphasis on mechanical measures: Most projects heavily favor mechanical measures while underemphasizing vegetative measures in soil erosion control. Integration of nara, bana, ipomoea, and bamboo imparts structural stability to mechanical measures. Quick-fix approaches without biological measure support lead to failures.

Inadequate catchment treatment: In earthen dam construction for rainwater harvesting, catchment area treatment using vegetative barriers in drainage lines is often ignored, leading to rapid reservoir siltation.

Soil health deterioration: While farmers traditionally maintained soil fertility through farmyard manure, legumes in rotation, and residue incorporation, chemical fertilizer use has introduced pollution and soil health deterioration problems.

Loss of traditional medicine: In remote foothill villages, normal human and livestock ailments were treated using medicinal plants from forests by vaids and hakeems. Obnoxious weed invasion and forest fires have decreased medicinal plant availability, with allopathic medicines taking over.

Guidelines for implementing various soil and water conservation projects are provided by the Ministry of Rural Development, Government of India under Watershed Development-2 and Pradhan Mantri Krishi Sinchai Yojana, strictly followed by state governments in foothill areas. State governments also provide guidelines for extension workers, particularly regarding MGNREGA component addition for rural poor. However, training needs, exposure

visits, and practical demonstrations on multiple ITK benefits in natural resource management projects are essential. Scientific validation of different practices has been provided throughout this synthesis, offering evidence-based support for extension recommendations.

3.11 | Synthesis of Key Findings

This comprehensive documentation across the Shivalik region over 30 years reveals several critical insights:

Farmer as engineer and economist: Farmers function as practical engineers and down-to-earth economists. Indigenous resource management techniques demonstrate the appropriate integration of local flora and available materials through simple, inexpensive, and effective methods. Experience and judgment have been consolidated and refined through critical analysis of past successes and failures.

Economic constraints and innovation: Farmers have the capacity for hard work, but lack substantial cash investment resources. They logically select vegetation for erosion control that serves multiple needs: can be cut, pruned, or lopped as needed; provides fuel/fodder; has self-regenerating capacity; tolerates adverse site conditions; and has strong root systems.

Barriers to adoption: Farmer silence does not necessarily indicate inability to understand. Rather, they have been silenced by inabilities to spend and bear risk on new innovation adoption. Skepticism is born from fear and lack of insurance.

Integration imperative: Blending ITK with modern scientific knowledge is essential to support sustainable, climate-resilient, environmentally friendly agricultural development. The thematic synthesis presented highlights broader implications of ITK integration for hill and mountain watershed management, climate resilience, and policy design.

4 | CONCLUSIONS

This synthesis of indigenous technical knowledge from the Shivalik region of North India, based on 30 years of field experience across 4.2 million hectares in five states, demonstrates the richness and relevance of traditional practices for sustainable hill and mountain ecosystem management. The documentation reveals that ITK encompasses comprehensive approaches to land development, water resource management, drainage system control, indigenous flora utilization, organic resource recycling, and wildlife management.

Key conclusions include:

1. **Effectiveness of ITK:** Indigenous practices are time-tested, cost-effective, eco-friendly, and readily accessible to communities. They have sustained subsistence agriculture through integration of local knowledge, materials, and flora.

2. **Farmer innovation:** Farmers are practical engineers who have refined techniques through critical analysis of successes and failures, selecting vegetation and methods that serve multiple purposes while tolerating adverse conditions.

3. **Ecosystem services:** ITK-based practices provide multiple tangible benefits (food, forage, water, medicinal resources, wood, fiber) and intangible benefits (climate regulation, carbon sequestration, erosion control, wildlife habitat, climate resilience).

4. Integration potential: Current government programs (IWMP, PMKSY) have begun incorporating ITK into natural resource management, but significant gaps remain in implementation, particularly regarding vegetative measures and catchment treatment.

5. **Policy recommendations:**
- Expand training and exposure visits for extension workers on ITK benefits
- Balance mechanical and biological measures in project designs
- Integrate ITK with self-help group income generation activities
- Preserve and document traditional medicinal plant knowledge
- Strengthen participatory approaches in project planning and implementation

6. **Research priorities:**
- Quantitative validation of ITK effectiveness under varying biophysical conditions
- Economic analysis of ITK versus modern technology adoption
- Climate resilience assessment of traditional versus modern practices
- Documentation of ITK in other hill and mountain ecosystems for comparative analysis

This compilation requires continuous enlargement, improvement, and updating as more indigenous techniques come to stakeholder attention. The thematic synthesis presented provides a framework for integrating indigenous technical knowledge into watershed management, climate adaptation strategies, and policy design for hill and mountain ecosystems beyond the Shivaliks.

ACKNOWLEDGEMENTS

The author acknowledges the cooperation of farmers, village elders, and knowledge holders across the Shivalik region who shared their traditional practices and experience. Appreciation is extended to field functionaries of various departments in Punjab, Haryana, Himachal Pradesh, Uttarakhand, and Jammu & Kashmir for validating the documented practices. This work was supported by experiences gained through the Integrated Watershed

Development Project funded by the World Bank and subsequent watershed projects in the Shivalik foothills.

CONFLICT OF INTEREST

The author declares that he has no known competing financial interest or personal relationship that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

All data supporting the findings of this study are available from the author upon reasonable request. Summary datasets generated or analyzed during the current study are included in the article.

AUTHOR'S CONTRIBUTION

The author has solely compiled the conceptual framework of the paper, review of literature, data related to material and method and results and discussions including conclusions and citation of references.

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How to cite this article: Grewal, S.S., 2025. Thematic Synthesis of Indigenous Technical Knowledge Relevant to Hill and Mountain Ecosystems : The *Shivaliks* of North India as a Representative Case. *Indian J. Soil Cons*., **53(3)** (*Hill & Mountain Agriculture S*pecial Issue)**: 279-287**

Received: 04 September 2025 | Accepted: 03 February 2026 | Published online: 06 April 2026

DOI: 10.53550/ijsc.v53.i3.212

ORIGINAL ARTICLE

Indian Journal of Soil Conservation

Farmer Producer Organizations and Agricultural Sustainability in Uttarakhand's Hills: A Cross-Sectional Analysis of Conservation Practices and Economic Outcomes

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Handling Editor:
Dr Abimanyu Jhajhria

Key words:
Collective action institutions
Farmer producer organizations
Hill farming system
Indian Himalayan Region
Resource conservation
Sustainable agriculture
Smallholder farmers
Uttarakhand

ABSTRACT

Hill agriculture in Uttarakhand is bottlenecked with multiple overlapping challenges. Fragmented landholdings, weak market linkages, severe soil erosion and growing climate variability are some of the major ones. Farmer Producer Organizations (FPOs) have been promoted as an institutional response to these constraints. But, the link between FPO membership and improved outcomes in ecological and economic domains has not been studied systematically in mountain agriculture. To address this gap, we studied 300 farm households (150 FPO members, 150 non-members) across three districts in Uttarakhand's Garhwal region. It was a cross-sectional survey using multistage random sampling. Key outcomes measured were: (1) a composite Resource Conservation Index (RCI; range 0-5) constructed from ten soil and water management practices, (2) agricultural income per *nali* (local land unit ≈ 0.02 ha) and (3) price realization ratio. Data was analysed for group differences and OLS Regression models controlling for farmer age, education, landholding size, market distance and district-level variations. FPO members demonstrated substantially higher conservation adoption (mean RCI: 3.25 vs. 2.15; 51% difference; $p < 0.001$), agricultural income (₹4,850 vs. ₹3,520 per *nali*; 38% difference; $p < 0.001$) and price realization (0.88 vs. 0.75; 13% difference; $p < 0.001$) compared to non-members. These associations persisted after multivariate adjustment (RCI: $\beta = 1.25$, $p < 0.001$; Income: $\beta = ₹1,156$, $p < 0.001$). The study found meaningful associations between FPO membership and improved performance in natural resource management and farm income. Interestingly, marginal (<3 *nali*) and less educated farmers showed stronger associations. These findings reinforce the role of FPO model for hill agriculture particularly when targeting marginalized farmers. The mechanism underlying these associations – whether through training, credit access, market linkage or other pathways – remains topic of future studies.

1 | INTRODUCTION

Nearly 70% of rural population in the Indian Himalayan Region (IHR) depends on hill farming system for its food and livelihood security (Sati, 2024). Notwithstanding the importance, this system operates under multiple pressures to its sustainability and economic viability (Singh *et al*., 2019). The challenges come from multiple directions. Landholdings are small and highly fragmented that resist mechanization (Tayang *et al*., 2024). Soil erosion steadily depletes fertility (Meena and Maikhuri, 2024), while increasingly erratic weather disrupts cropping calendars farmers have relied on for generations (Goel and Singh, 2024). Uttarakhand, our area of study, faces additional complications. Here the biophysical challenges are further complicated by the region's peculiar socio-economic dynamics. High rates of out-migration reduces labor pool and indigenous knowledge transfer (Balusamy *et al*., 2024; Mamgain and Reddy, 2017). Weak institutional support leaves farmers with reduced capacity to adapt as agro-ecological conditions grow more volatile (Joshi et al., 2023). These problems reinforce each other: small-sized farms restrict conservation investment thereby accelerating erosion and reducing productivity (Meena *et al*., 2022). Conventional solutions like improved seeds and irrigation often fall short where farmers lack awareness and bargaining power (Dinesh *et al*., 2022). What may be needed instead are institutional innovations that work at higher systemic level by reshaping how actors interact, how risk and rewards are shared and how decision are made (Schut *et al*., 2016).

Collective action programs in rural India include traditional cooperatives, Self-Help Groups (SHGs), watershed committees and NGOs. The Farmer Producer Organizations (FPOs) or Farmer Producer Companies

(FPCs) are a new addition to this list. FPOs enjoy greater statutory autonomy and less political interference compared to traditional cooperatives (Khiangte & Malsawmsanga, 2025). FPOs tend to adopt a more professional approach with salaried CEO and marketing team (Prabhavathi *et al*., 2023). FPOs integrate multiple services such as input supply, technical advice, credit facilitation and output marketing within a single institutional framework (Murugananthi *et al*., 2025). FPOs are selected for this study as they are built specifically around production aggregation and value chain participation. This design enables them to be of direct help in addressing the scale and market access constraints typical of hill agriculture (Bisht, 2021). The Indian government aimed to establish 10,000 FPOs by 2020 (Surendran-Padmaja & Ojha, 2025) supported by NABARD and various other government programs (Yazhini *et al*., 2025). However, empirical literature on FPO effectiveness shows geographic and thematic biases. Most studies concentrate on lowland regions and specific value chains (Kumar *et al*., 2023; Lalitha *et al*., 2024). Other studies highlight the FPOs importance in social capital especially for women and marg*inal*ized groups (Harrington *et al*., 2024; Prabhavathi *et al*., 2023). Much of the existing evidence focuses primarily on economic outcomes and market integration, with limited attention to ecological dimensions such as soil and water conservation. Empirical research on FPOs in hill agriculture is limited. Some studies from the Eastern Himalayas and Northeast India document the FPOs impact on farmers participation and economic welfare (Gurung & Choubey, 2023; Sharma *et al*., 2023), but systematic analysis of their dual resource conservation and income effect is rare. In Uttarakhand, most existing studies have focussed mainly on socio-economic impacts (Harrington *et al*., 2024; Prasad *et al*., 2023) or specific commodity (Choudhary *et al*., 2015; Kumar *et al*., 2021). Studies have not explored FPOs as a distinct institutional form. As a result, little is known if FPOs in Uttarakhand contribute to conservation and economic goals.

This study examines association between FPO membership and agricultural outcomes in Garhwal region of Uttarakhand. It makes three major contributions to hill agricultural literature. First, it provides one of the few quantitative household-level comparison of FPO members and non-members in Indian Himalayan Region thereby filling a critical gap. Next, it develops a composite Resource Conservation Index (RCI) that captures adoption of ten soil and water conservation practices. Third, it records heterogeneity in FPO benefits across farm size and education levels.

Guided by the above discussion, we derived two hypotheses for the study:

1. **H1:** FPO membership is positively associated with higher adoption of resource conservation practices among farmers in Uttarakhand, after controlling for farmers age, education, landholding size, market distance and district-level differences.

2. **H2:** FPO members demonstrate higher average agricultural income and better price realization for their produce compared to non-members in Uttarakhand, after controlling for farmers age, education, landholding size, market distance and district-level differences.

HIGHLIGHTS

- FPO membership is associated with better outcomes on both fronts: 51.2% higher resource conservation score, with 37.8% higher agricultural income per *nali* and 13 percentage points better price realization.
- Marginal farmers (< 3 *nali*) and less educated farmers show disproportionately larger differences, suggesting equity benefits of FPO membership.
- Cross-sectional design stops us from drawing causal inferences, though the associations we recorded are strong enough to encourage longitudinal research on FPO effectiveness.

Cross-sectional design we adopted cannot establish causality or rule out self-selection into FPOs. Farmers who join FPOs may differ from non-joiners in ways our data do not capture. Unobservable differences such as entrepreneurial orientation or social capital may influence both membership and outcomes. We therefore present our findings as association, rather than definite evidence of FPOs impact.

2 | MATERIALS AND METHOD

2.1 | Study Area

Our fieldwork focussed on three districts in the Garhwal region of Uttarakhand: Pauri, Chamoli, and Tehri Garhwal (Fig. 1). These districts were selected as – (i) they fall in the mid-Himalayan agro-ecological zone where 70% of the state's hill agriculture is practiced (Bisht, 2021) and (ii) each has at least two operationally active FPOs with minimum two years of establishment (Small Farmers' Agribusiness Consortium, 2022). The study region is characterized by fragmented landholdings and multi-crop hill farming systems described as *Baranaaja* system (Ghosh and Dhyani, 2004). Agricultural markets are typically 5 to 15 kilometres distant from villages making transport both time consuming and costly (Sati, 2012).

2.2 | Research Design and Sampling Procedure

We adopted a cross-sectional comparative research design to examine the associations difference between FPO membership, resource conservation practices and economic outcomes. The target population comprised smallholder farmers engaged in multi-crop hill agriculture in the three selected districts. The sampling procedure followed a multi-stage procedure:

Stage 1 (Block selection): From each of the three selected districts, we identified all blocks containing operational FPOs and randomly selected two blocks per district yielding six blocks: Pokhara and Yamkeshwar (Pauri),

arayanbagar and Tharali (Chamoli) and Devprayag and Bhilangna (Tehri Garhwal).

Stage 2 (Village selection): We constructed a sampling frame of all villages within selected blocks that contained at least one active FPO member. From this frame, 25 villages were randomly selected (approximately 4 villages per block), stratified to ensure proportional representation across districts.

Stage 3 (Farmer selection): Within each selected village, we randomly selected 6 FPO members from membership lists obtained from FPO offices. An equal number of non-member farmers were selected from the same village with similar landholding size (± 3 *nali*) and primary crop cultivation practices. This three-stage procedure produced a final sample of 150 FPO members and 150 non-members (total $N = 300$).

An a priori power analysis in G*Power 3.1 for an independent-samples t-test (two-tailed, $\alpha = 0.05$) assuming a small-to-medium effect size ($d = 0.35$)indicated that a minimum of 130 FPO members and 130 non-members (total $N = 260$) would be required to achieve 80% power. We therefore targeted a slightly larger sample and surveyed 150 members and 150 non-members (total $N = 300$)to provide a margin for non-response and data quality issues. FPO members and non-members may differ in unobservable characteristics (motivation, social networks, entrepreneurial capacity, risk averseness etc.) that influence both FPO participation and outcomes. Our analytical strategy controls for observable differences but cannot eliminate selection bias inherent in the cross-sectional comparative design.

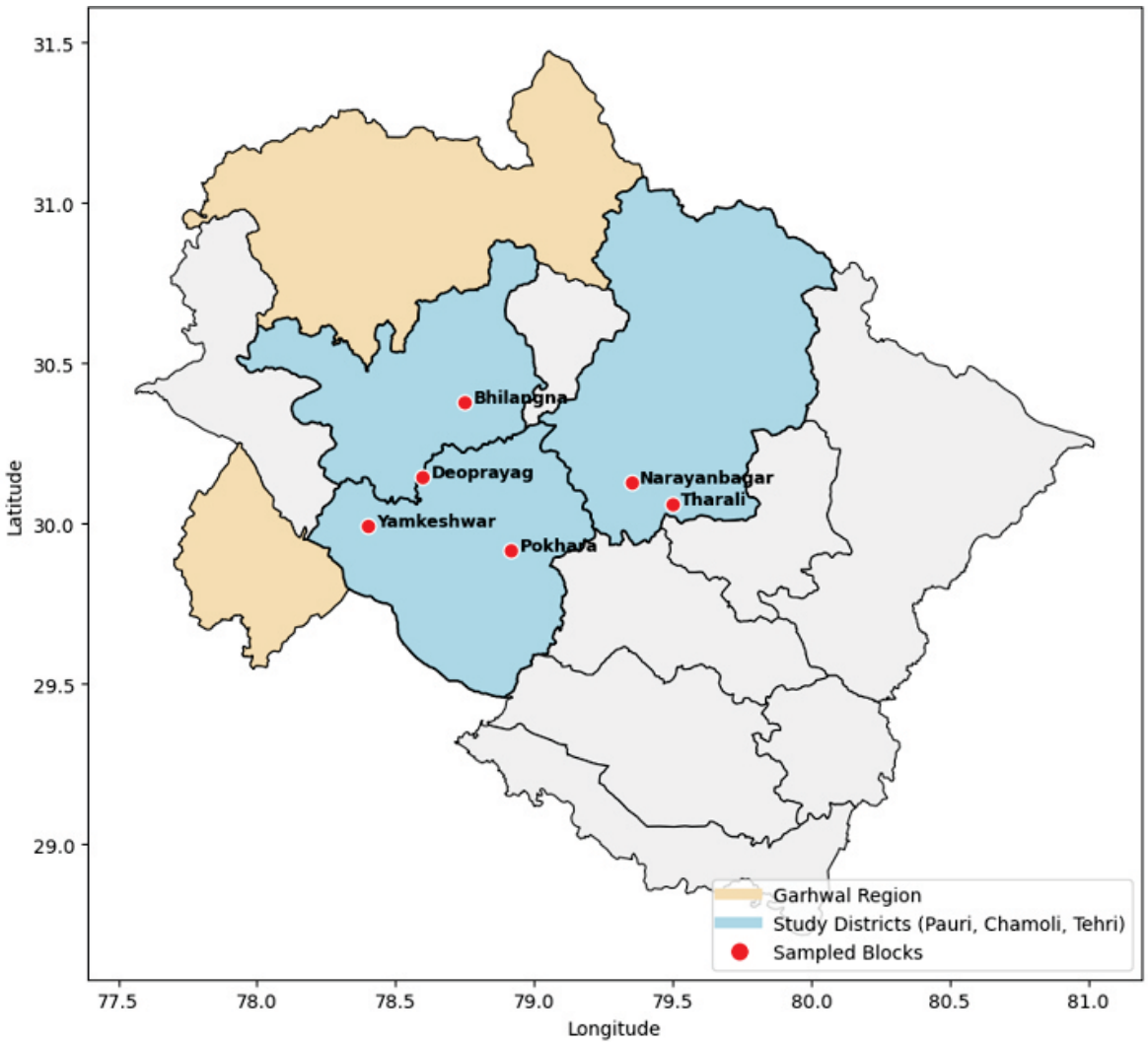


FIGURE 1 Study Area Map of Uttarakhand (Sampled FPO Blocks)

2.3 | Data Collection

Primary data were collected between October and December 2024 using a structured questionnaire administered in Hindi. The survey instrument captured household demographics, farming practices, income indicators, FPO participation details and resource conservation outcomes. The instrument was pilot tested with 30 farmers in a non-sample village in Pauri district (September 2024). Question phrasing was simplified based on pilot test feedback. The study relies exclusively on quantitative survey data. The absence of qualitative triangulation (FGDs or key informant interviews) is noted as a limitation. We addressed this limitation partially through interpretation of statistical patterns based on prior qualitative research.

2.4 | Variable Specifications

2.4.1 | Dependent Variables

- Resource Conservation Index (RCI, range: 0 – 5): explained in section 2.5
- Gross agricultural income per *nali* (traditional land measurement unit in Uttarakhand): 1 *nali* ≈ 0.02 hectare (Tiwari and Bhatt, 2021). Income was based on famers' reports of sale values and prices for 2023-24 (expressed in ₹).
- Price realisation ratio (actual farm-gate price ÷ prevailing mandi price): compares farm-gate prices to mandi prices for each crop. The ratio is typically between 0 and 1 when mandi prices are used as the reference benchmark for comparable crop/grade and period. Mandi prices were sourced from AGMARKNET (Agricultural Marketing Information Network) portal maintained by the Directorate of Marketing & Inspection, Ministry of Agriculture & Farmers Welfare, Government of India.

2.4.2 | Independent Variable

- FPO membership status: It is a binary variable (1 = member, 0 = non-member). Membership verification was conducted using FPO membership lists. Members were specifically defined as farmers who had joined at least 12 months before the survey date to ensure adequate exposure time.

2.4.3 | Control Variables

Control variables included age of the farmer (years), education (years of formal schooling), operational landholding size (*nali*), distance to nearest market town (km). District fixed effects were included using two dummy variables (Chamoli and Tehri; Pauri as reference).

2.5 | Resource Conservation Index (RCI)

The RCI was constructed as a composite measure capturing farmers' adoption breadth and intensity of 10 key sustainable agricultural practices. These ten practices were selected based on their relevance to hill agriculture as identified in prior agronomic research and in consultation with three field agronomists from Uttarakhand.

2.5.1 | Practices Included

The ten practices are divided into three domains:

- Soil conservation (3 practices): terracing, contour farming, farmyard manure (FYM) application. The three Soil Conservation practices include terracing (building and maintaining bench terraces or contour bunds); contour farming (ploughing and planting along contours instead of up and down the slope) and farmyard manure (FYM) application, which involves regularly incorporating composted animal waste.
- Water management (4 practices): mulching, rainwater harvesting, drip irrigation, on-farm water storage structures. The four Water Management practices are mulching (covering the soil surface with organic materials to conserve moisture); rainwater harvesting (collecting and storing roof or surface runoff); drip irrigation (using drip systems for water efficient watering) and on-farm water storage structures (building farm ponds, tanks or check dams).
- Integrated farming (3 practices): crop rotation, intercropping, agroforestry. The three Integrated Farming practices comprise crop rotation (systematic changing of crops in planned sequences); intercropping (growing two or more crops simultaneously on the same plot); and agroforestry (combining trees with crops and/or livestock).

2.5.2 | Scoring and Weighting

Each practice was scored on a three-point adoption intensity scale: 2 = regularly adopted (used every season), 1 = occasionally adopted (used irregularly or on some plots only), 0 = not adopted. All ten practices were assigned equal weight in the composite index. This choice reflects the study's conceptual focus on adoption breadth and intensity rather than on estimating the relative impact of individual practice. Also, no widely accepted empirical basis from Himalayan hill agriculture exists to justify differential weighting of soil, water and integrated farming practices.

For each household, the ten practice scores (each 0 – 2) were summed to obtain a raw conservation score ranging from 0 to 20. To express this on a 0 – 5 scale, the raw score was rescaled using:

$$RCI_i = \left(\frac{\sum_{j=1}^{10} Score_{ij}}{20} \right) \times 5$$

where $Score_{ij}$ is the 0/1/2 value for practice j for household i. The resulting RCI therefore ranges from 0 (no conservation practice adopted) to 5 (all ten practices adopted regularly). Higher scores indicate broader and more intensive adoption of conservation practices. Although the index does not apply explicit domain weights, domain-specific adoption patterns (soil, water, integrated farming) are analysed separately in the Results to ensure that domain differences are not obscured by aggregation.

2.5.3 | Index Validation

Internal consistency of the 10-items scale was assessed

using Cronbach's alpha (α = 0.76). Face validity was established through review by three agronomists with field experience in the study region. As a convergent validity check, we computed bivariate correlations between RCI and selected farmer characteristics. RCI scores correlated positively with education ($r = 0.34$, $p < 0.001$) and operational landholding size ($r = 0.28$, $p < 0.001$), while showing a negative correlation with distance to the nearest market ($r = -0.22$, $p < 0.001$). At the same time, the index relies on self-reported adoption and we did not perform on-site verification. We therefore cannot confirm the implementation quality on ground and measurable environmental benefits. Future research should complement survey-based adoption methods with direct observation and biophysical measurements.

2.6 | Analytical Framework

Data analysis was conducted in four stages: (i) descriptive comparison between members and non-members, (ii) multivariate OLS regressions with controls, (iii) heterogeneity checks by farm size and education, and (iv) robustness checks, including outlier sensitivity. All analyses were performed using IBM SPSS 26.

Differences between FPO member and non-members groups were tested using independent sample t-tests for continuous variables (viz. RCI, income per *nali* and price realization ratio) and chi-square tests for categorical variables (viz. adoption of each conservation practice). Effect sizes were calculated using Cohen's d.

Three OLS regression models were estimated to test hypotheses H1 and H2 while controlling for confounders:

- Model 1: $Resource_Conservation_Index = \beta_0 + \beta_1(FPO_Membership) + \beta_2(Age) + \beta_3(Education) + \beta_4(Landholding) + \beta_5(Market_Distance) + \beta_6(District_Chamoli) + \beta_7(District_Tehri) + \varepsilon$
- Model 2: $Income_per_Nali = \beta_0 + \beta_1(FPO_Membership) + \beta_2(Age) + \beta_3(Education) + \beta_4(Landholding) + \beta_5(Market_Distance) + \beta_6(District_Chamoli) + \beta_7(District_Tehri) + \varepsilon$
- Model 3: $Price_Realization_Ratio = \beta_0 + \beta_1(FPO_Membership) + \beta_2(Age) + \beta_3(Education) + \beta_4(Landholding) + \beta_5(Market_Distance) + \beta_6(District_Chamoli) + \beta_7(District_Tehri) + \varepsilon$

Heterogeneity in associations was examined using (i) stratified comparisons by farm size (marginal: < 3 *nali*; small: 3 – 6 *nali*; medium: > 6 *nali*) and education (low: ≤7 years; high: >7 years), and (ii) interaction models that added FPO × Landholding and FPO × Education terms to the baseline regressions.

Robustness checks and regression diagnostics were conducted to verify that the main inferences are not driven by modelling choices, aggregation decisions or influential observations. Multicollinearity was assessed using Variance Inflation Factors (VIF < 3 for all predictors) Heteroskedasticity was tested using Breusch-Pagan test ($\chi^2 = 18.4$, $p = 0.03$) and standard errors (HC3) were used where evidence of heteroskedasticity was found. Outliers were identified using Cook's distance (4 observations with D > 0.5; no major change in results after exclusion). Residual normality was confirmed via Q-Q plots.

3 | RESULTS AND DISCUSSION

3.1 | Sample Profile and Baseline Comparisons

Table 1 presents a comparison of key demographic and farm-level characteristics between FPO members (n=150) and non-members (n=150).

TABLE 1 Sample Profile and Baseline Comparison

Characteristics	FPO Members (n=150)	Non-members (n=150)	Test Statistic	*p*-value
Age (years)	43.1 ± 8.5	46.2 ± 9.8	$t = -3.11$	0.002**
Operational landholding (*nali*)	18.2 ± 5.4	17.8 ± 5.1	$t = 0.68$	0.497
Market distance (km)	7.1 ± 2.3	7.4 ± 2.6	$t = -1.12$	0.264
Education level			$\chi^2 = 11.45$	0.010**
• Illiterate	18 (12.0%)	31 (20.7%)		
• Primary (1-5 years)	42 (28.0%)	55 (36.7%)		
• Secondary (6-10 years)	65 (43.3%)	48 (32.0%)		
• Higher secondary and above (>10 years)	25 (16.7%)	16 (10.6%)		
District			$\chi^2 = 0.42$	0.811
• Pauri Garhwal	51 (34.0%)	48 (32.0%)		
• Chamoli	50 (33.3%)	52 (34.7%)		
• Tehri Garhwal	49 (32.7%)	50 (33.3%)		

Notes: Values for continuous variables are mean ± standard deviation. Comparisons use independent-samples t-tests (continuous) and Pearson's χ^2 tests (categorical). **p < 0.01, ***p < 0.001.

As detailed in Table 1, the two groups are broadly similar in mean operational landholding size (18.2 vs. 17.8 *nali*, $p = 0.497$) or the average distance to the nearest market town (7.1 vs. 7.4 km, $p = 0.264$). We did, however, find statistically significant differences in age and education level. On average, FPO members were slightly younger (43.1 vs. 46.2 years, $p = 0.002$) and more educated (higher proportion with secondary or above education, $p = 0.010$) compared to non-members. These differences underline the need to control for age and education in multivariate analyses.

3.2 | Resource Conservation Practice Adoption (H1)

3.2.1 | Overall Conservation Index Comparison

To test the hypothesis that FPO membership increases the adoption of resource conservation practices (H1), we compared the mean Resource Conservation Index (RCI) between groups. Fig. 2 shows the contrast very clearly. FPO members reported markedly higher mean RCI score (3.25 ± 0.85) than non-members (2.15 ± 0.92). The gap of 1.10 points on the 0-5 scale was statistically meaningful and substantively large ($t(298) = 11.4$, $p < 0.001$; Cohen's $d = 1.26$). Put simply, members' conservation adoption scores were 51.2% higher than non-members.

Inspection of the full RCI score distribution (Table 2) points to group differences in adoption patterns.

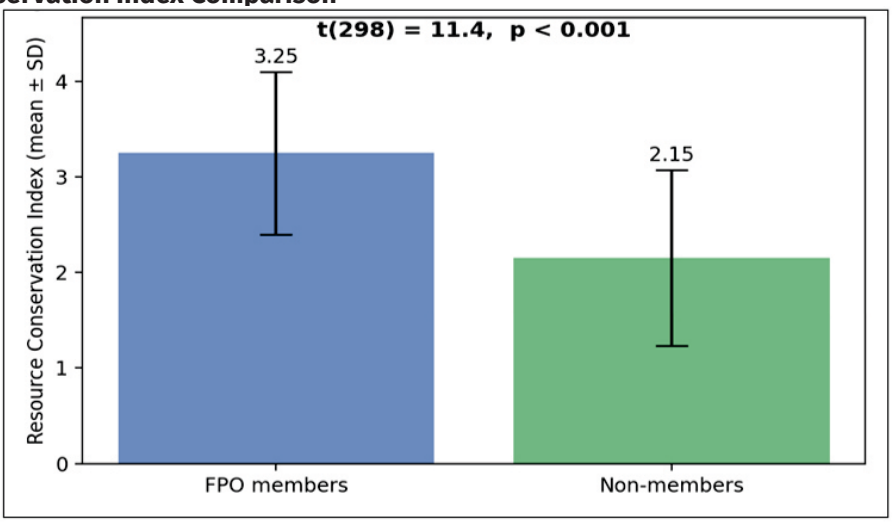


FIGURE 2 Mean Resource Conservation Index (RCI) for FPO members vs. Non-Members

TABLE 2 Distribution of Farmers by Resource Conservation Index Categories

RCI Category	Score Range	FPO Members	Non-Members	χ^2	p-value
Very Low	0.0-1.0	4 (2.7%)	28 (18.7%)	82.4	< 0.001***
Low	1.1-2.0	18 (12.0%)	52 (34.7%)		
Moderate	2.1-3.0	45 (30%)	47 (31.3%)		
High	3.1-4.0	62 (41.3%)	21 (14.0%)		
Very High	4.1-5.0	21 (14.0%)	2 (1.3%)		

Among FPO members, 55.3% scored in the "High" or "Very High" adoption categories (RCI > 3.0), while only 15.3% of non-members reach these levels. The pattern is reversed at the lower end of the scale: 53.4% of non-members are classified in the "Low" or "Very Low" categories, compared with just 14.7% of FPO members. The distribution difference was highly significant ($\chi^2 = 82.4$, $p < 0.001$).

3.2.2 | Domain-Specific Conservation Adoption

We grouped the ten conservation practices into three domains to see where the aggregate RCI difference was coming from. The three domains were: soil conservation (3 practices), water management (4 practices) and integrated farming (3 practices). Table 3 presents adoption rates for individual practices within each domain.

FPO members showed higher adoption rate than non-members for the ten conservation practices ($p < 0.001$ for all comparisons). The largest adoption gap was observed in mulching (27.3 pp), contour farming (26.6 pp). Even widely adopted traditional practices such as FYM application showed higher rate of adoption among FPO farmers (94.7% vs. 81.3%). At the domain level, mean adoption was highest for integrated farming practices (75.1% vs. 56.7%; 18.4 pp), followed by soil conservation (86.2% vs. 67.3%; 18.9 pp) and water management (44.0% vs. 20.7%; 23.3 pp).

3.2.3 | Multivariate Analysis - RCI Regression Model

To isolate the association between FPO membership and conservation adoption while controlling for confounding factors, a multiple regression model was estimated with the Resource Conservation Index (RCI) as the dependent variable. Results appear in Table 4.

After controlling for demographic and locational

characteristics, FPO membership remained a highly significant predictor of RCI (β = 1.251, p < 0.001). FPO members scored, on average, about 1.25 points higher on the 0 – 5 RCI scale than comparable non-members. Education (β = 0.052, p = 0.004) and operational landholding size (β = 0.028, p = 0.002) were also positively and significantly associated with conservation adoption, while market distance was negatively and significantly associated with RCI (β = -0.045, p = 0.003). Each additional kilometre from the market was linked to a 0.045-point decrease in RCI. Age was not statistically related to RCI. District dummy variables for Chamoli and Tehri Garhwal showed no significant effects, suggesting that the positive association between FPO membership and RCI was consistent across districts. Overall, the model accounted for 48.2% of the variance in RCI scores (R^2 = 0.482; Adjusted R^2 = 0.473), indicating substantial explanatory power.

TABLE 3 Adoption Rates of Specific Conservation Practices by Domains

S. No	Domain & Practice	FPO Members Adopters (%)	Non- FPO Members Adopters (%)	Difference (pp)	χ^2 value	*p*-value
A. Soil Conservation						
1	Terracing	88.7	72.0	16.7	13.7	<0.001***
2	Contour Farming	75.3	48.7	26.6	22.1	<0.001***
3	FYM Application	94.7	81.3	13.4	12.3	<0.001***
Mean soil conservation adoption		86.2	67.3	18.9		
B. Water Management						
1	Mulching	62.0	34.7	27.3	22.0	<0.001***
2	Rainwater Harvesting	51.3	28.0	23.3	16.7	<0.001***
3	Drip Irrigation	24.7	5.3	19.4	24.1	<0.001***
4	On-farm Water Storage Structures	38.0	14.7	23.3	20.9	<0.001***
Mean water management adoption		44.0	20.7	23.3		
C. Integrated Farming						
1	Crop Rotation	92.0	78.0	14.0	11.6	<0.001***
2	Intercropping	85.3	66.7	18.6	13.8	<0.001***
3	Agroforestry	48.0	25.3	22.7	16.6	<0.001***
Mean integrated farming adoption		75.1	56.7	18.4		

Notes: "pp = percentage points". ***p < 0.001 (Pearson's chi-square test).

TABLE 4 Multiple Regression Results – Resource Conservation Index (Model 1)

Variable	Coefficient (β)	Robust SE	*t*-value	*p*-value
Constant	1.854***	0.215	8.62	<0.001
Age (years)	-0.008	0.006	-1.33	0.185
Education (years)	0.052**	0.018	2.89	0.004
Landholding (*nali*)	0.028**	0.009	3.11	0.002
Market distance (km)	-0.045**	0.015	-3.00	0.003
FPO Membership (1=Yes)	1.251***	0.102	12.26	<0.001
District: Chamoli	0.150	0.121	1.24	0.216
District: Tehri	-0.098	0.120	-0.82	0.414

Model diagnostics: R^2 = 0.482, Adjusted R^2 = 0.473, F(7, 292) = 54.67, $p < 0.001$, N = 300.
Notes: Dependent Variable = RCI (0-5 scale). Robust standard errors (HC3) used to address heteroskedasticity. Reference category for district = Pauri Garhwal. **p < 0.01, ***p < 0.001.

3.3 | Economic Outcomes : Income and Price Realization (H2)

3.3.1 | Descriptive Comparison

Table 5 compares gross agricultural income per *nali* and price realization ratio between FPO members and non-members.

FPO members reported mean gross agricultural income of ₹ 4,850 per *nali* which is 37.8% higher than that of non-members (₹ 3,520 per *nali*). This difference was statistically significant (t(298) = 11.25, p < 0.001) with a large effect size (Cohen's d = 1.29). Price realization ratio also differs. FPO members achieved a mean price realization ratio of 0.88, indicating they captured 88% of the prevailing mandi price at the farm gate (Table 5). In contrast, non-members realized only 75% of mandi prices (mean ratio = 0.75). The difference of 0.13 (13 percentage points) was statistically significant (t(298) = 8.41, p < 0.001, Cohen's d = 0.97).

TABLE 5 Comparison of Economic Outcomes by FPO Membership Status

Outcome Indicator	FPO Members	Non-FPO Members	*t*-value	*p*-value	Cohen's *d*
Gross agricultural income (₹ per *nali*)	4,850 ± 1,120	3,520 ± 980	11.25	<0.001***	1.29
Price realization ratio	0.88 ± 0.12	0.75 ± 0.15	8.41	<0.001***	0.97

Notes: Values are mean ± standard deviation. Independent-samples t-tests. ***p < 0.001. Cohen's d > 0.8 indicates large effect size.

3.3.2 | Multivariate Analysis - Economic Outcome Regression

Two regression models were estimated to test whether FPO membership effects on economic outcomes persisted after controlling for confounding variables. Results are presented in Table 6.

In model 2 (Income per *nali*), FPO membership showed a highly significant positive association with income. FPO members earn ₹1,156 more per *nali* than non-members after controlling for demographic and farm characteristics (β = 1,155.8, p < 0.001). Education and operational landholding size were also positively associated with income (β = 58.4, p = 0.016; β = 45.2, p < 0.001, respectively). On the other hand, greater market distance was associated with significantly lower income, with each additional kilometer from the market town reducing income by about ₹28.5 per *nali* (β = −28.5, p = 0.040). No strong income differences across districts were shown once other variables are held constant. Overall, Model 2 explains a substantial share of the variation in income per *nali* (R^2 = 0.455, Adjusted R^2 = 0.446, F(7, 292) = 49.12, p < 0.001).

In model 3 (Price realization ratio), FPO membership remained a strong predictor of price realization (β = 0.121, p < 0.001). Education, landholding size, and market distance again displayed smaller but significant effects. Additional schooling and larger operational area were associated with modest improvements in price realization (β = 0.006, p = 0.028; β = 0.002, p = 0.009 respectively), whereas greater distance from the market was linked to lower realized prices (β = −0.005, p = 0.024). Neither age nor district indicators were found to be significant for predicting price realization ratio. Model 3 explains a substantial share of the variance in the price realization ratio (R^2 = 0.389, Adjusted R^2 = 0.378, F(7, 292) = 37.45, p < 0.001), underscoring that FPO membership is not a peripheral covariate but a central lever shaping both what farmers earn and the prices they are able to command.

TABLE 6 Multiple Regression Results – Economic Outcomes (Models 2 & 3)

Variable	Model 2: Income per *nali* (₹)				Model 3: Price Realization Ratio			
	Coef. (β)	Robust SE	*t*-value	*p*-value	Coef. (β)	Robust SE	*t*-value	*p*-value
Constant	2,650.4***	185.2	14.31	< 0.001	0.650***	0.021	30.95	< 0.001
Age (years)	-12.3	8.2	-1.50	0.135	-0.001	0.001	-1.0	0.317
Education (years)	58.4*	24.1	2.42	0.016	0.006*	0.003	2.2	0.028
Landholding (nali)	45.2***	10.1	4.48	< 0.001	0.002**	0.001	2.61	0.009
Market distance (km)	-28.5*	12.8	-2.23	0.04	-0.005*	0.002	-2.27	0.024
FPO Membership (1=Yes)	1,155.8***	95.5	12.11	< 0.001	0.121***	0.014	8.64	< 0.001
District : Chamoli	120.5	105.1	1.15	0.251	0.015	0.015	1.03	0.318
District : Tehri	88.2	104.5	0.84	0.400	0.011	0.015	0.73	0.465

Model 2 diagnostics: R^2 = 0.455, Adjusted R^2 = 0.446, F(7, 292) = 49.12, p < 0.001; N = 300. Model 3 diagnostics: R^2 = 0.389, Adjusted R^2 = 0.378, F(7, 292) = 37.45, p < 0.001; N = 300.

Notes: Dependent Variable in Model 2 = Gross agricultural income per *nali* (₹) and in Model 3 = Price realization ratio. Robust standard errors (HC3) used to address heteroskedasticity. Reference category for district: Pauri. *p < 0.05, **p < 0.01, ***p < 0.001.

3.4 | Heterogeneity in FPO Association

3.4.1 | Differential Effects by Farm Size

To probe if FPO association differ across farmers type, we classified the sample by the conventional landholding size: marginal farmers (< 3 *nali*), small farmers (3 – 6 *nali*), and medium farmers (> 6 *nali*). Table 7 places mean outcomes across these strata by FPO membership status.

There was a clear pattern that the marginal farmers gained the most. Among marginal farmers, FPO membership correlated with 64.4% increase in RCI scores and a 45.1% boost in income. The corresponding gains for medium farmers (> 6 *nali*), though still sizable, fall to 38.0% and 28.1%. Absolute differences also favor marginal farmers (RCI: 1.34 vs. 0.82 points; income: ₹ 1,600 vs. ₹ 970). Whether these differences were statistically meaningful required testing interaction effects. So, the regression model was extended by adding interaction terms

between FPO membership and landholding size (FPO × Landholding). The interaction term for RCI was negative and statistically significant (β = -0.158, p = 0.022), confirming that FPO impacts on conservation adoption decrease as farm size increases. Similarly, the income model interaction term was significant (β = -124.3, p = 0.038).

TABLE 7 Heterogeneity Analysis – Outcomes by Farm Size Category

Farm Size Category	n	Mean RCI		Mean Income per *Nali* (₹)	
		FPO Members	Non Members	FPO Members	Non Members
Marginal (< 3 *nali*)	102	3.42 ± 0.81	2.08 ± 0.88	5,150 ± 1,180	3,550 ± 1,090
Difference		1.34***		1,600***	
% Difference		64.4%		45.1%	
Small (3-6 nali)	138	3.28 ± 0.84	2.18 ± 0.93	4,820 ± 1,210	3,580 ± 1,140
Difference		1.10***		1,240***	
% Difference		50.5%		34.6%	
Medium (> 6 *nali*)	60	2.98 ± 0.89	2.16 ± 0.96	4,420 ± 1,320	3,450 ± 1,210
Difference		0.82***		970***	
% Difference		38.0%		28.1%	

Notes: Values are mean ± SD. All within-category differences significant at ***p < 0.001 (independent *t*-tests).

3.4.2 | Differential Impacts by Education Level

The sample was divided at the median education level (7 years of schooling) into low education (≤7 years, n=162) and high education (>7 years, n=138) subgroups. Table 8 presents mean outcomes by education level and FPO membership status. FPO impacts on conservation were larger among low-education farmers (+60.6% vs. +40.8%), while income impacts were relatively similar across education levels. Regression interaction tests confirmed that the differential conservation effect by education was statistically significant (β = -0.185, p = 0.031), but the income effect interaction was not (β = -68.4, p = 0.412).

TABLE 8 Heterogeneity Analysis – Outcomes by Education Level

Education Level	n	Mean RCI		Mean Income per *Nali* (₹)	
		FPO Members	Non Members	FPO Members	Non Members
Low (≤ 7 *years*)	162	3.18 ± 0.87	1.98 ± 0.85	4,680 ± 1,280	3,320 ± 1,110
Difference		1.20***		1,360***	
% Difference		60.60%		41.0%	
High (> 7 years)	138	3.35 ± 0.82	2.38 ± 0.95	5,080 ± 1,150	3,780 ± 1,160
Difference		0.97***		1,300***	
% Difference		40.8%		34.4%	

Note: All within-category differences significant at ***p < 0.001 (independent t-tests).

3.4.3 | Geographic Variation in Outcomes

While district dummy variables in the main regression models (Tables 4 and 6) showed no statistically significant effects, descriptive comparisons reveal some geographic variation in absolute outcome levels (Table 9). Tehri Garhwal showed the highest absolute RCI scores (3.45 for FPO members, 2.23 for non-members), while Chamoli showed the lowest (3.02 and 2.04 respectively). However, the FPO membership effect (difference between FPO and non-FPO groups) remained consistently large and significant across all three districts, ranging from 0.98 to 1.22 points on the RCI scale.

TABLE 9 Mean Outcomes by District and FPO Membership

District	n	Mean RCI		Mean Income per *Nali* (₹)	
		FPO Members	Non Members	FPO Members	Non Members
Pauri	99	3.28 ± 0.83	2.18 ± 0.91	4,920 ± 1,210	3,580 ± 1,140
Chamoli	102	3.02 ± 0.89	2.04 ± 0.94	4,650 ± 1,310	3,420 ± 1,180
Tehri Garhwal	99	3.45 ± 0.80	2.23 ± 0.90	4,980 ± 1,190	3,560 ± 1,130

3.5 | Robustness Checks

We ran sensitivity analyses to test our findings robustness. Cook's distance identified 4 observations with D > 0.5 (about 1.3% of the sample). Re-estimating Models 1–3 after excluding these cases produced essentially similar outcomes for the FPO membership coefficients. This confirmed that the results are not driven by a small number of extreme observations. Because the RCI combines practices across three domains viz. soil conservation (3 practices), water management (4 practices), and integrated farming (3 practices), we examined domain-wise patterns to ensure that the composite index does not obscure domain-specific effects. The membership advantage remained present across domains. Water management shows the largest gap (1.17 points), consistent with Table 3. We tested for potential non-linearities in the relationship between landholding size and outcomes by adding a quadratic landholding term to the regression specifications. This did not indicate meaningful non-linear effects. Finally, we implemented Coarsened Exact Matching (CEM) using age, education and landholding size as matching variables. The matched sample retained 128 comparable pairs. The estimated association between FPO membership and RCI in the matched model ($\beta \approx 1.18$, $p < 0.001$) remained close to the full-sample estimate ($\beta \approx 1.25$). These checks indicate that the main RCI associations are robust across alternative specifications and to matching on key observables. However, we do acknowledge that no robustness exercise can fully rule out selection on unobserved factors in a cross-sectional design.

3.6 | Summary of Key Findings

Five main patterns emerged from our analysis:

1. Conservation adoption: FPO members showed 51.2% higher Resource Conservation Index scores than non-members (3.25 vs. 2.15, $p < 0.001$). After controlling for confounders, FPO membership is associated with a 1.25-point increase in RCI ($\beta = 1.251$, $p < 0.001$). This is in direct support to hypothesis 1 (H1).
2. Economic outcomes: FPO members earned 37.8% higher income per *nali* (₹4,850 vs. ₹3,520, $p < 0.001$, $d = 1.29$) and achieved 13 percentage points better price realization (0.88 vs. 0.75, $p < 0.001$, $d = 0.97$). Both effects remained highly significant in multivariate models, proving hypothesis 2 (H2) true.
3. Market access: Market distance is associated with worse outcomes – lower RCI ($\beta = -0.045$, $p = 0.003$), lower income per *nali* ($\beta = -28.5$, $p = 0.040$) and also lower price realization ratio ($\beta = -0.005$, $p = 0.024$). This indicates that market access is a bottleneck for hill agriculture.
4. Heterogeneity**:** FPO membership proved most beneficial for marginal farmers (< 3 *nali*) and less educated ones. Marginal farmers showed 64.4% higher conservation scores and 45.1% higher incomes versus 38.0% and 28.1% respectively for medium-sized farmers (> 6 *nali*).
5. Conservation domains: FPO members vs. non-members adoption gaps were large across all three conservation domains. The largest mean gap is in water management practices (23.3 percentage points), followed by soil conservation (18.9 pp) and integrated farming (18.4 pp). Several practices showed particularly pronounced differences as in mulching (27.3 pp), contour farming (26.6 pp), agroforestry (22.7 pp), drip irrigation (19.4 pp) and on-farm water storage structures (23.3 pp).

These patterns maintained consistency when we added demographic and geographic controls. Across the regression models, the explained variance ranged from about 38% to 48% ($R^2 = 0.389 – 0.482$) which indicates substantial explanatory power for both conservation and economic outcomes.

Our question going into this research was straightforward: can FPOs in Uttarakhand's hill agriculture work as institutional innovation that is associated with improvements in both resource conservation and economic outcomes at the same time? The answer appears to be yes, though with some notable patterns in how benefits distribute. Three primary results emerged from the analysis: markedly higher conservation practices adoption among members, sizeable gains in both income and price realization and disproportionately larger effects for marginal and less-educated farmers.

3.7 | FPO Membership and Conservation Adoption

The sizeable gap in Resource Conservation Index (RCI) scores between FPO members and non-members (3.25 vs. 2.15; a 1.10-point gap on 0–5 scale) is the most consequential finding of the study. The fact that these differences remain large after controlling for age, education, land size and market distance suggests that FPOs matter beyond simple compositional differences in who joins.

Our findings resonates with Pradhan et al. (2016)'s work on conservation agriculture adoption in Eastern India. They also found that collective institutions created room for farmers to experiment with sustainable practices. What stands out in our data, though, is the magnitude: a 51% higher RCI compared to 20-30% gains usually seen in technology adoption studies (e.g., improved seeds, micro-irrigation). This suggests something more than individual practice uptake is happening. FPO members appear to be implementing conservation practices as part of a coordinated package. This fits with arguments that institutional innovations like FPO matter most where sustainability depends on multiple practices working together, not just on individual solutions.

Our quantitative design did not directly capture mechanisms of FPO influence, the domain-specific adoption patterns provide useful hints. The largest gaps occur for practices that are relatively knowledge- and capital-intensive such as on-farm water storage (23.3 pp) and drip irrigation (19.4 pp). This is consistent with institutional theory of collective action which emphasises how local organizations can help overcome indivisibilities and cost barriers in provision of capital-intensive

technologies like drip irrigation (Ostrom, 2019). FPOs appear to reduce both cognitive and economic barriers to adopting more demanding conservation technologies (North, 1990).

That said, we should be careful not to overstate our findings. We did not measure biophysical outcomes (soil erosion reduction, soil quality changes etc.) directly. While FPO members report higher adoption of conservation practices, we can't claim from our data whether this translates into measurable environmental improvements.

3.8 | Economic Outcomes and Market Access

The story is equally layered on the economic side. FPO members earn substantially higher income per unit of land and secure a larger share of prevailing market prices. For a household with 5 *nali* (an illustrative smallholder plot size), the estimated agricultural income gain is about ₹6,650. This uplift is an indicator that FPO members occupy a stronger position within value chains, probably through aggregation that allows for negotiations and direct sales to bulk buyers. Lower per-unit transport costs and better price information likely play a role too. These income gains are broadly comparable to evidence from Andhra Pradesh (Kumar *et al*., 2023) and Maharashtra (Lalitha *et al.*, 2024), yet the configuration here diverges in key respects. For one, we document simultaneous improvements in conservation adoption and income. Also, while our income gains are broadly similar to those in better-connected plains regions, they occur in a context of far more severe physical and market constraints. This suggests that FPOs can partially offset structural disadvantages associated with remoteness and small holdings even with weak market density and infrastructure.

Role of market access also emerges as a key point. Greater distance from the nearest market town is seen to be associated with lower conservation adoption, lower income per *nali* and lower price realization. This reinforces a basic point: institutional innovations can help farmers negotiate markets better, but they cannot fully substitute for the structural constraints created by remoteness.

Our results are broadly in line with international evidence that producer organizations can overcome market failures in smallholder farmers (Liu *et al*., 2020; Tomorri *et al.*, 2022). The literature though also documents high failure rates and underperformance among farmer organizations globally due to weak professional management and elite capture (Khiangte & Malsawmsanga, 2025).

3.9 | Heterogeneity and The "Equalizing" Pattern

One of the most policy-relevant patterns from this study is that the FPO members vs. non-members differences are largest among marginal farmers (< 3 *nali*) and farmers with lower education. This finding is encouraging from an equity standpoint. FPOs are acting as equalizing institutions benefiting those groups who need them most. This is in contrast to many other support programs that amplify gains for the already-advantaged groups.

There could be many possible explanations for this heterogeneity. One possibility is complementarity: farmers facing strongest constraints may gain proportionally more when FPOs lower barriers to investment, information and market participation. This aligns with Olson's (2003) theory that small disadvantaged actors have stronger incentives for collective action when individual capacity is minimal. Another reason could be selection: many FPO-promoting programs deliberately target smaller and socially disadvantaged farmers (Gurung & Choubey, 2023). Policy implications vary by interpretation. If complementarity dominates, policies should focus on forming and recruiting marginal/less-educated farmers into FPO. The benefits here would be maximum and it would be an equity-promoting strategy. If selection dominates, addressing participation barriers would promote equity. Longitudinal data tracking farmers before and after joining could clarify these mechanisms.

3.10 | Study Limitations and Interpretation

This study faces limitations that restrict causal inference and generalizability. This study is cross-sectional and compares FPO members and non-members at one point in time. We should therefore read the results as associations rather than causal impacts. We controlled for observable characteristics (age, education, landholding size, market distance, and district effects), but unobserved factors like motivation, social networks, risk preference, time preferences etc. may influence FPO participation. So, selection bias cannot be ruled out.

Our sampling focussed on FPOs operational for at least 2 years excluding the failed or struggling FPOs. This introduces a survivor bias as we only see successful instances. Given that approximately 40% FPOs become non-operational within the critical 3-5 years mark (Anand et al., 2025), our estimates likely represent an optimistic upper limit of the outcomes.

Measurement limitations also apply. The Resource Conservation Index is based on self-reported data without independent verification. Income and price realization may also be affected by recall issues. The study explores FPOs simplistically in terms of membership and outcomes only without studying mechanisms and organizational processes. Understanding these mechanisms requires detailed data and qualitative insights. Combining qualitative with quantitative methods would give a fuller picture.

3.11 | Policy Implications

Our findings provide several policy considerations for hill agriculture in Uttarakhand stated carefully as conditional recommendations:

1) Successfully operating FPOs in Garhwal are associated with substantially higher adoption of resource conservation practices and better economic outcomes among members.

This supports continued experimentation with FPO model in hill regions. Here it is important to recognize what we do not know. FPO outcomes may depend on organizational design, management quality, service delivery and other factors we have not identified.

2) Marginal (< 3 *nali*) and less educated farmers benefit more from FPO membership. Promotion should focus on small and marginal farmers. This differs from usual programs favouring early adopters (Aditi et al., 2025). It's unclear if benefits come from complementarity or selection. Still, FPOs seem accessible to broader groups. Government and NGOs could set membership goals (e.g. ≥ 60% marginal/small farmers) and improve outreach for disadvantaged groups.

3) The largest adoption gaps occur in water management and other relatively demanding practices (e.g., drip irrigation and on-farm storage structures). In hill agriculture, support programs that treat FPOs only as marketing vehicles may miss this part of the picture. Our findings show that conservation-related investments may be as important as output aggregation. NABARD and state departments could tie FPO financing to conservation training and adoption goals.

4) Our sample studied only active FPOs, so the results should not be interpreted as evidence that simply forming an FPO will reliably deliver improvements. There is a case for systematic work on organizational traits and contextual factors that differentiate successful from failed FPOs. Aggressive FPO promotion without understanding success conditions risks wasted resources and farmer disappointment.

5) Market access remains a binding constraint. Market distance is negatively associated with all outcomes in the study. While institutional innovations like FPOs help, they can't replace infrastructure investment. Successful hill agriculture development needs strategies combining physical infrastructure (roads, cold storage, market yards) and institutional support (FPOs, value chains). Support for FPOs should be integrated with rural infrastructure programs, not viewed as alternative.

3.12 | Research Agenda

This study establishes clear empirical patterns, but is also highlights gaps that require complementary research designs and data. Future research could prioritize the following:

Priority 1 – Causal identification : Use longitudinal data that track the same farmers before and after joining FPOs (e.g. panel designs and difference-in-differences) to better separate membership effects from selection.

Priority 2 – Mechanism studies: Collect detailed information on FPO functioning such as services offered, service quality, member utilization data etc. Test which specific services are linked to which outcomes. This should be complemented with qualitative work (FGDs/KIIs) to understand how services operate on the ground.

Priority 3 – Success/failure analysis: Sampling both operational and defunct FPOs to identify organizational and contextual success factors; tracking FPO life cycle dynamics.

Priority 4 – Biophysical verification: Combine adoption surveys with biophysical checks (e.g. soil indicators, erosion proxies, water retention/availability measures etc.) to validate whether environmental benefit claims.

Priority 5 – Scalability assessment: Conduct comparative multi-region studies to identify FPO effectiveness in diverse agro-ecological and market situations.

4 | CONCLUSIONS

The study establishes FPOs as crucial institutional platforms in Uttarakhand. FPOs are associated with dual improvements in resource conservation practices and economic outcomes. Using a cross-sectional survey of 300 farm households (150 FPO members and 150 non-members) from three Garhwal districts, we find clear and consistent associations: FPO members report substantially higher adoption of conservation practices and better economic performance than non-members from the same villages.

A major contribution of the study is that it reveals how these associations are distributed across farmers groups. Differences between members and non-members are largest among marginal farmers (<3 *nali*) and farmers with lower formal education. This stands in contrast to many other agricultural schemes which tend to benefit the already advantaged groups. In this sense, FPOs appear to function as equalizing institution in Uttarakhand's hill agricultural economy. This equity dimension in central to their design logic as collective action matters most where individual capacity is most constraints.

For policymakers and practitioners in Uttarakhand and similar hill states, the finding suggests that FPO formation efforts can be targeted toward clusters with high proportion of marginal farmers. FPO promotion should move towards capacity enhancement. Government should shift programme design to performance-oriented support for existing FPOs. Conservation practices adoption should be integrated as a core FPO performance metric alongside economic returns. For NABARD and other financing institutions, the results support extending credit lines specifically for conservation-related capital investment (water storage, drip system, organic input production units) that FPOs can procure collectively.

The study establishes the case for giving serious attention to collective institutional arrangement as part of sustainable hill agriculture strategies. However, FPOs are neither automatic solutions nor uniformly effective. How well they perform seems to depend on several factors including their design, governance, external support and fitment with local agro-ecological conditions.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the farmers of Pauri, Chamoli and Tehri Garhwal districts who generously shared their information and experience during the field survey. We

are thankful to the staff of the concerned Farmer Producer Organizations (FPOs) for cooperation.

CONFLICT OF INTEREST

The author declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data is available with the corresponding author and can be provided on request.

AUTHOR'S CONTRIBUTION

RSB conceptualized the project, conducted the study and wrote the manuscript. PM reviewed the draft manuscript and coordinated the work.

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How to cite this article: Bisht, R.S. and Mamgain, P. 2025. Farmer Producer Organizations and Agricultural Sustainability in Uttarakhand's Hills: A Cross-Sectional Analysis of Conservation Practices and Economic Outcomes. *Indian J. Soil Cons*., **53(3)** (*Hill & Mountain Agriculture S*pecial Issue)**: 288-301**

LIST OF REVIEWERS DURING THE YEAR 2025

The editorial board of the Indian Association of Soil and Water Conservationists (IASWC) places on record its sincere thanks to the following reviewers for reviewing the manuscripts during the year 2025. It would not have been possible for the editorial board of the Association to discharge its responsibility of considering and deciding about the suitability of large number of articles received for publication in the Indian Journal of Soil Conservation without the active co-operation and help by the learned reviewers.

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INDIAN ASSOCIATION OF SOIL AND WATER CONSERVATIONISTS
BALANCE SHEET AS ON 31ST MARCH 2025

SOURCES OF FUNDS	SHD NO	AS ON 31ST MARCH 2025		AS ON 31ST MARCH 2024	
		Rs. P.	Rs. P.	Rs. P.	Rs. P.
1 SOCIETY CAPITAL FUND					
ASSOCIATION CAPITAL FUND:					
Last Balance:		8,349,695.56		8,220,508.48	
Life Members Subscription:		249,000.00		207,000.00	
		8,598,695.56		8,427,508.48	
Add/(Less): Accumulation Made During the Year:		-		(250,000.00)	
Add/(Less): Surplus/(Deficit) for LNSWSEC		(729,903.00)		81,540.00	
Add/(Less): Surplus/(Deficit) for the year:		(6,745.04)	7,862,047.53	90,647.07	8,349,695.56
EARMARKED FUNDS:	1				
Conference & Seminar Fund:		-		50,000.00	
Dr. K. G. Tejwani Awards:		200,000.00		200,000.00	
Dr. D. N. Puri Award:		500,000.00	700,000.00	500,000.00	750,000.00
ACCUMULATED FUNDS:					
Conference Seminar & Workshops:					
To be Utilized upto 31.03.2029:		250,000.00		250,000.00	
Utilized during the Year 24-25:		(250,000.00)	-	-	250,000.00
Asset Replacement & Maintenance Fund:					
To be Utilized upto 31.03.2026:		57,784.00		100,000.00	
Utilized during the Year 24-25:		(57,784.00)	-	(42,216.00)	57,784.00
2. CURRENT LIABILITIES AND PROVISIONS:					
CURRENT LIABILITIES:					
Professional Fees Payable		60,100.00	60,100.00	38,000.00	38,000.00
TOTAL RS...			**8,622,147.53**		**9,445,479.56**
			-		-

[M. MADHU]
President

[RAMAN JEET SINGH]
Secretary

[J.M.S TOMAR]
Treasurer

GUPTA SAWHNEY & ASSOCIATES ✡ DEHRADUN ✡ Chartered Accountants

10-Convent Road, Dehra Dun
Dated: 31.05.2025
UDIN BS
UDIN TAR

As per our separate report of even date.

For Gupta Sawhney & Associates
Firm Registration Number 015283C
Chartered Accountants

[Varun Thakur Das Sawhney]
Membership Number 408361
Partner

INDIAN ASSOCIATION OF SOIL AND WATER CONSERVATIONISTS
BALANCE SHEET AS ON 31ST MARCH 2025

SOURCES OF FUNDS	SHD NO	AS ON 31ST MARCH 2025		AS ON 31ST MARCH 2024	
		Rs. P.	Rs. P.	Rs. P.	Rs. P.
3 NON-CURRENT ASSETS					
FIXED ASSETS:	2		312,697.27		321,040.30
INVESTMENTS:					
In Fixed Deposits:					
With Schedule Banks:		7,261,199.00		7,776,415.00	
Interest Accrued		128,510.00	7,389,709.00	178,309.00	7,954,724.00
4 CURRENT ASSETS, LOANS AND ADVANCES:					
Cash and Bank Balances:					
Cash in hand Main Account:		9,767.00		797.00	
With Bank of Baroda, in Savings Bank A/c :		735,078.80		1,093,274.80	
With State Bank of India Saving A/c (LNSWSEC)		107,185.46		9,948.46	
Postage in hand:		6,295.00		13,132.00	
Advance for Expenses:		-		10,000.00	
Balance with Revenue:		61,415.00	919,741.26	42,563.00	1,169,715.26
TOTAL RS...			**8,622,147.53**		**9,445,479.56**

[M. MADHU]
President

[RAMAN JEET SINGH]
Secretary

[J.M.S TOMAR]
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Membership Number 408361
Partner

INDIAN ASSOCIATION OF SOIL AND WATER CONSERVATIONISTS
BALANCE SHEET AS ON 31ST MARCH 2025

INCOME		AS ON 31ST MARCH 2025		AS ON 31ST MARCH 2024	
		Rs. P.	Rs. P.	Rs. P.	Rs. P.
TO MEMBERSHIP FEES/SUBSCRIPTION:			75,852.00		74,636.00
TO RECEIPTS FOR CONFERENCE LNSWSEC 2024					
Grant From ICAR, New Delhi		300,000.00		100,000.00	
Registration Fees		635,003.00		196,000.00	
Grant From NABARD, Dehradun		100,000.00		-	
Grant From NBA, Chennai		100,000.00		-	
Grant FOR LNSWSEC-2024		1,000,000.00		-	
Other Receipts for Conference		670,000.00		-	
Grant for Conference LNSWSEC-2024		400,000.00		-	
Misc Income		-		23,796.00	
Full Settelment LMPFRS -2022		-	3,205,003.00	92,860.00	412,656.00
TO DR. K G Tejwani / DN Puri Award :			1,500.00		2,000.00
TO INTEREST RECEIVED					
Interest on Savings Bank :		14,292.00		23,703.00	
Interest on Fixed Deposits:		525,549.00		528,053.00	
Interest on TDS Refund:		3,188.00	543,029.00	-	551,756.00
TO GRANT FOR PUBLICATION OF JOURNAL			200,000.00		-
TO ONLINE SALE OF JOURNALS / BOOKS:			-		750.00
TO MISC. INCOME:			6,644.00		6,000.00
TO TRF FROM CONFERENCE & SEMINAR FUND			50,000.00		-
TO RESERVES AND ACCUMULATIONS UTILISED:			307,784.00		-
TOTAL RS...			**4,389,812.00**		1,047,798.00

[M. MADHU]
President

[RAMAN JEET SINGH]
Secretary

[J.M.S TOMAR]
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Partner

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BALANCE SHEET AS ON 31ST MARCH 2025

EXPENDITURE	AS ON 31ST MARCH 2025		AS ON 31ST MARCH 2024	
	Rs. P.	Rs. P.	Rs. P.	Rs. P.
BY PUBLICATION CHARGES:				
Indian Journal of Soil Conservations	351,375.00		202,696.00	
Salary	390,172.00		379,255.00	
Honorarium & Award Screening	7,500.00		10,600.00	
Postage	90,980.00		65,000.00	
Calendars & Stationery	58,523.00	898,550.00	59,854.00	717,405.00
BY ADMINISTRATIVE EXPENSES:				
Travelling & Conveyance Charges	10,248.00		12,152.00	
Telephone Charges	4,942.00		5,768.00	
Refereshment Charges	16,428.00		6,243.00	
Legal & Professional Expenses	45,300.00		37,307.00	
Bank Charges	45.00		116.54	
Office Expenses:	15,215.00		9,007.00	
Website AMC Expenses	40,096.00		28,153.00	
Miscellenous Expenses	1,621.00		1,150.00	
Expenses on Elections E-voting	59,000.00		-	
Audit fees, Filing of Income Tax return	32,400.00	225,295.00	38,000.00	137,896.54
BY LNSWSEC-24 CONFERENCE EXPENSES:				
Momentos Expenses Conference	97,774.00		-	
Awards - KG Tejwani & D. N. Puri	50,000.00		29,260.00	
Traveling Expenditure Conference	27,738.00	175,512.00	-	29,260.00
Bank Charges	1,239.00		542.03	
Misc Conference Expenses	230.00		-	
Printing & Stationary Expenses	649,600.00		-	
Postage & Courier Expenses	3,289.00		-	
Travelling & Conveyance Expenses	103,277.00		-	
Accommodation	28,600.00		-	
Audit Fee	25,000.00		-	
Food Exp	1,188,188.00		-	
Conference & Function	147,289.00		-	
Honorarium	33,000.00		-	
Momentos & Gifts	666,332.00		-	
Photography and Videography	24,962.00		-	
Venue Expenditure and Rentals	663,900.00	3,534,906.00	-	542.03
BY REPAIRS AND MAINTENANCE:		64,449.00		25,258.00
BY GRANT TO INDIAN SOCIETY OF SOIL SCIENCE, NEW DELHI		150,000.00		-
BY DEPRECIATION:		77,748.04		46,789.36
BY SURPLUS / (DEFICIT) (being excess of income over expenditure transferred to Association Capital Fund)		(736,648.04)		90,647.07
TOTAL RS...		**4,389,812.00**		**1,047,798.00**

[M. MADHU]
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UDIN TAR

As per our separate report of even date.

For Gupta Sawhney & Associates
Firm Registration Number 015283C
Chartered Accountants

[Varun Thakur Das Sawhney]
Membership Number 408361
Partner

Indian Association of Soil and Water Conservationists

218, Kaulagarh Road, Dehradun - 248195, Uttarakhand

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INDIAN ASSOCIATION OF SOIL AND WATER CONSERVATIONISTS

218, Kaulagarh Road, Dehradun - 248 195, Uttarakhand, India

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