



WATERSHED BULLETIN

Water Augmentation Technologies for Ecological Restoration
and Societal Holistic Economic Development

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Water Augmentation Technologies for Ecological Restoration
—— and Societal Holistic Economic Development ——

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Editorial

It is with deep satisfaction and a renewed sense of purpose that I welcome readers to the tenth volume of what is now the *Watershed Bulletin* — a milestone that invites both celebration and reflection. This publication of the Indian Association of Soil and Water Conservationists (IASWC) began its journey in 2016 as the *Soil and Water Conservation Bulletin*, serving for seven years as a platform where science, practice, and field experience could converge without the rigid constraints of a formal research journal. In 2023, as the scope of our concerns expanded to embrace the watershed as an integrating unit of landscape, livelihood, and ecology, the publication was renamed the *Watershed Bulletin* — while its volume numbering carried forward unbroken, honouring the continuity of purpose that has defined this venture from the outset. That we now reach Volume 10 is a testament to the commitment of our contributors and the vitality of the soil and water conservation community in India and beyond.

The contributions in this volume span from the hill ecosystems of Odisha and the Shivaliks of North India to the tribal watersheds of Gujarat and the tank landscapes of southern India. The pursuit of resilience is the common thread woven through these pages. Whether it is designing climate-smart crop calendars for rainfed agroforestry farms, exploring the strategic desiltation of tanks for livelihood security, or harnessing the quiet potential of Napier grass and seed balls in watershed restoration, each contribution affirms that practical ingenuity remains our most durable resource. This volume highlights new scientific frontiers, including soil biodiversity in erosion modeling, nano nitrogen fertilizers to reduce leaching, and links between soil moisture and carbon sequestration. It also showcases GIS-based erosion assessment of the Mandakini watershed and a convergence model from Panchmahal, illustrating how spatial tools and multi-stakeholder approaches are transforming conservation. Perspectives emphasizing people are equally important, including green and carbon credits in conservation, tribal watershed interventions, and leadership from these landscapes. Conservation involves more than just technical aspects; it is also social and ethical.

As we mark ten years of the Watershed Bulletin, we reaffirm its founding conviction: that good ideas deserve to be heard before statistical validation, and that the wisdom accumulated in the field — through failure, adaptation, and perseverance — is as vital as any laboratory finding. We continue to invite contributions in the form of success stories, technology updates, perspective pieces, and reflective narratives that bridge research and outreach.

Sd/-
(Rajive Kumar Singh)
Chief Editor



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Designing a Climate-Smart Crop Calendar and Resilience Package for 1-Acre Agroforestry-based Family Farms in the Rainfed Hill Ecosystems of the Eastern Ghats, Odisha

Prasanta Kumar Mishra^{1*}, Pravu Charan Lenka², Raman Jeet Singh³, Rajive Kumar Singh⁴, Achyut Das⁵ and Kulaswami Jagannath Jena⁶

1. Introduction

The Eastern Ghats region of southern Odisha is characterised by undulating to steep hill slopes, shallow red and lateritic soils, and a predominantly rainfed production system marked by high inter- and intra-seasonal rainfall variability. These fragile landscapes are largely inhabited by tribal communities whose livelihoods traditionally depend on millets, pulses, oilseeds, indigenous rice varieties, forest produce, and mixed farming systems. Over the past several decades, however, commercial forest extraction, mining activities, shortening of fallow cycles, and unchecked soil erosion have led to widespread land degradation, declining soil fertility, and loss of agro-biodiversity.

Climate variability has further intensified these stresses. Delayed monsoon onset, prolonged dry spells during the cropping season, and high-intensity rainfall events have disrupted traditional farming calendars, increased crop failure risks, and reduced the reliability of rainfed agriculture. As a result, food insecurity, seasonal migration, and livelihood vulnerability have become persistent features of tribal households in the region (Das *et al.*, 2023). These interacting pressures underscore the urgent need for land-use systems that simultaneously address ecological degradation, climate risk, and livelihood security

based on Odisha Climate Change Action Plan (2018) maps the present and future vulnerabilities of Odisha under different climatic conditions.

In this context, the 1-Acre Agroforestry-based Family Farm model, developed and promoted by the NGO Agramee over more than a decade of field experience in southern Odisha, has emerged as a promising pathway for restoring degraded hill slopes while enhancing farm income, food security, and ecosystem services. Empirical observations and recent assessments indicate that the model can enhance household income by several folds, improve soil organic carbon stocks, reduce erosion, and strengthen on-farm biodiversity when compared to conventional monocropping systems (Mishra *et al.*, 2025).

However, sustaining and scaling such regenerative systems requires more than physical soil and water conservation interventions. It demands scientifically designed, climate-responsive cropping systems that align with rainfall patterns, labour availability, household nutrition needs, and market opportunities—while remaining rooted in Indigenous and Local Knowledge (ILK). This aligns closely with the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) framework, which emphasises nature-based solutions, social-ecological resilience, and policy coherence in land restoration (Mishra *et al.*, 2024).

Against this backdrop, the present article documents the development of a climate-smart crop calendar and resilience package for a 1-acre agroforestry-based Family Farm model being implemented on degraded hill slopes of the Eastern Ghats of Odisha (average annual rainfall ~1500 mm). The approach integrates agroforestry, diversified cropping, soil and water conservation, and risk - contingency planning to ensure year-

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round food, nutrition, income, and employment, while strengthening soil health, biodiversity, and carbon sequestration.

1.1 Why Crop Calendars Matter for Climate Adaptation

Climate adaptation in agriculture is frequently discussed in terms of technologies, crop varieties, or infrastructure. This study underscores that timing and sequencing of farm operations are equally critical adaptation levers, particularly in rainfed systems exposed to increasing climate variability.

The Climate-Smart Crop Calendar enables farmers to:

- Anticipate and respond to delayed monsoons and dry spells,
- Optimise the use of conserved soil moisture,
- Diversify production to spread climate risk, and
- Maintain food and income security under uncertain rainfall regimes.

By embedding contingency options within the calendar, the approach shifts adaptation from reactive coping to proactive planning. Importantly, the calendar translates complex climate information into actionable, field-level decisions, making it accessible to farmers, extension workers, and local institutions.

2. 1-Acre Agroforestry-based Family Farm Model

The 1-Acre Agroforestry-based Family Farm model represents a landscape-informed, household-centred approach to restoring degraded hill slopes while securing sustainable livelihoods in rainfed tribal regions. Promoted by Agramee in southern Odisha, the model is premised on the idea that every family should manage a compact but diversified land unit capable of generating food, income, and ecosystem services throughout the year. The key benefits of the Family Farm model include food security, income generation, soil conservation, biodiversity enhancement and eco-restoration leading to climate resiliency. The time bound institutional support requirements (seed supply, nursery support, extension services, market linkages etc.) were addressed by the NGO Agramee through the project funding and

administrative support locally.

Unlike conventional single-crop or seasonal farming systems, the Family Farm integrates high density plantations of permanent tree components, annual crops with soil–water conservation structures within a one-acre plot, designed to mimic natural forest processes while remaining economically productive. The system combines agroforestry, organic/natural farming practices, and selective modernisation—blending Indigenous and Local Knowledge with context-appropriate technical inputs. Fig. 1 illustrates how the Family Farm model addresses regional agricultural challenges—land degradation, climate variability, livelihood insecurity, and biodiversity loss—through an integrated and adaptive farming framework.

2.1 Structural Composition of the Family Farm

A typical 1-Acre Agroforestry-based Family Farm accommodates approximately 150–170 multipurpose plants belonging to around 12–15 species, strategically arranged according to slope position, moisture availability, and canopy architecture. These include:

- Low-input fruit trees such as mango, cashew, custard apple, banana, and papaya, which provide medium- to long-term income;
- Nutritional and functional species such as moringa (drumstick) for year-round dietary support;
- Forest and multipurpose trees (e.g., chakunda, karanja, neem, tamarind) that enhance biomass, improve microclimate, and contribute to soil fertility;
- Medicinal and minor forest produce species such as amla, harida, bahada, and simarouba, which diversify income sources.

Intercropping with millets, pulses, oilseeds, vegetables, and tuber crops is a permanent feature of the system, ensuring continuous ground cover, efficient resource use, and early returns during the establishment phase of trees.

2.2 Nursery Raising and Community Engagement

The establishment of decentralised nurseries is a

foundational activity in the Family Farm approach. These nurseries are typically managed by village youth and women's groups for strengthening local capacity, reducing dependence on external planting material, and generating skills related to seedling care, grafting, and plant health management. This process also reinforces community ownership over restoration efforts.

2.3 Cropping and Soil Health Management

Intercropping serves dual objectives: generating short-term income and enhancing soil health. A diverse range of vegetables (*e.g.*, brinjal, cowpea, chilli, gourds, radish, pumpkin) and traditional millets are cultivated in place of high-risk crops such as maize. Chemical fertilisers and pesticides are avoided; instead, soil fertility and crop protection rely on farmyard manure, compost, vermicompost, botanical extracts, cow urine formulations, and biomass recycling. These practices improve soil organic matter, enhance moisture retention, and reduce production costs—key considerations for rainfed and marginal farmers.

3. Climate-Smart 1-Acre Family Farm Crop Calendar

A defining strength of the 1-Acre Family Farm model is its ability to convert a rainfed, sloping,

and climate-vulnerable landscape into a year-round livelihood system. This is achieved not through a single crop intervention, but through a carefully designed set of interlinked calendars that guide farmers on what to grow, when to grow, how much labour is needed, when food and nutrition security become available, and when income can be expected—while also preparing them for climate risks.

To make the Family Farm system more scientific, predictable, and climate-responsive, a comprehensive Climate-Smart Crop Calendar Package has been developed. This package serves both as a planning tool for farmers and as a decision-support framework for field facilitators, extension workers, and watershed managers. The key components of this package include:

1. Crop calendar
2. Labour calendar
3. Nutrition availability calendar
4. Income and market calendar
5. Climate risk and contingency plan
6. Indigenous crop diversity inventory
7. Embedded climate-resilience mechanisms
8. Topo-sequence-based land-use planning (upper, mid and lower slopes)

Together, these elements transform the family farm from a seasonal subsistence activity into a resilient production–nutrition–income system.

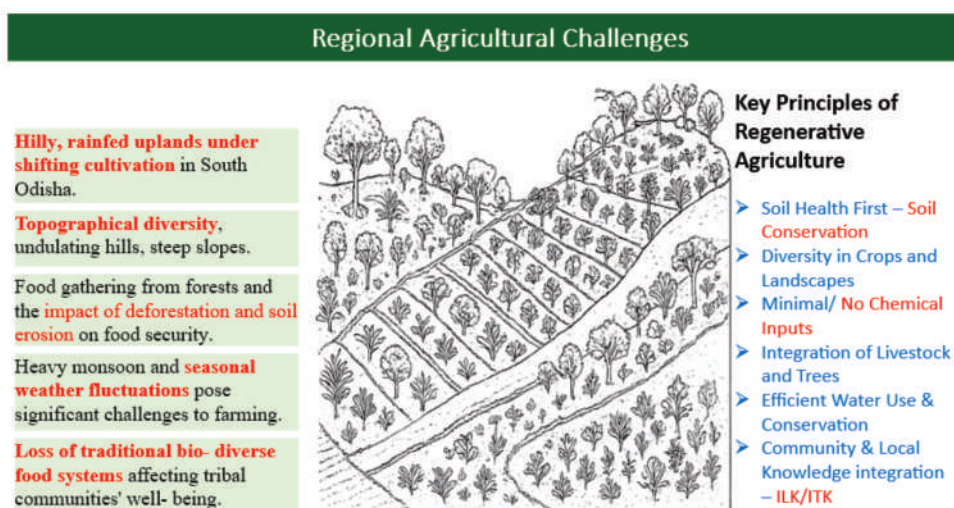


FIGURE 1 Regional agricultural challenges being addressed by a Family Farm

3.1 Crop Calendar: Sequencing Crops with Rainfall and Soil Moisture

The crop calendar (Table 1) aligns sowing, crop growth, and harvesting activities with the monsoon rhythm, soil moisture availability, and slope position. The emphasis is on mixed cropping of millets, pulses, oilseeds, vegetables, and fruit trees to spread risk and ensure continuous production. This was developed based on the field experience and long-term observations by the NGO Agramee backed by local agroclimatic situation.

During June–July, land preparation coincides with the onset of monsoon rains. Millets, pulses, and oilseeds are sown on upper and mid-slopes, while vegetables are planted closer to homesteads and lower slopes where moisture is relatively higher. At the same time, bund strengthening, pruning of trees, and repair of terraces ensure protection against early monsoon runoff.

The August–September period focuses on crop establishment and vegetative growth.

Intercultural operations, weeding, and organic pest management dominate farm activities, supported by high biomass availability for composting and mulching.

In October–November, the system transitions from production to harvest. Millets and pulses are harvested, winter vegetables are sown, and fruit trees such as mango, cashew, and papaya enter flowering or fruit-setting stages. This overlap ensures that food availability continues even after the monsoon ends.

The dry season months (December–March) are used productively through winter vegetables, nursery raising, compost preparation, and limited supplemental irrigation from farm ponds. Finally, April–May is devoted to soil moisture conservation, mulching, harvesting late fruits, and preparing land and pits for the next monsoon cycle.

This seasonal sequencing allows even a one-acre rainfed holding to remain productive for most months of the year.

TABLE 1 Crop Calendar: Month-wise with activities

Month	Crop Activity
June–July	Land preparation, sowing of millets, pulses, oilseeds; planting vegetables; strengthening bunds, pruning of trees
August–September	Vegetative growth phase; intercultural operations; pest management
October–November	Harvesting millets and pulses; sowing winter vegetables; papaya fruiting, fruit-set in mango/cashew
December–January	Winter vegetable harvest; composting
February–March	Dry-season vegetables with supplemental irrigation; nursery preparation
April–May	Harvesting late fruits; soil mulching; water conservation before monsoon

3.2 Labour Calendar: Distributing Work- load Across the Year

One of the major challenges in rainfed tribal agriculture is seasonal unemployment and labour migration. The labour calendar addresses this by mapping month-wise labour demand across farm activities (Table 2). The women farmers actively got involved in the Family Farm activities in nursery management, vegetable cultivation, harvesting and value addition.

Intensity of demand varies depending on the

farm operations with peak during sowing and harvesting operations. Importantly, labour demand does not collapse during the dry months; instead, medium-intensity work continues through vegetable harvesting, composting, nursery raising, and orchard management.

The April–May lean period is deliberately utilised for moisture conservation, pit preparation, and bund repair—activities that require lower labour but generate high returns once the monsoon arrives. This staggered labour demand helps retain family labour within the village and provides meaningful engagement for women and youth.

TABLE 2 Labour Calendar of a 1-Acre Family Farm (Month-wise Workload)

Month	Major Activities	Labour Intensity - Family labour (Manpower days)
June-July	Land preparation, sowing millets/pulses, planting vegetables, bund repair, preparation of pits	45
August–September	Weeding, intercropping, composting, pest management, planting and management of fruit plants and forest species	65
October–November	Millet harvest, sow winter vegetables, tree care and management, sowing of oilseed and pulses	30
December–January	Vegetable harvest, compost pit filling, pruning and training of fruit trees	25
February–March	Irrigated vegetables, nursery preparation	25
April–May	Mulching, moisture conservation, fruit harvest, selection of lands for raising fruit and forest species, preparation of pits and bunds	30
Total		220

3.3 Nutrition Calendar: Ensuring Year-Round Household Food and Nutritional Security

The nutrition calendar translates cropping diversity into dietary diversity. Rather than focusing only on yields or income, the Family Farm model explicitly tracks when different food groups become available for household consumption (Table 3).

Millet, pulses, and oilseeds harvested between October and January form the staple food base. Leafy vegetables and seasonal vegetables are

available for most of the year, significantly improving micronutrient intake. Fruits such as papaya and banana provide near year-round nutrition, while mango, jackfruit, cashew, and custard apple add seasonal dietary richness.

The inclusion of moringa as a perennial nutritional crop ensures continuous access to greens, particularly during lean months. Overall, the nutrition calendar demonstrates how a one-acre farm can meet calorie, protein, micronutrients and vitamins needs of a tribal household with minimal external dependence.

TABLE 3 Nutrition Calendar (Year-Round Household Consumption)

Food Group	Availability Window	Major Nutrients
Millet	Oct–Jan	Complex carbohydrates, dietary fibre, calcium, iron, magnesium, B vitamins
Pulses & oilseeds	Oct–Dec	Plant protein, healthy fats, iron, zinc, folate, calcium, vitamin E
Leafy vegetables	Aug–Mar	Iron, calcium, vitamin A, folate, vitamin K, antioxidants
Root & tubers	Sept–March	Carbohydrates, dietary fibre, potassium, vitamin A (especially orange sweet potato), vitamin C
Seasonal vegetables	July–April	Vitamins A and C, folate, potassium, fibre, antioxidants
Fruits (banana, papaya, citrus)	Year-round (with staggered planting)	Vitamin C, vitamin A, potassium, dietary fibre, natural sugars
Mango, cashew, jackfruit, custard apple	Mar–July	Vitamin A, vitamin C, carbohydrates, healthy fats (cashew), potassium, antioxidants
Moringa	Round the year	Protein, calcium, iron, potassium, vitamins A, C and E, antioxidants

3.4 Income and Market Calendar: From Seasonal Cash Flow to Year-Round Earnings

The income calendar complements the nutrition calendar by identifying marketable surplus windows. Instead of one or two distress sales after harvest, farmers benefit from multiple income points across the year (Table 4).

Vegetables generate quick and frequent cash flow during both kharif and rabi seasons. Millet and pulses contribute bulk income post-monsoon, while fruits such as mango and cashew provide high-value seasonal returns. Banana and papaya act as income stabilisers due to staggered harvesting.

By spreading income across months, the

Family Farm model reduces vulnerability to price shocks and crop failure, enabling households to

meet education, health, and social expenses without distress borrowing.

TABLE 4 Income Calendar of a typical (Marketable Surplus Timing) of 1-acre Family Farm

Commodity	Market Window	Average Family Farm income (₹/acre)
Millets & Pulses	Oct–Jan	16500/-
Vegetables (Kharif)	Aug–Nov	32500/-
Vegetables (Rabi)	Dec–Mar	22500/-
Banana & Papaya	Year-round	7500/-
Mango, Cashew	Apr–July	28000/-
Turmeric & Ginger	Jan–March	7000/-
Leafy vegetables	Round the year	11000/-
Total		1,25,000/-

4. Risk & Climate Contingency Plan: Managing Uncertainty in Rainfed Hill Agriculture

Rainfed agriculture in the Eastern Ghats is inherently exposed to multiple climate risks, including delayed monsoon onset, prolonged mid-season dry spells, high-intensity rainfall events, and episodic pest and disease outbreaks. The Family Farm model addresses these uncertainties through a pre-planned, calendar-linked climate contingency framework, rather than reactive, post-failure responses. The contingency plan is embedded directly within the crop and labour calendars, enabling farmers to make timely tactical adjustments based on rainfall behaviour and field conditions (Table 5).

4.1 Delayed Onset of Monsoon

In years when monsoon arrival is delayed, farmers shift from long-duration crops to short-duration and drought-tolerant millets, pulses, and oilseeds. Dry sowing of hardy crops such as cowpea and sesame is encouraged where feasible. The availability of community-managed seed reserves ensures that contingency crops can be deployed without market dependence.

4.2 Mid-Season Dry Spells

To buffer crops against intermittent moisture stress, the system relies on *in-situ* moisture conservation through mulching, leaf litter incorporation under tree canopies, and reduced soil disturbance. Greywater reuse from household sources and limited protective irrigation from farm ponds are prioritised for vegetables and young tree saplings, thereby safeguarding both food and future income streams.

4.3 High-Intensity Rainfall and Soil Erosion

Extreme rainfall events pose a major threat on sloping terrain. Reinforced contour bunds, terracing, vegetative barriers, and legume cover on risers are used to dissipate runoff energy and prevent soil loss. This ensures that rainfall extremes contribute to soil moisture recharge rather than land degradation.

4.4 Pest and Disease Outbreaks

Rather than relying on external chemical inputs, the system promotes ecological pest management through mixed cropping, crop rotations, botanical extracts (e.g., neem, garlic), and continuous field monitoring. Crop diversity acts as a biological buffer, reducing the likelihood of large-scale pest outbreaks.

TABLE 5 Climate Risk and Contingency Plan

Climate Risk	Contingency Plan
Delayed Monsoon	• Shift to short-duration millets, tuber crops • Use stored seeds of cowpea, sesame • Dry sowing practices
Mid-season Dry Spells	• Mulching of all plots • Supplemental irrigation for vegetables • Leaf litter addition under trees
Heavy Rainfall & Erosion	• Reinforce bunds and terraces • Increase vegetative barriers • Sow legumes on risers
Pest/Disease Outbreaks	• Use botanical extracts (neem, garlic, organic based pesticides and fungicides) • Mixed cropping to dilute pest pressure • Regular field monitoring

5. Indigenous Crop Diversity as a Strategy for Crop Diversification and Resilience

Crop diversification in the Family Farm model is not incidental; it is a deliberate resilience strategy grounded in Indigenous and Local Knowledge (ILK). Traditional crops cultivated by tribal communities have evolved under local climatic and edaphic conditions, making them inherently tolerant to moisture stress, poor soils, and low external inputs (Table 6).

Functional Role of Indigenous Crops

- Millets such as finger millet, little millet, and foxtail millet form the backbone of the rainfed system due to their short duration, deep rooting, and high nutrient density.
- Indigenous pulses (cowpea, black gram, green gram, pigeon pea) improve dietary protein intake while biologically fixing nitrogen and enhancing soil fertility.
- Traditional oilseeds (niger, sesame, mustard) provide household energy needs and market income with minimal water requirement.
- Local vegetable varieties are better adapted to erratic rainfall and pest pressure, ensuring reliable yields under organic management.
- Root and tuber crops act as food security buffers during extreme climate events, surviving conditions where other crops may fail.
- Traditional fruit and medicinal species diversify income, enhance nutrition, and strengthen ecosystem services.

This multi-layered diversity reduces systemic risk by ensuring that failure of one crop does not translate into total livelihood failure.

TABLE 6 Indigenous Crop Diversity List

Crop Type	Crop (Local Names)
Millets	Finger millet (Mandia), Little millet (Suan), Foxtail millet (Kangu)
Pulses	Cowpea (Jhudunga), Black gram (Biri), Arhar (Kandula), Greengram (Mung)
Oilseeds	Niger, Sesame (Til), Mustard, Castor
Vegetables	Brinjal local ×3 types, Okra local, Pumpkin local, Cucurbits, Chilli, Cowpea, Beans, Tomato, Radish, Cauliflower, Cabbage, Bitter gourd, Moringa, Leafy vegetables
Tuber crops	Colocasia, Sweet potato, Yam, Elephant foot yam
Fruits	Jackfruit, Mango, Custard apple, Kaju, Banana, Papaya, Guava, Litchi, Amla, Jamun, Ber, Bel
Medicinal Spices	Turmeric, Ginger, Tulsi, Aloe vera
Others	Broom grass, Bixa

6. Climate-Resilience Mechanisms Embedded in the Family Farm System

Climate resilience in the Family Farm model emerges from the interaction of multiple reinforcing mechanisms, rather than from any single intervention. These mechanisms operate at plot, farm, and landscape scales.

6.1 Micro-climate Regulation

Agroforestry canopies moderate temperature extremes, reduce evapotranspiration, and create favourable micro-climates for understorey crops. This is particularly critical during heat stress periods and extended dry spells.

6.2 Soil and Water Processes

Terraces, bunds, vegetative cover, and organic matter additions collectively reduce runoff velocity, increase infiltration, and enhance soil moisture storage. Over time, organic farming practices improve soil structure and soil organic carbon, strengthening drought resilience.

6.3 Biological and Functional Diversity

Millet–pulse–oilseed mixtures, combined with tree components, distribute risk across species, rooting depths, and growth periods. This functional diversity enhances system stability under climate variability.

6.4 Carbon Sequestration and Ecosystem Services

Perennial trees and increased biomass contribute to long-term carbon sequestration while supporting pollinators, beneficial insects, and soil biota. These ecosystem services improve productivity while aligning the model with climate mitigation goals.

6.5 Institutional and Knowledge Resilience

Community seed banks, farmer-to-farmer learning, and women-led nurseries enhance social resilience and ensure continuity of adaptive practices across seasons and generations.

6.6 Farmers Participation

Farmers participation and contribution in establishing the Family Farm and maintaining it like digging the pit, supporting the SWC work and propagating the concept and practice of Family Farms to other Farmers who want to set up such Family Farms.

7. Topo-sequence-Based Planning: Matching Crops and Trees with Landscape Hydrology

Toposequence-based planning is a core scientific principle underpinning the Family Farm model. Recognising that water availability varies systematically along the slope, land use is designed to align crop water requirements with hydrological position (Table 7).

7.1 Upper Slopes (Low Moisture, High Erosion Risk)

Upper slopes are allocated to drought-tolerant millets, pulses, and oilseeds, along with deep-rooted and hardy tree species. Structural measures such as graded bunds, trenches, and mulching reduce runoff and protect fragile soils.

7.2 Mid Slopes (Moderate Moisture Availability)

Mid slopes support fruit orchards (mango, cashew, custard apple, guava) combined with seasonal vegetables and short-duration pulses. Intercropping with legumes enhances soil fertility, while biomass recycling maintains soil health.

7.3 Lower Slopes (High Moisture Accumulation)

Lower slope areas, where runoff converges, are reserved for water-loving crops such as banana, papaya, turmeric, and gourds. Farm ponds located at the lowest points provide critical irrigation and additional livelihood options such as fish culture.

7.4 Policy and planning implication

Toposequence-based crop planning offers a scalable, low-cost approach for aligning watershed hydrology with farm-level livelihood outcomes. The idea of Family Farm can be

incorporated in the Government's Model Village Development Plan based on Gandhi's visualisation of Gram Swaraj.

TABLE 7 Toposequence-Based Planning (Upper–Mid–Lower Slopes)

Slope position	Interventions
Upper Slope (Low Moisture Zone)	• Drought-tolerant millets: Finger millet, little millet, foxtail millet • Pulses: Arhar, cowpea, black gram • Oilseeds: Niger, sesame • Deep-rooted trees: Jackfruit, tamarind, moringa • Graded bunds + mulch retention/ Terracing/ Trenching
Mid Slope (Moderate Moisture Zone)	• Horticulture: Mango, cashew, custard apple, guava, amla, ber • Seasonal vegetables: Brinjal, okra, cowpea, pumpkin, cucurbits, root crops • Short-duration pulses • Intercropping with legumes for soil fertility • Farmyard manure and biomass recycling • Mulching, Micro-catchment
Lower Slope (High Moisture Zone)	• Water-loving crops: Banana, papaya, turmeric • Creepers and gourds • Seasonal vegetables with supplemental irrigation • Agroforestry + vegetable alley cropping • Farm pond for critical irrigation and fishery • Contour cultivation, conservation tillage

Conclusions

The 1-acre climate-smart agroforestry-based Family Farm model presented in this paper demonstrates that rainfed hill agriculture can be transformed from a high-risk subsistence activity into a resilient, diversified livelihood system when cropping decisions are embedded within a scientifically designed calendar framework and aligned with landscape hydrology (Fig. 2). By integrating agroforestry, indigenous crop diversity, soil and water conservation, and climate contingency planning, the model delivers multiple outcomes simultaneously—enhanced food and nutrition security, stable farm income, improved soil health, reduced erosion, and strengthened climate resilience.

The Climate-Smart Crop Calendar is not merely a scheduling tool; it functions as a decision-support system that links rainfall behaviour, landscape position, labour availability, nutrition needs, and market access. The experience from the Eastern Ghats of Odisha illustrates that even a small landholding, when managed as a

diversified and ecologically informed system, can contribute meaningfully to land restoration, livelihood security, and climate adaptation goals.

The experience from the Eastern Ghats demonstrates that climate-smart crop calendars, when embedded within diversified family farming systems, can serve as powerful instruments for landscape climate adaptation and land restoration. For scientists, the model offers a field-validated framework linking hydrology, agroecology, and livelihoods. For policy makers, it provides a scalable, low-cost pathway to convert landscape investments into durable social, ecological, and economic gains.

The framework presented here demonstrates how the landscape development, regenerative agriculture, and climate adaptation can be operationalized at the farm scale—providing actionable insights for programs such as PMKSY–IWMP, climate-resilient agriculture missions, and land restoration initiatives.

The Family Farm Model of the Eastern Ghats

demonstrates how a smallholder-based, locally adapted farming system can become a powerful instrument for achieving multiple global commitments simultaneously. By restoring degraded landscapes, conserving biodiversity, strengthening household resilience, improving nutrition and incomes, and enhancing carbon sequestration, the model contributes directly to SDGs 1, 2, 3, 5, 6, 8, 12, 13, 15, and 17 (SDG 1: No Poverty, SDG 2: Zero Hunger, SDG 3: Good Health and Well-being, SDG 5: Gender Equality, SDG 6: Clean Water and Sanitation, SDG 8: Decent Work and Economic Growth, SDG 12:

Responsible Consumption and Production, SDG 13: Climate Action, SDG 15: Life on Land, SDG 17: Partnerships for the Goals). It also advances the objectives of Land Degradation Neutrality under UNCCD, aligns with the IPBES conceptual framework, and provides an effective community-based response to climate adaptation and mitigation challenges in vulnerable tribal landscapes of the Eastern Ghats. In this way, the Family Farm Model represents a practical example of how local innovations rooted in indigenous knowledge can help translate global sustainability goals into measurable action on the ground.

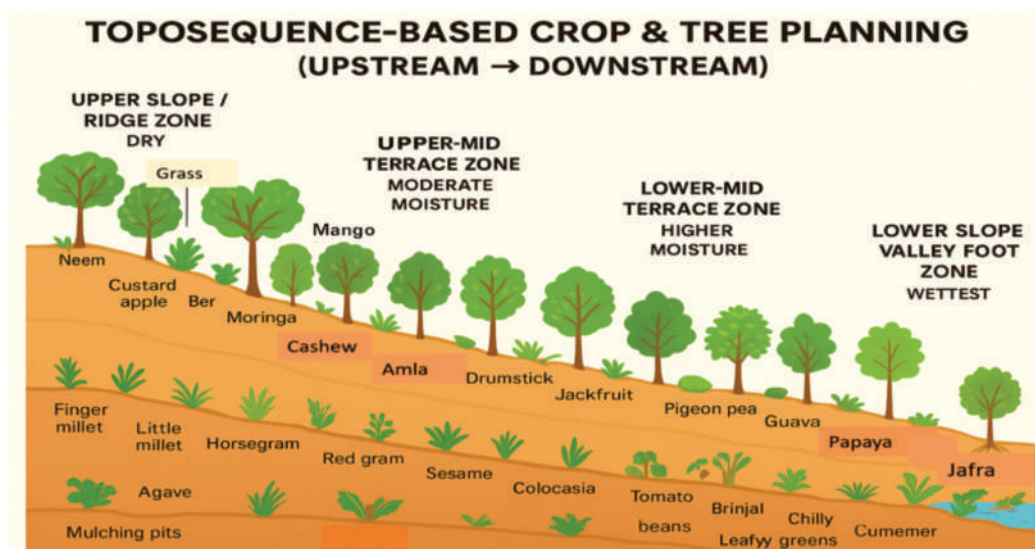


FIGURE 2 Topo sequence-based crop and tree planning in a family farm. Average 150-170 Plants in a 1-Acre Family Farm with spaces are earmarked for annual crops, horticulture, forest species, vegetables and flowers.

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Watershed Development Initiatives in the *Shivaliks* of North India: A Perspective

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Abstract

The degradation of the natural resource base in the *Shivaliks* of north India remained a serious problem much before independence and continued unabated thereafter. The routine soil conservation works like contour bunding, terracing, check damming and particularly *choe* training works were prioritized initially. The institutional frame work to tackle the problem was established during sixties. The watershed based technology to reverse the trend of environmental degradation emerged from the famous Sukhomajri watershed development project which clearly demonstrated that the rainwater harvested from the hilly forest watersheds and used for gravity irrigation to unproductive rain-fed lands can generate economic, ecological and social benefits to the communities which get motivated to protect the forests to which they were denuding before. The concept was replicated under the Operational Research Projects at Nada and Bunga in Haryana, Relmajra in Punjab and Behdala in Himachal Pradesh. The overwhelming success of these projects lead to the first World Bank funded Kandi Area Watershed Development Project for Rain-fed Areas (KAWDPRA) in Punjab but badly suffered from coordination problems. The World Bank then supported an ambitious Integrated Watershed Development Project Hills-1 in the *Shivaliks* of four states of north India basically to reverse the trend of degradation with cost effective package of practices and institutional development. With satisfactory results, the project was extended with revised guidelines as IWDP-II with addition of Uttar Pradesh. Subsequently, the Govt. of India Ministry of Rural Development supported Integrated Watershed Management Program (IWMP) first in the *Shivalik* district of Punjab but due to groundwater depletion problem, it was

extended to 11 plain area districts. Ultimately the program was converged with the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) with major focus on water resources development Har Khet Ko Pani, More Crop per Drop. The introductory part of the paper presents the *Shivalik* ecosystem features. Taking a historical perspective, the detail of programs and watershed development projects taken up to reverse the trend of degradation has been presented. Key lessons learnt from these watershed interventions, institutional innovations, role of community mobilization have been described. Major un-addressed gaps, implementation constraints, institutional loopholes and a comparative and critical analysis of previous studies/ publications including constraints in replication are discussed. The policy implications for current and future watershed development programs are deliberated. Since the valuable information on various facets of *Shivalik* ecosystem was scattered in diverse sources, bundle of files and not put on public domain, an attempt has been made to compile for the benefit of watershed managers, policy planners, funding agencies and other stakeholders.

1. Introduction

The *Shivaliks* of north India are located below the rocky Himalayas and above the alluvial plains in a long narrow belt spread in the parts of four northern states of India namely Jammu and Kashmir, Himachal Pradesh, Punjab and Uttarakhand covering an area of 4.2 million hectare (GOI, 1998). The *Shivaliks* are considered as one of the eight most degraded ecosystems of the country. The erratic distribution of rainfall, lack of irrigation facilities, limited availability of suitable land for cultivation, heavy soil erosion and fertility depletion, small and fragmented holdings, low yields, frequent crop failures, scarcity of food, fodder, fuel wood and large scale dependence and heavy biotic pressure on natural forests are the

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major limitations of handicapped ecosystem. High intensity monsoon rains, undulating and uneven topography, heterogeneity of rock formations, presence of calcareous soils with high pH in pockets and high silt content and inadequate vegetation cover are some of the conditions which contributed to instability of slopes, landslides, landslips and rampant soil erosion. These low hills suffered from denudation caused by excessive human and livestock pressure.

The process of land degradation in the *Shivaliks* started about 150 years ago and has continued unabated and defied solution (Mishra and Sarin, 1987). An FAO study (FAO, 1991) has shown that success stories are few but failures are common in conservation programs attempted to stem the problem of soil erosion. The lack of success in the past was attributed to the failure of programs which attempted to treat the symptoms of the disease rather than the cause. Secondly, most of the programs were imposed from above disregarding the pressing requirements of the land users. Although the prime responsibility for arresting land degradation rests with the Government, land and water resources can be best conserved and rehabilitated by those who make their living from these resources (Bhumbla, 1976; Bajwa, 1983; Hudson, 1991).

The area once dotted with perennial springs and gentle streams got converted into a tract of ferocious torrents overflowing with muddy water and choked drainage systems with huge debris washed down from barren hills. The flood water erode banks, deposit senile sand on fertile land, inundate large areas, disrupt communication network and cause innumerable other problems down below in the alluvial plains. The unrestricted tree felling, over grazing and clearing of land for agriculture were responsible for large scale denudation of the forest. An area dotted with perennial springs and gentle streams got converted into ever widening and deepening ferocious torrent beds (called chos) which brought flash floods from the denuded hills (Holland, 1928; Grewal *et al.*, 1990; Grewal *et al.*, 2002).

Against the huge magnitude, complexity and diversity of the problem, individual farmers could not pick up the courage to fight the battle. The group action was missing and the rape of the hills

has continued. The area is inhabited mostly by 'Gujjar' community, who are traditional graziers. They maintained large herds of cattle and goats to sustain the livelihoods. The foraging Gujjars' attacked the tiring hills with renewed vigor as they yield less and less (Bajwa, 1983). It is reported that the *Shivaliks* had thick luxurious natural forest full with wildlife and perennial streams before becoming the target of human greed. The settlements of loyal followers were attempted by the Britishers as reward for their help and support. The Britishers exploited the forest wealth for meeting the timber and fuel-wood needs of military cantonments (Holland, 1928). As more and more areas were cleared by new settlers, agriculture flourished first along the rivers and streams and then extended to interiors. The desperate search for more and more agricultural lands forced the resource poor farmers to cultivate marginal sloping lands and thus denuded the sensitive areas of their protective vegetation cover. A vicious cycle of poverty and denudation was in operation for the last more than 150 years and continued unabated.

The *Shivaliks* ecosystem is characterized by water scarcity, low and uncertain crop production, small holdings and resource poor small farm economies (Grewal, 2018). The limited access to irrigation reduces the prospects of assured economic returns to the larger section of the farming community (Yadav *et al.*, 2015). Water scarcity, therefore, limits economic growth in whole of this foot-hill region. The foot-hill agriculture could not benefit much from the green and white revolutions mainly due to the lack of assured irrigation facilities. The Government water supply schemes meet only fraction of the drinking water requirements. Traditional ponds, wells and springs, the traditional common property resources are not being maintained due to lack of community involvement.

Most farmers depends upon livestock to supplement low farm income but then face acute fodder shortage and hence depend upon illicit grazing in the nearby forests causing problems of denudation (Bhumbla, 1976). In the high risk farming, the use of recommended inputs is made very hesitatingly and sparingly. Male members migrate to cities for employment or move with livestock to distant pastures. In the absence of

decision-making elite of a family, the acceptance of new innovations and research recommendations remains quite low. A store house of natural forests and rich in fauna and flora, rehabilitation of *Shivaliks* remained an area of priority much before independence and thereafter (Photos).

Several state, central and foreign funded projects operated in the *Shivaliks* of north India basically to reverse the trend of degradation by adopting participatory approaches of natural resources management for poverty alleviations and sustainable economic and ecological development. There was no comprehensive document enlisting the status of degradation, implementation of soil and water conservation/

watershed development schemes and projects to address these problems of degradation and their consequences, analysis of success and failures. Unfortunately, most of the information could not be placed in the public domain. The lessons learned from the implementation of such projects would be useful for policy planners and other stakeholders. It is important that such information is compiled in a historical perspective for younger officers and field functionaries, students and fellow research workers. An effort has been made to collect information from the diverse sources and placed in a historical perspective after a detailed review so that valuable information on outcomes of millions of dollars spent are not lost in the bundles of files and reports.



PHOTOS: *Shivaliks* of North India

2. Materials and Methods

2.1 Study Area

The study relates to the *Shivaliks* hill region of north India located below the rocky Himalayas and above the Indo-Gangetic alluvial plains in a long narrow belt spread in the parts of four northern states of India namely Jammu and Kashmir, Himachal Pradesh, Punjab and Uttarakhand covering an area of 4.2 million hectare (GOI, 1998) (Fig. 1).

2.2 Climate of the Study Area

Most of the *Shivalik* region enjoys semi-arid type of climate characterized by extreme summer temperature above 40°C in May-June and near freezing winter temperature of 4-5°C in December and January. October to November is autumn and February to March is pleasant season of spring. The normal wind velocity is 10-12 km/hr. The sunshine hours are 11 to 12 hours in summer and 8-9 hours in winter. The relative humidity is nearly

90% in the rainy season and varies from 70 to 85 in other months of the year. Frost occurs for 8 to 10 days during December-January. Hailstorms are also received occasionally.

The mean annual rainfall of region is 1100mm with low of 600 to high of 2200mm. The monsoon season starts normally by the end of June and continues up to end of September. Early/late start and early/late withdrawal of monsoon rains are very common. Almost 80% of the mean annual rainfall is received during the monsoon season and about 15% in December-January which is referred as bi-modal pattern of rainfall distribution (Fig. 2).

October and November are dry months (no rainfall) of the year. The 10 year data indicate maximum rainfall intensity is around 120mm hr⁻¹ and one day maximum rainfall may exceed 200mm which causes flash floods. Three day continuous rainfall is around 450mm. There are frequent gaps between rainfall events varying from 15 to 25 days intermittent dry spells which cause drought conditions even in monsoon season.

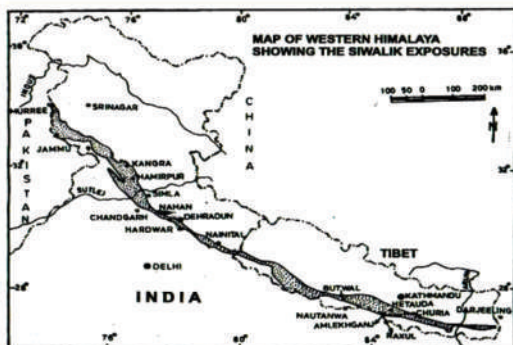


FIGURE1 Geographical setting of *Shivaliks* in foot hills of India

2.3 Landscape Characteristics

The general landscape in the upper part is steeply sloping hills covered with mixed forest and high drainage density of 8-9km/km². The area is having vertical cliffs and landslide scars. The hill soils are generally sandy loam to loam with admixture of boulders and gravels. The middle part is moderately steep and generally divided into level terraces' industry, and ravine type cut off area by

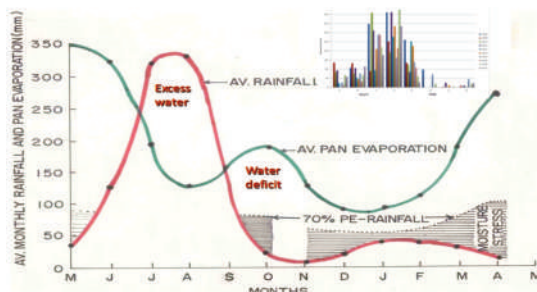


FIGURE2 Bimodal pattern of rainfall distribution in *Shivaliks* of North West India

choes. There are lot of boulders, gravels and stones in the profile. Mostly soils are loamy sand with admixture of gravels and their pH ranged from 7.2 to 8.7 with low EC. There is no problem of salinity and alkalinity or water logging but soil erosion is a serious problem in the hilly forest area and along the *choes/nalas*. Stream bank erosion by *Sirsa* is a serious problem. These characteristics have been presented in detail by Grewal *et al.*, 1989 and Grewal, 1995.

2.4 Review of Literature and Unpublished Reports and Documents

The perspective on the watershed development initiatives in the *Shivaliks* of north India basically drive its strength from the review of published literature, personal communications, unpublished reports and documents and large number of publications of the author starting from Sukhomajri project. The author was part of the technical support group of the World Bank funded projects in the *Shivaliks*. Had the opportunity of handing capacity building trainings and workshops at Regional Watershed Development Center and PAU Regional Research Station for Kandi area Ballawal for ten years. This provided access to all reports and documents of all five participating states covered under these projects and strong interaction with staff and officers of five participating states. Voluminous information was generated during the compilation of draft project reports; monitoring, evaluation, impact assessment and learning assignments related to watershed development projects (Grewal, 1995; Sagwan *et al.*, 1995; Jain *et al.*, 1998; Grewal *et al.*, 2002; Grewal, 2002; Grewal *et al.*, 2003a,b; Dogra *et al.*, 2005; Grewal and Bhushan, 2005; Dhar *et al.*, 2006; Grewal, 2006; Bharat and Grewal, 2007; Grewal, 2016; Grewal, 2018.). A genesis of this information base was attempted to highlight the key lessons learnt from these watershed interventions, institutional innovations, role of community mobilization, un-addressed gaps, implementation constraints, institutional loopholes and a comparative and critical analysis of previous studies/ publications including constraints in replication are discussed. The policy implications for current and future watershed development programs are deliberated.

3. Results and Discussion

3.1 A Historical Perspective on Watershed Development in the *Shivaliks* of North India

3.1.1 Pre-Independence Work in the *Shivaliks*

L.B. Holland, the then Deputy Conservator of Forest Punjab compiled a report in 1928 titled “Denudation and Erosion in the Low Hills of the

Punjab: published in Civil and Military Gazette Lahore. He traversed the foot-hill areas of Punjab and provided detailed account of degradation and reasons thereof. R. MacLagan Gorrie a Scottish Forest Officer posted in Hoshiarpur authored a classical book titled “Soil and Water Conservation in the Punjab” published in 1946 from Lahore. Gorrie attempted to lay down the details of practical field work in afforestation of catchment areas, reclamation of torrent beds and waste lands and the control of runoff and erosion processes. He highlighted the problem of soil erosion and enactment of Punjab Land Preservation (Choes) Act 1900 as modified in 1944. The problem of soil erosion and land degradation remained in focus since long. Glover, 1944 described the problem of soil erosion in the *Shivalik* foot hills and its consequences narrated in an Oxford University pamphlet.

The area affected by 'choes'(rain torrents) in Hoshiarpur district of Punjab increased from 194 km² in 1852 to 286 km² in 1886 and to 2000 km² in 1939. The devastation was later reported to have affected an area of 2.5 million hectare (Anonymous, 1976). As the problem assumed serious proportions, the Punjab Land Preservation (choes) Act was passed in 1902 to prevent further deterioration. The resistance by the local people to the act led to the grant of limited grazing and tree cutting rights in forest areas close to villages (Hudson, 1991). The intention was to contain their influence in a limited area of the forest called the protected forest. The areas away from the villages were completely closed and called Reserve Forests. The implementation of the law remained weak and the situation further deteriorated after independence.

3.1.2 Early Post Independence Initiatives

A wing of soil conservation under a joint director was created in the department of agriculture Punjab in 1961. Sh. MSV Rama Rao an experienced soil conservation officer from Maharashtra was engaged as soil conservation adviser. In the Govt. of India, soil conservation was a wing of the agriculture department and a first contour bunding project at *Fauji* Colony Banur was funded by the GOI in late fifties. In this project, a patch of salt affected soil was allotted to retired army officers for reclamation. After a

detailed topographic survey, a contour bunding plan was prepared and implemented. First gauging station was established to measure runoff and soil loss from the treated area. Unfortunately, no report was generated.

Soil and Water Conservation Research and Training station was established at Dehradun under the Ministry of Agriculture and Cooperation. The Soil Conservation Research & Training Station at Chandigarh was established in 1955 with 700 acres research farm near Mansa Devi Temple of Manimajra town. A separate soil and water conservation department was created in the year 1962.

The trainings of all categories of staff in the department of soil & water conservation were compulsory. While DSCOs and ASCOs were sent for 5.5 months training at Dehradun Institute, soil conservation inspectors and JEs were sent for assistant trainings at Kota center of Dehradun institute and sub inspectors and surveyors were sent for training at Training Institute Hoshiarpur.

3.1.3 Main activities of the department of soil and water conservation in the Punjab

- Contour bunding on erosion prone sloping lands was the most common activities during sixties in foot hills areas. A contour bund with 6ft base, 2ft top and 3ft height was a common norm.
- Land leveling and bench terracing was introduced subsequently where soil depth was not a problem. A cut/fill method of calculation of earth work in land leveling was introduced to work out the cost of work.
- Low height masonry check dams were approved for field safe disposal of excess runoff in terrace lands.
- Similarly, two to three meter height check dams were constructed in drainage lines/gullies to break the velocity of runoff water and induce siltation of gully bed. In case of Rajgarh Project near Kurali, in the gully bed 11 check dams were constructed in series and after three years, farmers started raising sugarcane in silt deposited gully bed.
- After the success of Sukhomajri Project, the construction of earthen dams for rainwater harvesting was started in Ropar, Hoshiarpur and

Pathankot areas. A provision of underground pipe lines was made to carry the harvested water for limited irrigation in designated command areas. A conflict with the state forest department was reported often where the dam sites were located in the forest area. They wanted to construct such dams themselves and wanted that the funds be transferred to the forest department. The conflict was resolved because Forest and Soil and Water Conservation were with the same minister.

- Gradually, the base flow harvesting projects got introduced after the success of Makkowal project. One of the best base flow harvesting projects was at village Ballowal in Balachaur block of Hoshiarpur district which provided gravity irrigation through two underground pipelines to about 60 acres of land of Ballowal and Takarla villages and farmers raised poplar plants along the open channels and an oasis of greenery was created in the barren landscape. The soil and water conservation department replicated the mode in number of perennial khads in the Kandi area.

3.1.4 Construction of medium height earthen dams by the Irrigation Department

In late eighties, the Irrigation Department Punjab earned a World Bank project for the construction of medium height earthen dams for rainwater harvesting and irrigation in command areas. A dozen such dams were constructed varying in height from 25 to 30 m length varying from 150 to 230m across major khads having base flow. Since catchment area treatment was not paid due attention, faster siltation gradually emerged as a serious problem.

3.1.5 Kandi Watershed and Area Development Project (KWADP)

The first conscientious efforts to reverse ecological degradation in the foothills of Punjab was made through the Kandi Watershed and Area Development Project (KWADP) during 1980-88 with the financial assistance of 30 million US\$ from the World Bank. In this pilot project, multi-disciplinary approach of resource conservation was followed in 11 major watersheds covering one lakh hectare of farm and forest lands. One of the objectives was to harvest rainwater from the forest

catchments by the construction of medium height dams across major torrents to irrigate an area of 10,800 ha. The Irrigation and Drainage Department of the Punjab state constructed these dams on the outermost fringes of the low hills where rain-fed agricultural lands were located down below in close proximity. Such dams are 21.4 to 38.8m high and covered cultivable command area varying from 450 to 3750 ha. The experience with dams indicated that their reservoirs are silting at a much faster rate ($>60 \text{ t/ha-1 yr.}^{-1}$) than originally planned ($<15 \text{ t ha}^{-1} \text{ yr.}^{-1}$). The funds were provided for dam construction but the catchment area was not treated with soil conservation measures. Concerted efforts were not made to close the catchment areas against grazing and fuel wood extraction. The rapid siltation reduced the functional life of the reservoirs.

The important lesson is that dam was constructed by the Irrigation and Drainage Department but forest catchment area was under the control of Forest Department. A unified implementing agency is necessary for effective results and catchment area treatment is necessary to prolong the functional life of the reservoirs.

3.1.6 Small earthen dams



3.1.6.1 Sukhomajri Operational Research Project

The first successful attempt was made in the Sukhomajri Operational Research Project (ORP) near Kalka in the Haryana state (ICAR, Ford Foundation funded) where three earthen dams were constructed between 1976-81 to store rainwater from hilly forest catchments and conveyed through gravity fed underground pipe lines to 60 acres of farm land (Grewal *et al.*, 1990). This facility of limited irrigation revolutionized

the rain-fed agriculture and mean crop yield increased from 2.0 to $5.7 \text{ t ha}^{-1} \text{ yr.}^{-1}$. The average grass yield in forest catchment improved from 0.1 to $0.95 \text{ t ha}^{-1} \text{ yr.}^{-1}$ and tree density from 64 to 464 trees/ha with simultaneous reduction in soil loss from 191 to $27 \text{ t ha}^{-1} \text{ yr.}^{-1}$ (Mittal and Sud, 1982). The availability of water from the adjoining forests for thirsty farm lands encouraged farmers to become interested in catchment protection. A village co-operative emerged which took over the responsibility of protecting the degraded forest land (social fencing). Grazing was replaced by stall-feeding. Forest contractors were replaced by village co-operatives contracting for the extraction of forage and commercial grass (Mittal *et al.*, 1988). Arya, 1994 evaluated the impact of Sukhomajri watershed development project and noted that there was increase in number of buffaloes and cows and decrease in number of goats. The availability of green fodder from farmlands increased by 144% and dry fodder by 56% . The hills regained the lost greenery and people regained faith in conservation and joint management of resources (Grewal *et al.*, 1995).

3.1.6.2 Dams construction in Nada Sahib Watershed

The successful example of Sukhomajri was replicated at Nada Sahib with similar results. In a watershed of 649 ha at Nada (Haryana), six earthen dams were constructed between 1980-89 having total catchment area of 138.9 ha, storage capacity of 49.29 ham, command area of 64.7 ha at a cost of Rs. 27.42 lakhs. Unlike bigger irrigation projects, the gestation period in such small projects was less than a year. Moreover, local people particularly laborers got employment near their homes (Grewal *et al.*, 1995).

3.1.6.3 Earthen dam construction in Bunga watershed

The overwhelming success at Sukhomajri and Nada resulted in the selection of 47 National Watersheds under different institutes of ICAR/SAU's to give application test to this technology under varying agro-ecological conditions. Out of these, Bhunga watershed was selected in Ambala Shiwaliks where an earthen dam of 16m height was constructed to harvest rainwater from 154.3 ha forest catchment having

water storage capacity of 59.6 ha m, spread area of 11.7ha, command area of 243 ha and total cost was ₹ 3.55 million in 1985.

Arya and Samra, (1996) evaluated the impact of Watershed Management Program at Bunga village on animal husbandry sector and reported that milk production increased from 231 to 723 thousand litres from 1983-84 to 1991-92 and 233 percent decline in number of goats. The number of cows, buffaloes, and bullocks increased by 47,172 and 33 percent, due to increased availability of fodder and grass. Arya (2010) reported significant decline in livestock migration with substantial increase green and dry fodder availability. The increase in productivity of crops and milk and other results were identical to previous projects where the impacts of droughts were moderated through life saving irrigation and such projects provided economic and ecological security to resource poor communities (Grewal *et al.*, 1989).

3.1.6.4 Earthen dam in Relmajra watershed

A similar project was selected in village Relmajra village during 1991 near Ropar in the Punjab *Shivaliks* with the financial assistance from the Ministry of Environment and Forests, Government of India. In this project, rainwater harvesting, development of marginal lands under horticulture and forage component and drainage line treatment technology was successfully demonstrated. The village society generated social funds for maintenance and to creating welfare facilities for the community (Samra *et al.*, 1995).

The construction of small earthen dams to harvest rainwater and use of the stored water for limited irrigation to increase agricultural production has since been demonstrated by the operational research programs. As a result of economic viability and social acceptance of this approach, large-scale replication in the *Shivalik* foot hills was observed. The Forest Department of Haryana and Soil and Water Conservation Department Punjab took the lead.

Large numbers of small earthen dams with impermeable care-wall of heavy soil, height varying from 6 to 16m storage capacity from 1.2 to 60 ham, forest catchments varying from 20 to 157 ha and a provision of masonry spillway made for

the disposal of excess water have been constructed in the foothill areas of Haryana (180), Punjab (120) and Himachal Pradesh (60) by early nineties. The salient details of these successful watershed development projects formed the subject matter of several studies (Grewal *et al.*, 1989, Grewal *et al.*, 1990 and Grewal, 1995).

Some guidelines on the judicious use of harvested water were suggested:

- The first preference should be given to domestic and livestock use if quality of water is good. Water quality should in fact be tested before use.
- This water should be used for high value crops like vegetables and fruits.
- The tendency to use water for raising paddy should be discouraged.
- Fish should be reared if conditions permit to augment the income of the society.
- The reservoirs should be brought to dead storage level before the next monsoon season.
- A good amount of research work on the production gains by the supplemental irrigation has been carried out. The pre-sowing irrigation in case of wheat gives the maximum advantage followed by irrigation at CRI-stage.
- The cost of dam construction is recovered in a period of 4 to 5 years through increased crop production.

3.1.7 Govt of India supported special program

Several watershed development projects funded by the Ministry of Agriculture and Cooperation, Govt. of India were supported in the *Shivalik* region. These were River Valley Project, Flood Prone Area Program. Drought Prone Area Project operated by Agriculture/ Soil and Water Conservation Departments. Since funds were limited and areas were scattered visible impacts could not be achieved.

3.1.8 National Watershed Development Project for Rain-fed Areas (NWDPA)

The Ministry of Agriculture and Cooperation, Government of India, intended to generate successful watershed development models in all the community development blocks of the country where less than 30% of arable area was under assured means of irrigation. The project was

planned to act as a pace setter for comprehensive development of dry land areas adopting farming systems approach on watershed management principles in order to conserve precious rainwater and top soil. The soil and water conservation programs using vegetative technologies were promoted including animal husbandry, agro-forestry, horticulture, fisheries, sericulture and primary agro-processing.

In the Punjab *Shivaliks*, 13 watersheds were selected under NWDPR (1990-91) covering 19,559 ha of area with financial outlay of 63.8 million. The Department of Soil and Water Conservation was made the nodal agency for coordination of activities with the line departments. The funds for associated activities in the selected watersheds were placed at the disposal of the line departments. The program suffered from coordination problems and activities by line departments were so scattered that the real impact was hardly visible. The important lesson was that a unified agency and single window of providing goods and services is required to produce visible impacts. Hudson, 1991 evaluated the performance of the soil conservation project and brought out the reasons of their sub optimal performance.

3.1.9 Integrated Watershed Development Project (IWDP) Hills-I

This World Bank funded project operated in four northern states of India (Haryana, Himachal Pradesh, Jammu and Kashmir and Punjab). It was designed to address the most serious problem of degradation in fragile ecosystem of the *Shivaliks* with cost effective vegetative technology for soil and water conservation on both arable and non-arable lands. Introduction of rain-fed horticulture on marginal land, livestock improvement, forage production, drainage line treatment were other components of this project. It was aimed to adopt participatory approach involving beneficiaries (small farmers, landless people and livestock owners) to ensure sustained management of common property resources.

Adoption of a single window system with built-in mechanism of monitoring, evaluation, research and training involving state agricultural universities was an important feature of this project. The runoff and soil loss measurements and

impact assessment studies were conducted for quantification of conservation and production benefits to justify investments. This was a 7-year (1990-1997) project, which was extended for two more years up to March 31, 1999. A Regional Training Center for Integrated Watershed Development was established at PAU Kandi Research Station at Ballawal under this Project.

Water resources development to meet the pressing demands of drinking water, livestock use and supplemental irrigation was given a very high priority after the Mid Term Review in 1995. Perennial flow from small streams was harvested by specially designed, simple and cost effective structures (Makowal). Rainwater was also harvested by constructing small earthen dams and stored water used for limited supplemental irrigation which produced green fodder (clover) for stall fed buffaloes and resulted in increased milk and manure production. A total area of 180,100 ha was treated in 75 priority watersheds of four participating states up to March 1998 benefiting more than 82,500 families at a cost of 2454.4 million rupees (GOI, 1998).

Based on the experiences of this project, Jain *et al.*, 1998 emphasized guidelines for the future watershed management projects:

- Sustainability of project activities require emphasis on community-based organizations to own the responsibility of maintenance of assets created, ensure cost sharing and full commitment for post project operation.
- Cost sharing by beneficiaries should be much less in the community-based activities on common lands than the private owned lands and within the private lands it should be much higher for cultivable lands than non-cultural lands (degraded wastelands).
- While treating Government/forest lands, communities' interest in terms of benefit sharing must be ensured.
- The project components should be broad based, include income generating activities for the women self help groups.
- Institutional development in the form of community-based organizations should be given top priority and should precede the project identification and implementation.
- Complementarity should be established between

the various agencies (Government, donors, NGOs) implementing the project in the same area/district/state to avoid unhealthy competition.

As a result of seven years of operation, satisfactory results were achieved as summarized by Singh, 1998.

3.1.10 Integrated Watershed Development Project Phase II

The community participation in project planning, implementation and subsequent maintenance remained a weak link in IWDP-I. This was then made the pre-requisite along with cost and benefit sharing arrangements in IWDP Phase II started from April 1999 in five states (UP included) with financial assistance of about ₹ 9000 million from the World Bank. Directors were appointed in all the five participating states. The components of soil and water conservation, forestry, horticulture and animal husbandry were integrated in a single window system and services of experts in these disciplines were placed on board. Silt observation posts were established at representative watersheds for impact assessment. The areas of operations were also enlarged. For example, in the Himachal Pradesh, the operational area was shifted from the *Shivaliks* to mid Himalayas. This project concluded in March 2005 with a comprehensive review carried out by the World Bank from an independent agency and was rated as satisfactory achievements against objectives.

3.1.11 Integrated Watershed Management Programme

Integrated Watershed Management Program (IWMP) of the Government of India was supported by the Ministry of Rural Development, Directorate of Land Resources after revised guidelines issued in 2011. Five districts of Kandi area were first prioritized but due to serious groundwater depletion and soil health problems, this program was extended to 11 district of Punjab in 2012-13. However in 2015, the program was redesigned as Pardhan Mantri Krishi Sinchai Yojna (Watershed-2). The focus was to provide access to irrigation by different technological options. *Har khet ko pani*, more crop per drop was made the slogan. The program was shifted to the Ministry of Jal Shakti.

In this perspective on watershed development initiatives in the *Shivaliks* of north India, the first introductory part of the paper covered the basic information about geological setting, major problems, socio-economic consequences, and climate and water scarcity in the *Shivalik* ecosystem. In the results and discussion section, a historical perspective starting from pre independence to the detail of programs, institutional strengthening and different watershed development projects taken up to reverse the trend of degradation have been described in detail. What emerged from the implementation experiences of these initiatives is now presented in this section of the paper.

3.2 Analysis of issues and concerns emerged from implementation of programs and projects taken up for ecological restoration of the degraded Shivalik ecosystem

3.2.1 Key lessons learnt from the past watershed interventions

- The rigid modules of treatment (like vetiver as contour barrier) should not be imposed. Native grasses are far superior to vetiver. Flexibility must be introduced to accommodate experience-dictated changes adopting bottom up and not top down approach.
- Five years is too short a period for effective implementation of watershed development projects where all preparatory, implementation and withdrawal phases has to be consolidated where new infrastructure has to be created and plantations to be raised and nursed.
- Amelioration of highly degraded forests is difficult to achieve at low cost without effective closure/social fencing and without optimum mix of biological and mechanical measures. Thinly spread resources seldom produce good results.
- Single window system of administration is more efficient in which all disciplines work under one watershed team leader. Subject matter specialists of each discipline should be placed on board to provide blue prints and technical support.
- The institutional and implementation capacity building of all stakeholders including exposure visits must lead rather than follow project

- implementation.
- Local experience, expertise and indigenous technical knowledge be effectively internalize for effective need based and demand driven packages of watershed treatment. The choice and preferences of farmers must be accommodated to ensure sustainability.
- A practice which promises returns after 3-5 years (long generation period) with no visible impact and does not take into account the immediate needs is not accepted by the beneficiaries. Interventions which provide direct, visible and immediate returns motivate communities for participation and cost sharing. Water resource development is one such most preferred intervention.
- Adopting an inclusive growth model, the involvement of landless, weaker sections, women need to be involved in equitable sharing of resources created. The cost sharing norms should also be designed accordingly.
- The non-transparency in accounts, favoritism, leadership and caste conflicts, political interference and social and economic disparities in communities, strongly influence project achievement, result in delays and sub optimal performance.
- The social dimensions of watershed development approach are becoming increasingly important but staff is not well attuned to democratized set of operations and needs a lot of training and orientation. The NGOs should be activated to share such responsibilities.
- Convergence with line departments and use of MNREGA funds remained a low key affair in spite of guidelines.
- The course of action both in research and development must attempt on a thorough and objective quantification of resource base and problems, undertake research to refine science and technology relevant to restoration and find ways and means to motivate people to understand the problems, their far reaching consequences and make them to stand on their own feet rather than look for support and subsidies. In such an endeavor, creating an enabling environment with a onetime investment would, however, be necessary.
- The soil and water conservation (SWC) research carried out by the central research institutions and the state agricultural universities (SAU's) have helped in characterization of resource base, better understanding of cause and effect relationships and development of useful technologies for resource conservation.
- The Chandigarh based Research Center of the Central Soil and Water Conservation Research and Training Institute Dehradun successfully implemented the Operational Research Project Sukhomajri and generated technological package for integrated watershed development with sharp focus to community partnership and resource sharing. The concept was replicated on large scale and was considered the foster mother of watershed development in the *Shivaliks* of north India.
- The watershed development projects were approved using the nomenclature of Sukhomajri Pattern. The effectiveness of this package was demonstrated in term of improvement of crop and milk production in Bunga and many other such projects.
- Simultaneously, the Punjab Agricultural University, Ludhiana, with the support from the World Bank under the National Agricultural Research Project (NARP) took a bold initiative to establish a full-fledged Regional Research Station for foothill areas of the state in 1983 to develop and disseminate technologies for rain-fed agriculture, horticulture, agro forestry, forage production, soil and water conservation and watershed management. The micro-watershed hydrology studies were initiated at Saleran (Hoshiarpur) and Patiala-ki-Rao (Ropar) watersheds to generate research information on rainfall-runoff relationships and sediment loss. Studies on runoff harvesting and efficient use of limited water were initiated in Karoran, Ballowal Saunkhri and Takarla watersheds. Experiments were also conducted to evaluate the effect of different vegetative barriers on runoff, soil loss and crop yields. This research station generated very useful information and package of practices which were disseminated through various means including the Krishi Vigyan Kendras and Farm Advisory Services operating in the *Shivalik* region. The region specific and research supported packages of practices for integrated natural resource management started supporting

3.2.2 Institutional innovations and their role in improving watershed governance and program effectiveness

the watershed development projects in this region.

- In the World Bank funded IWDP (Hills) project, A Regional Training Center for Watershed Development was established in 1992 at the Regional research Station Ballawal for capacity building of all categories of professional staff of all the four participating states. In a period of ten years, 112 training courses were organized on various facets of watershed development where 2200 staff members were trained. The impact assessment indicated that there were improvements in designs of earthen dams and soil conservation structures.
- Similarly, the watershed development Bunga project in Haryana was planned, and designed by the scientists of CS&WCR&TI, Research Center Chandigarh and implemented by the state agriculture department. So was the case of Relmajra project in Punjab *Shivaliks*. The hydrological norms used in structural designs were followed in similar project.
- Lot of research information was generated on the implementation experience, success and failures by large number of impact assessment studies by ICAR and SAUs. The trainings and experiences of operation research project demonstrated by impact assessment studies played a significant role in improving watershed governance and program effectiveness.

3.2.3 Role of community mobilization, participatory approaches and local institutions in watershed management

In case the local communities were not mobilized to actively participate in the planning and implementation of programs related to management of common property resources and as a result SWC works done at a great expense mainly by the Government initiatives were seldom maintained by the beneficiaries. This led to serious doubts about the viability and suitability of the technological packages. Eckholm, 1976 emphatically held that the application of technical answers to the ecological problems seldom turns out to be simple. He felt that social dimensions of SWC were largely ignored. Hudson, 1991 felt that low level of success in SWC is caused to some extent by attempts to use unsuitable technology for a particular set of conditions. The technology, which is based on the development of an existing

practice stand better chances of adoption than something, which is new to the area. It must be considered necessary to appreciate the positive points of the traditional production and land-use systems and strengthen them through science and technology inputs so as to enhance their value and efficiency (GBPIHED, 1993). This is better than advocating changes involving the replacement of traditional systems by new one's found suitable elsewhere. The explicit role of common interest groups, women self help groups, water user associations must be inbuilt at project planning.

3.2.4 Major un-addressed gaps, implementation constraints, institutional loopholes and regional disparities within existing watershed programs

About 30 years research and development work on watershed development have solved many questions but many remain unsolved or answers need more debate.

- Use of remote sensing interventions in the study of small watershed hydrology and micro-planning of watershed/water resource development could not reach to the operational stage.
- The sedimentation of reservoirs without adequate catchment area treatment has reduced the operational life of large number of reservoirs. Catchment treatment before the construction of dams is advised but seldom done. There is seldom convergence between agriculture/soil conservation departments with forest department when catchments are located in the territory of forest department.
- In view of denudation of catchment areas, how to get more water but much less sediment remains an issue. More work on filter vegetation is needed. Water yield tend to decrease when catchment is well protected. How to maintain water yield to reservoirs upon watershed rehabilitation by manipulating the vegetative cover is yet an unanswered question.
- How to control seepage from leaky reservoirs.
- Spread of limited water over large commands at low cost.
- Effective control of landslides in highly erodible catchment soils.
- Share benefit with landless, labourers and poorer

farmers.

- Enlisting active community participation and enforcing cost sharing norms.
- Activate research and training to support expansion of programmes and coordination between research institutions located in Kandi area of all five states.
- The rural communities in general and resource poor in particular must be involved effectively in the decision making process.
- Lastly, it is not important that how many trees have been planted or how many hectares have been irrigated but most important is that how many poor, landless, deprived families have been given gainful employment, access to common property resources and avenues of livelihood security.
- Regional disparities- the per hectare cost of treatment is higher in Himachal Pradesh as compared to Haryana because of higher material transport costs on difficult terrain. The implementation arrangements varied across states. While watershed development projects in Haryana was operated by the agriculture department but in HP and J and K by forest department.

3.2.5 A comparative and critical analysis of previous studies publications

The watershed development related research work largely emerged from CS&WC R& Training Institute Dehradun and its Research Centre Chandigarh. Simultaneously, research input was also added from Ballawal and Daulakuan Regional Research Station of Palampur Agriculture University.

Samra, J.S., Singh, R.P. and Mohan, A.N. 2000 compiled an annotated document of publication of the Central Soil and Water Conservation Research and Training Institute, Dehradun providing summaries of published papers by the Institute Scientists from 1954 to 1998. The abstracts of 1388 papers and bulletins were included in the form of a book. These publications were divided into seven area of research. The analysis of these previous studies indicated that the rate of publications gradually started from 1954-58 but remained at low key up to 1974-78. However, the rate of publication suddenly increased in 1979-83 and 1984-88 when

watershed development research starting from Sukhomajri expanding to other 47 operational research project across all the nine centers of the institute. In case of Watershed Development Research in *Shivaliks*, the publications started from Sukhomajri and out of 69 publications covered by Samra *et al.*, 2000, the maximum are on various facets of Sukhomajri watershed project, followed by Bunga, Nada, Tibbi in Haryana, Relmajra in Punjab and Behdali in Una district of Himachal Pradesh. Lot of research information was added after this publication. An effort was made to catalogue watershed based research and development in *Shivaliks* of North India and lessons learnt.

3.2.6 Constraints in replication and lack of community participation

The local communities were not made to actively participate in the planning and implementation of programmes related to management of individual and common property resources and as a result SWC works done at a great expense mainly by the Government initiatives were seldom maintained by the beneficiaries. This led to serious doubts about the viability of technological packages. The failures in SWC and lack of community participation became a common problem.

Eckholm, 1976 emphatically held that the application of technical answers to the ecological problems seldom turns out to be simple. He felt that social dimensions of SWC were largely ignored. Hudson, 1991 felt that low level of success in SWC is caused to some extent by attempts to use unsuitable technology for a particular set of conditions. The technology, which is based on the development of an existing practice stand better chances of adoption than something, which is new to the area. It must be considered necessary to appreciate the positive points of the traditional production and land-use systems and strengthen them through science and technology inputs so as to enhance their value and efficiency (GBPIHED, 1993). This is better than advocating changes involving the replacement of traditional systems by new one's found suitable elsewhere.

3.2.7 Policy implications for current and future watershed development programs

Remote sensing based appraisal and monitoring of resource base need serious push through participatory, de-centralized watershed development in the Shivaliks. Attempting farming system approach, small farm based hill agriculture should integrate local fruits, vegetables, floriculture and high value crops like ginger, turmeric and garlic. The impending labour shortage, provisions for machinery, tools and plants for small farms and generation of small farm technologies are challenges which has to be addressed. Water scarcity, diminishing supplies, drying of natural springs, and dilapidated condition of irrigation Kuhls against climate change mitigation challenges, water security remains a challenge waiting for innovation and financial support. Promotion of bio fertilizers and pesticides, processing, value addition and marketing needs a strong push. Skill improvements through capacity building, easy credit and crop insurance and agriculture and industry partnership are one of the priority areas. Funding support to research and extension is equally important. Only salient issues generally debated have been flagged but many more could be added.

Conclusions

The genesis emerging from the discussion part of the paper clearly indicates that the sustainability of the watershed interventions shall strongly depend upon institutional capacity building, strengthening of community organizations and continuity of funding support. The communities shall have to be brought at the central stage of decision making and bottom-up approaches shall have to be adopted for the success of the projects. Taking a historical perspective, the detail of programs and watershed development projects taken up to reverse the trend of degradation has been presented starting from pre independence to Pardhan Mantri Krishi Sinchai Yojna covered 11 sections. Key lessons learnt from these watershed interventions, institutional innovations, role of community mobilization have been described. Major un-addressed gaps, implementation constraints, institutional loopholes and a comparative and critical analysis of previous studies/ publications including constraints in replication are discussed. The policy implications for current and future watershed development programs are deliberated.

Watershed management as a tool for environmental rehabilitation of degraded ecosystems is now well recognized all over the country. Common guidelines for systematic implementation of participatory watershed development were prepared at the national level and were made the pre-requisite along with cost and benefit sharing arrangements. It was suggested that integrated watershed development be undertaken systematically with GIS support in demand driven and participatory approaches by strengthening social institutions (VLDC's, Panchayats), focusing to local flora and immediate community needs giving due priority to water resource development for drinking, irrigation, improving moisture regime and ground water recharge. The strengthening of data base by systematic studies can lay strong foundation not only for rehabilitation of degraded *Shivaliks* but also for ensuring sustainability of biological production systems. It is, therefore, recommended that all out efforts should be made for an integrated approach to rainwater harvesting in *Shivaliks* with national and international financial support. There is an urgent need to prepare a holistic perspective plan for this purpose. The conclusions of this paper are briefly summarized as under:

- Large scope with basket of options is well demonstrated. However, sufficient data support and continuity of efforts is required, with national and international funding support.
- Possibilities to tie up forest protection, livestock improvement, horticulture, fish rearing, employment generation and economic development should be further explored by adding high value crops, processing and marketing.
- There is a need for integrated/holistic perspective plan to garland *Shivaliks* with water bodies with committed financial support. Punjab needs to float proposals for foreign funding support like Himachal Pradesh.
- Continued research and training to refine technologies is necessary. There is a scope to reduce failures, economize on cost and build in sustainability concerns more seriously.
- Experiences are building up which need compilation for the benefit of user groups and managers of future projects.
- Efforts must be harmonized with poverty alleviation, environmental rehabilitation welfare

of women, landless, weaker sections which needs to be targeted more seriously.

Moreover, it must be clearly understood that land cannot be reclaimed or conserved through sporadic efforts and short term projects and by a thin spread of monetary resources. Long-term programs backed by sound land use policies and strategies by involving local communities are urgently needed. We must not only internalize the double shift in research paradigm but must also absolutely couple it with sound policies, tireless extension and effective natural resource management so that benefits reach to those who failed to get them before (Ismail, 1998).

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Leveraging Carbon and Green Credits For Sustainable Conservation : Key Insights

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1. Introduction

Climate change has become a challenge of the millennium due to the excessive emission of greenhouse gases (GHGs) from anthropogenic activities such as burning fossil fuels, industrialization, and urbanization. The current situation necessitates identifying and implementing carbon-neutral or carbon-negative practices to curtail GHG emissions and sequester carbon. The concept of carbon trading emerged as an institutional approach to provide economic incentives for promoting carbon-neutral or carbon-negative practices to mitigate GHG emissions and thus address the consequences of climate change. Carbon trading is not a recent idea, as it was initially introduced under the Kyoto Protocol in 1997. This was the first international agreement that set legally binding emission reduction targets for developed countries. It entailed the issuance of Certified Emission Reductions (CERs) to individuals or organizations that achieved significant cuts in emissions. These CERs could be traded in the market, and this system continued for several years.

Agriculture, being dependent on varying monsoons, is most vulnerable to climate change. It is also regarded as a key contributor to climate change through the activities of submerged paddy cultivation, which emits methane, burning agricultural residues, and so on. It has been estimated that if sufficient adaptation and mitigation measures are not taken up, annual emissions from agriculture could be up to 400 million tons of CO₂ equivalent. India is the world's

third largest emitter of GHG, with 74% of its carbon emissions attributable to methane from livestock and cultivation and another 17.5% of agricultural carbon emissions derived from rice cultivation. Every year in northern India, 23 million tonnes of paddy stubble are burned, contributing as much as 40% of New Delhi's pollution during winter months, and there is an annual health and economic cost of around \$30 billion (Bhuvaneshwari *et al.*, 2019).. Agriculture plays a crucial role in mitigating emissions and sequestering significant amounts of carbon, thus making it an essential component of the proposed solutions. Average farm land holdings at the global level can store up to 1.2 billion tons of carbon and could offset 4% of average annual GHG emissions over the rest of the century. Climate change, an unavoidable consequence of carbon-intensive activities, has posed some severe and irreversible impacts on the ecosystem. The government of India has acknowledged the urgency of addressing the consequences of climate change and aims to attain net-zero emission targets by 2070. In addition, there is a commitment to reduce carbon emissions by one billion tonnes by 2030. To facilitate these goals, the government has proposed the creation of a voluntary carbon and green credit market within India. This market will provide a platform for individuals and organizations to actively participate in efforts to mitigate climate change and promote sustainable practices.

2. The Global Carbon Market

There are broadly two categories: the voluntary market and the compliance market. In the voluntary market, buyers choose to reduce emissions without legal obligation, driven by their commitment to improving the environment, even if it requires financial investment. The voluntary carbon market (VCM) was valued at \$2 billion in 2020, with projections suggesting a potential increase to \$50 billion by 2030, depending on the

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market price of carbon credits (GOI, 2023). Conversely, the compliance market involves purchasers legally required to reduce their emissions. This market typically operates through a cap-and-trade mechanism, which sets emission baselines or permits a specific level of emissions. Entities bound by law must limit their emissions to the level established by the governing authority. If their emissions fall below this level, they are awarded carbon credits. However, if their emissions exceed the prescribed level, they can purchase carbon credits from entities that have successfully reduced them. This cap-and-trade market is sometimes referred to as the allowance market, with the carbon credits in this market known as allowances.

Current projections indicate that the average price in global carbon markets is between \$3 and \$5 per tonne of CO₂ equivalent. If projects successfully exceed baseline emissions reductions, this price will climb to \$20 and \$50 per tonne of CO₂ equivalent by 2030. Moreover, prices could reach as high as \$100 per tonne of CO₂ equivalent, with an ongoing increase anticipated until 2050. The International Carbon Reduction and Offset Alliance (ICROA) offers an accreditation program and supports organizations through advocacy and action-oriented services to promote best practices in the Voluntary Carbon Market (VCM). It also provides carbon finance to help countries meet their commitments under the Paris Agreement.

3. Carbon Market in India

The Ministry of Power, Government of India, notified the Carbon Credit Trading Scheme, 2023 (CCTS 2023) under the Energy Conservation Act, 2001, to develop the country's first domestic carbon market. The notification provided the necessary framework and outlined the roles of diverse stakeholders for the development and functioning of the Indian Carbon Market (ICM) within the compliance mechanism. The market will set Greenhouse Gas (GHG) emission intensity reduction targets in line with India's Nationally Determined Contributions (NDC) for selected entities obligated under CCTS 2023. A carbon credit permits the emission of one ton of greenhouse gases per permit. These credits are periodically awarded to companies contributing to

pollution, limiting their emissions while enabling them to sell excess credits to another company that needs them. One carbon credit certificate will equal one tonne of CO₂e (carbon dioxide equivalent). The credits will first be traded in the domestic market instead of being exported until the nation meets its climate goals of reducing 1 billion tons of carbon by 2030 and achieving net zero by 2070. The system allows an industrial unit to emit a specific amount of GHG, and certain industries may inevitably emit more GHG. They will require additional permits, acting as buyers in the VCM. The carbon credits generated by projects focused on carbon sequestration will act as sellers in the market.

4. Green Credit Programme (GCP)

Green credit is a single unit of incentives provided for a specified activity, positively impacting the environment. The Green Credit System is a mechanism that complements the domestic carbon market. While the domestic carbon market focuses solely on CO₂ emission reductions, the Green Credit System aims to meet other environmental obligations as well, incentivizing sustainable practices by various stakeholders. The Green Credit Programme (GCP) was launched at the National level by the Government of India on 12th October 2023. Given increasing climate variability and its associated effects on livelihoods, GCP aims to support rural livelihoods and enhance agricultural resilience by incentivizing the implementation of sustainable and eco-friendly farming practices and technologies. Additionally, it promotes the Mission LiFE, which aims at nudging individual and collective action towards 'Lifestyle for Environment' by protecting and conserving natural resources. This strategy utilizes a market-based approach to incentivize positive environmental actions and commitments. Green credit is different from the carbon credit. An activity generating green credit under GCP may also be eligible to generate carbon credits simultaneously. The Indian Council of Forestry Research and Education (ICFRE), an autonomous body under the Ministry of Environment and Forests, is the nodal authority of GCP. The activities considered under GCP are tree plantation, water management, sustainable agriculture waste management, air pollution reduction, mangrove conservation and

restoration, eco-mark label development and sustainable building and infrastructure. Under the green credit programme, individuals, industries, Farmer Producer Organizations (FPOs), urban local bodies, gram panchayats and the private sector, among a host of other entities, will be able to earn green credit by undertaking environment-friendly actions.

5. Incentivizing Sustainable Agricultural Practices

These voluntary carbon credit markets play a vital role in reducing emissions through incentivizing the adoption of sustainable agricultural practices such as reduced tillage, afforestation, agro-forestry/horticulture, integrated farming system, regenerative farming and adoption of climate resilient genotypes with greater adaptation to drought, flood, salinity and high temperatures. Minimizing wastage, preventing agriculture residue burning, reducing carbon footprints, and adopting agroforestry and horticultural cropping systems are key areas for improving environmental sustainability (Dhyani *et al.*, 2019). The carbon sequestration potential of an agroforestry system on a farmer's field varies from 0.29 to 15.21 tonnes C ha⁻¹ yr⁻¹ (Kumar & Kunhamu, 2021, Hombe-gowda *et al.*, 2016). By participating in the carbon markets, farmers gain an additional source of income and contribute to adopting enhanced practices that ensure ecological and environmental benefits.

6. Role In Soil And Water Conservation

The government takes VCM and GCP to incentivize the farmers who adopt the climate resilient and sustainable agricultural practices which are being promoted under Rashtriya Krishi Vikas Yojana (RKVY), National Mission on Sustainable Agriculture, Organic farming, Natural farming, Per Drop More Crop and *Pradhan Mantri Krishi Sinchayee Yojana* (PMKSY). These programs mainly promote sustainable soil and water conservation practices such as mulching, field bunding, contour cultivation, terracing, check dams, farm ponds, micro irrigation, agriculture residue & waste management, rainwater harvesting, crop diversification, etc., improving soil health quality, productivity of crops and climate resilience. Implementing

sustainable agricultural practices that address soil erosion, preserve natural resources, save energy, and sequester carbon may be considered for green credits. Moreover, practices that result in a reduction of carbon equivalent emissions are eligible for earning carbon credits (Subrata *et al.*, 2021).

For example, projects on a regional scale in watershed mode, aiming at rehabilitating degraded lands with carbon sequestration, will have more demand in voluntary carbon and green credit markets. It will not only reduce carbon emissions by adopting improved agricultural practices, but also earn income from the credits generated by the farmers. According to estimates, farmers in India have the potential to earn cash incentives ranging from ₹ 700 to ₹ 1000 per credit. On average, they can sequester 2-6 credits per hectare of land. Projects aiming at the conservation of natural resources, biodiversity, soil health, nutrient availability, carbon sequestration, and forest ecosystems will not only enhance climate resilience and reduce vulnerability but also earn additional income and help achieve social equity (Fig. 1).

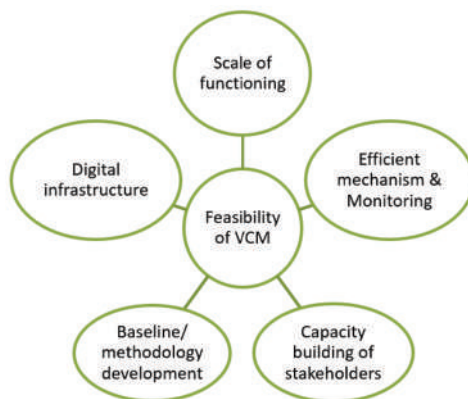


FIGURE 1 Characteristics of the feasible Voluntary Carbon Market (VCM) in India

7. Operation Mechanism of Credit Market

The process of setting targets and determining a baseline for buyers proves to be a substantial obstacle when it comes to establishing a comprehensive regulatory framework for carbon markets. The carbon market mechanism faces numerous challenges in India, including adequate

monitoring and certification, ethical concerns, and environmental considerations. To ensure the success of a national carbon market, it is imperative to have the appropriate support mechanisms in place to meet the concurrent demand while also considering feasibility and cost-effectiveness. Minimizing transaction costs associated with implementing and achieving a competitive credit market is crucial. Agriculture-related carbon credit systems are predominantly limited to large-scale holdings in developed economies, where farmers have greater access to information sources, technology, and necessary mechanization and equipment. However, exploring the potential benefits for small and marginalized farmers in the developing world is essential. Simplifying the carbon credits' validation and verification process is critical for accelerating project scalability and fostering sustainable practices. Technology and private sector engagement can also facilitate the inclusion of small acreage farmers in carbon credit systems or other carbon sequestration initiatives. A transparent, user-friendly, and easily accessible common trading platform is essential for the efficient functioning of the carbon/green credit market.

Conclusions

It is essential to align the economic advantages gained from the agricultural sector with the preservation of the natural resource base, which is crucial for ecological benefits. Success hinges on increasing agricultural productivity through economic efficiency while also pursuing social equity and environmental sustainability. Facilitating sustainable agricultural practices can be achieved through voluntary carbon and green credit markets, which bolster rural livelihoods and fortify resilience in agriculture. These markets may incentivize farmers to adopt eco-friendly practices, thus enhancing the overall sustainability of the agricultural sector. Moreover, it is vital to develop farmer-producer organizations, community-based groups, and non-governmental organizations to facilitate market engagement. These entities can offer vital resources and services, especially for smallholders, including access to information, technology, and markets, thereby advancing sustainability and tackling climate change challenges. To meet national

priorities and sustainable development goals, the voluntary carbon market (VCM) and green credit program (GCP) must operate seamlessly together. This requires significant outreach and awareness efforts across various stakeholders. The intersection of new technologies and digital connectivity with carbon credit systems offers a promising pathway for farming communities to adopt climate-positive practices and enhance their livelihoods. However, the effectiveness of these efforts relies on robust monitoring and the optimization of verification and validation processes through an integrated approach.

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Convergence for Sustainability: A Case Study of Tribal Watershed in Panchmahal District of Gujarat

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1. Introduction

In recent years, convergence has attracted considerable momentum in rural development policy as it focuses on sectoral programs converging to obtain more effective and less expensive outcomes (Karmakar, 2025). One such possibility exists in the convergence of water resource management and rural infrastructure programs (Vanitha *et al.*, 2021). De-siltation of community-based water harvesting systems not only increases their water retention capacity but also creates useful by-products like nutrient-rich silt (Everard *et al.*, 2020). This approach aligns with the principles of Watershed Guidelines 2.0, which emphasize the strategic convergence of sectoral programs to enhance the efficiency and sustainability of rural interventions (WDC-PMKSY 2.0 (2021), Kumar *et al.*, 2022). Such integration mandates that watershed initiatives transcend isolated conservation efforts, instead harmonizing water resource management with broader infrastructural schemes to produce synergistic, long-term socio-economic benefits. This material can also be utilized as fill in rural road embankments, minimizing the requirement of virgin earth excavation and environmental degradation (Geetha *et al.*, 2025). Furthermore, the strategic integration of these resource management objectives into broader rural development frameworks promotes a shift toward sustainable water recharge, reducing reliance on exclusively engineered extraction (Everard *et al.*, 2017). The de-siltation of existing water harvesting structures in synchronization with the rural infrastructure development schemes such as

Pradhan Mantri Gram Sadak Yojana (PMGSY) and job schemes such as VB-G RAM G (Viksit Bharat – Guarantee for Rozgar & Aajeevika Mission (Gramin) can be done for the synergetic model of development. This approach not only optimizes public investment in natural resource management but also facilitates the creation of sustainable assets that mitigate climate change impacts and foster economic resilience in rural areas (Gavali *et al.*, 2025). Moreover, the decentralized water harvesting approach, often coupled with guaranteed rural employment programs, significantly bolsters local water availability and addresses equity concerns by broadly distributing benefits across communities (Anantha *et al.*, 2021). This type of convergence not only maximizes resource utilization but also promotes environmental sustainability, enhances rural connectivity, and strengthens livelihood prospects in rural areas of the country, making it a promising strategy for cohesive rural development.

2. Location of the Study area

The Bhadroli Khurd-Karada watershed has a 659.85 ha total geographical area located in Kalol Taluka in the southwest part of Panchmahal district in Gujarat. The watershed falls in two villages, Bhadroli Khurd (22° 41' 50" N Latitude and 73° 30' 23" E Longitude) and Karada (Latitude 22° 40' 26" N and 73° 30' 23" E Longitude), as shown in (Fig. 1). The watershed was taken up for implementation during financial year 2020-21 by ICAR-Indian Institute of Soil and Water Conservation, Research Centre-Vasad, District-Anand, Gujarat, for development under the Tribal Sub-Plan (TSP) scheme funded by the Ministry of Agriculture and Farmers Welfare, Government of India (Singh *et al.*, 2025).

3. Problems of the Watershed

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The Bhadroli Khurd-Karada watershed, located in the semi-arid zone of Kalol Taluka, Panchmahal district, sustains an agricultural economy predominantly reliant on monsoon precipitation. Erratic rainfall and the absence of irrigation infrastructure restricted most farmers to kharif-season cultivation, rendering rabi lands fallow and compelling many to seek seasonal migrant labour amid constrained incomes and resource scarcity. To disrupt this cycle, a comprehensive lift irrigation project was initiated to enhance water storage, broaden irrigation access, and promote rabi cropping, while adhering to regionally recommended agronomic practices (Singh *et al.*, 2025).

The watershed was selected due to its fully rainfed character and its exclusively tribal population practicing subsistence agriculture with indigenous, low-yielding varieties of maize, cotton, castor, pigeon pea, and pearl millet. Crop production was limited to the kharif

season owing to inadequate water resources and irrigation facilities, compounded by stray animal depredation. Yields fell substantially below state averages, attributable to severe soil erosion, deficient irrigation, and the lack of soil and water conservation measures. Farm mechanization was rudimentary, relying primarily on bullock traction, while livestock holdings were sparse with low milk productivity stemming from poor animal health and fodder shortages. Participatory rural appraisals identified seasonal youth outmigration to urban areas for better livelihoods, eroding interest in farming. Literacy rates for both genders trailed state averages, alongside limited awareness of conservation practices. Accordingly, multifaceted interventions were implemented to achieve holistic socio-economic development. Over the project period (2021-2024), annual rainfall in the watershed ranged from a minimum of 650 mm in 2021 to a maximum of 830 mm in 2024 (Singh *et al.*, 2025).

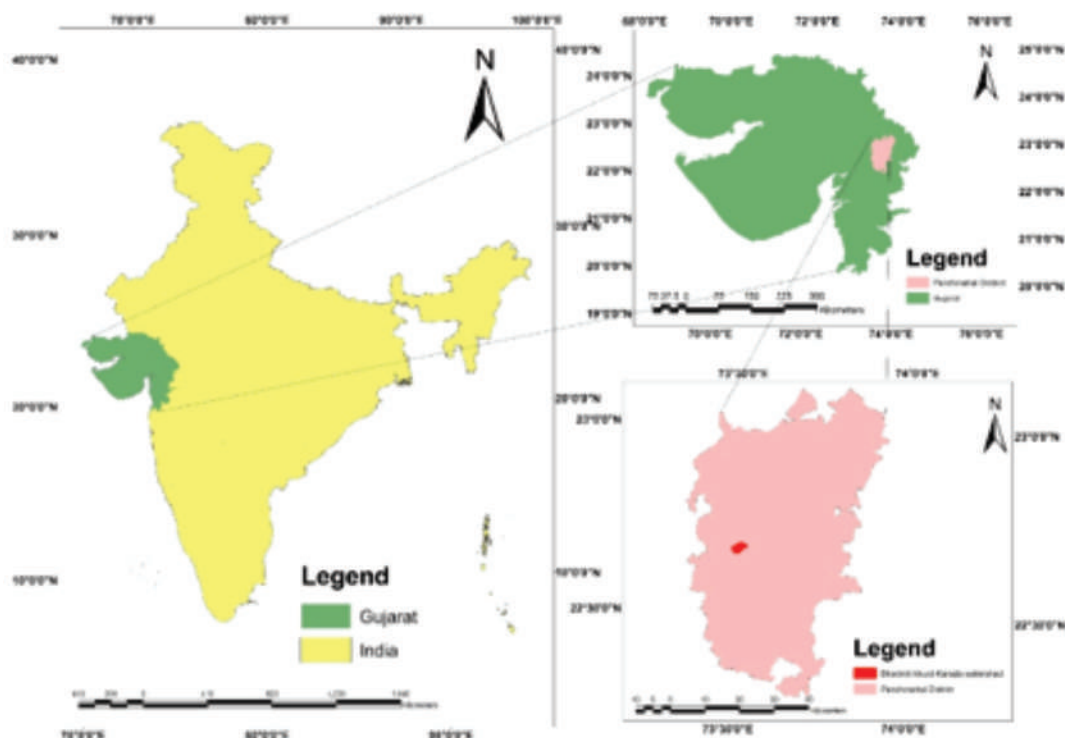


FIGURE 1 Location of Bhadroli khurd-Karada watershed in Panchmahal district of Gujarat in Western India

4. Interventions Made in the Project

The construction of the Delhi-Mumbai expressway necessitated substantial earth material, which was sourced by the involved construction firms. Numerous community-based water harvesting structures in the vicinity were observed to be heavily silted over time, with damaged inlets and outlets impairing their functionality. Researchers from the ICAR-Indian Institute of Soil and Water Conservation, Research Centre-Vasad, identified an opportunity to repurpose silt from these structures for expressway development within the watershed. Under the Tribal Sub-Plan program, ICAR-IISWC, RC-Vasad provided financial assistance to restore these structures through repairs to their inlets and outlets. Additionally, a two-lift irrigation system was established, incorporating a 3.6 km underground pipeline network across farmers' fields to facilitate rainwater utilization for crop production. A farmers' water users' association was formed, and training was imparted on the efficient management and maintenance of the lift irrigation system. Under the TSP initiative, 8 hp diesel pump

sets and single-phase electric submersible pumps were supplied to enable water lifting from the harvesting structures to agricultural fields. The underground pipeline network enhanced water use efficiency and minimized conveyance losses compared to surface irrigation methods. Furthermore, high-quality seeds of cotton, pigeon pea, paddy, maize, and pearl millet were distributed, alongside demonstrations of recommended cultivation practices via the Krishi Vigyan Kendra, Panchmahal. Exposure visits were organized by ICAR-IISWC, RC-Vasad for approximately 120 tribal beneficiary farmers to progressive farms, fostering confidence in adopting scientific crop cultivation techniques and irrigation system operations. This integrated approach, encompassing both structural restoration and capacity building, aligns with successful strategies observed in other regions facing similar challenges, where community-based participatory methods for water resource management have led to significant groundwater recharge and socio-economic regeneration (Everard *et al.*, 2017). It is shown in (Fig. 2).



a. De-silted water harvesting structure in the watershed



b. Repair of inlet and outlets of the water harvesting structure



c. Over head tank for lift irrigation system



d. PVC pipes for underground pipeline network

continued on next page

Fig. 2 continued



e. Diesel pumpset for lift irrigation system



f. Electric pumpset for lift irrigation system



g. Installation of underground pipeline in farmers field



h. Outlets of underground pipeline in farmers field



i. Good crop yield in farmers field



j. Vegetable crops taken by farmers



k. Growth of cotton crop in farmers field



l. Bumper cotton yield in farmers field

FIGURE 2 Different interventions in the Bhadroli khurd-Karada watershed

5. Impact of Project Implementation

5.1 Enhancing Water Storage for Multi-Purpose Use

Existing check dams along the watershed's drainage lines and village ponds were deepened from 1.0 to 2.5 meters, thereby generating an additional storage capacity of 95,850 cubic meters. This harvested water also contributed to highway construction activities, exemplifying effective convergence between rural development initiatives and infrastructure requirements. Additionally, the construction of new check dams and low-cost gully control structures on the stream network, with individual storage capacities ranging from 1,000 to 6,500 m³, further augmented the overall water storage and facilitated groundwater recharge (Garg *et al.*, 2020; Singh *et al.*, 2013). The water supported the watershed's crop production systems via a lift irrigation setup and an underground pipeline network installed across farmers' fields. Furthermore, villagers employ these revitalized water harvesting

structures for pisciculture during the monsoon season, enabling multifaceted utilization of the harvested rainwater and thereby enhancing farmers' incomes.

5.2 Groundwater Recharge

Water level measurements from nearby open wells before and after interventions in the watershed demonstrate that enhanced water harvesting capacity increased groundwater recharge, reducing the average depth to the water table from 45 m to 24 m. It is shown in (Fig. 3).

5.3 Lift Irrigation With Underground Pipeline

A 3.6 km underground pipeline system was developed, connecting the storage structures to farms via a network powered by energy-efficient electric pumps, including diesel-operated ones. This drastically reduced water losses from surface transport and improved conveyance efficiency of the irrigation system.

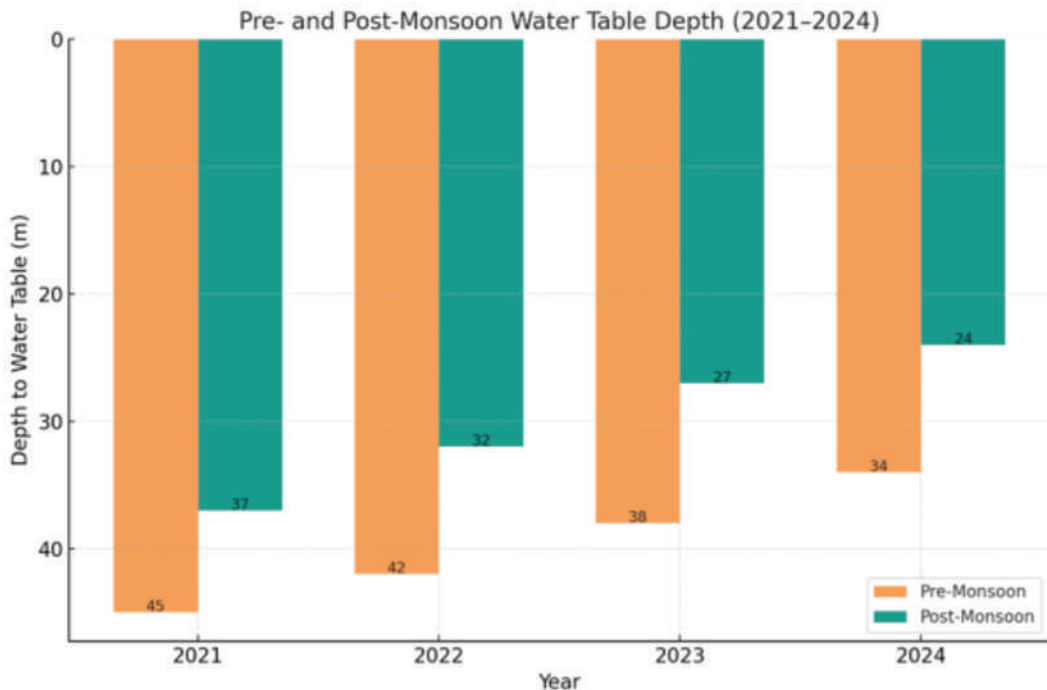


FIGURE 3 Average depth to water table from 2021-2024 in the watershed

5.4 Capacity Building and Crop Planning

The local agricultural experts from ICAR-Krishi Vigyan Kendra (KVK) and Panchmahal representatives collaborated to guide farmers on selecting regionally recommended rabi crops and adopting best practices in irrigation and soil fertility management.

5.5 Crop Yield Improvements

With a reliable water supply, farmers adopted high-yielding crops provided by the ICAR-IISWC, RC-Vasad and regionally recommended cropping practices, resulting in substantial improvements in the crop yield. It is shown in (Fig. 4).

5.6 Socio-Economic Benefits

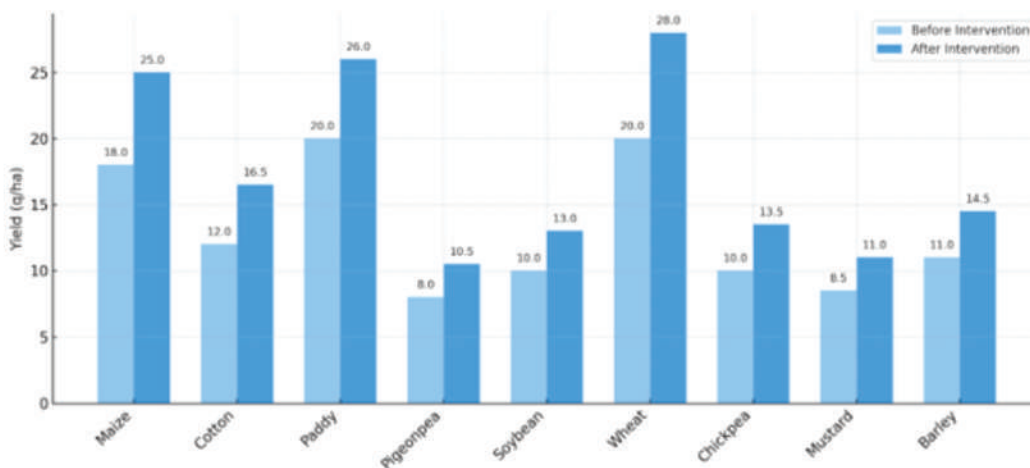


FIGURE 4 Crop yield before and after the interventions in the watershed

Conclusions

The success of this intervention under the Tribal Sub-Plan (TSP) program of ICAR-IISWC, RC-Vasad is an example of convergence of the government schemes for the multi-facet development in a region. The lift irrigation project in Bhadroli Khurd has become a success story in tribal agriculture revitalization. By combining infrastructural innovation with crop advisories and community participation, the initiative not only ensured water security but also empowered farmers to transition from subsistence to surplus. The model exemplifies how region-specific interventions can lead to sustainable, inclusive

·Increase in farm income: The average net income per farmer increased from ₹35,000 to ₹55,000-₹65,000 per season.

·Improved Cropping Intensity: Land under cultivation during rabi increased by 40%, leading to higher productivity per acre.

·Reduction in Migration: Stable income and local employment opportunities significantly curbed seasonal out-migration.

·Women's Empowerment: With better water availability, tribal women were engaged more in crop planning, kitchen gardening, and agri-based microenterprises.

·Community Governance: A Water Users Association (WUA) groups were established to manage water distribution, repair and maintenance of lift irrigation system, ensuring transparency and equity.

development, setting a replicable benchmark for similar rural and tribal regions across India.

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GIS -Based Erosion Susceptibility Evaluation of Mandakini Watershed Using WERM Model

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Abstract

The identification of erosion-prone areas is essential for effective watershed management, particularly in fragile Himalayan ecosystems. This study employs Geographic Information System (GIS) and Remote Sensing (RS)-based prioritization approach to assess soil erosion susceptibility in the Mandakini river watershed, Uttarakhand. ALOS PALSAR Digital Elevation Model (DEM) data were utilized to derive slope and drainage parameters, while Land Use/Land Cover (LULC) data for 2022 were generated from Landsat imagery. A long-term average rainfall surface (1982-2022) was also developed using ArcGIS. Thematic layers representing key erosion influencing factors were classified and assigned weights based on their relative significance and integrated within a geospatial framework to produce a soil erosion susceptibility map. The results reveal that 49.24% of the watershed falls under moderate susceptibility, followed by 25.58% under low and 7.52% under least susceptibility classes. High and very high susceptibility zones constitute 16.49% and 1.17% of the total area, respectively, indicating critical hotspots requiring immediate intervention. Spatial analysis indicates higher erosion intensity in the northern region compared to the southern part of the watershed. The prioritization of erosion-prone areas provides a scientific basis for implementing targeted soil and water conservation measures,

thereby supporting sustainable watershed management and environmental planning in the Himalayan region.

1. Introduction

Watersheds are fundamental units of landscape organization, though they rarely align with socio-economic boundaries (Chaudhary and Kumar, 2018). Soil and water resources are critical for sustaining watershed ecosystems and human livelihoods, with soil providing essential goods and services that support civilization (Mase *et al.*, 2015). However, soil erosion-the detachment and transport of soil particles by water or wind remains a major environmental concern (Makhdumi *et al.*, 2023). It occurs through processes such as sheet, rill, and gully erosion, and is influenced by factors including intensive agricultural practices (Jie *et al.*, 2002), rainfall erosivity (Nearing *et al.*, 2017), and surface runoff events (Fernández-Raga *et al.*, 2017). Human activities further accelerate erosion, leading to the loss of fertile topsoil and reduced agricultural productivity.

In India, out of 328.7 million hectares of geographical area, about 120.7 million hectares are degraded, with soil erosion affecting nearly 92.4 million hectares (ICAR, 2010). The Himalayan region is particularly vulnerable due to fragile geology, steep slopes, and intense rainfall, making it prone to landslides and severe erosion (Choudhury *et al.*, 2022). The Mandakini river watershed in Uttarakhand exemplifies this vulnerability due to geomorphic instability and increasing anthropogenic pressure (Pundir, 2022; Bohat and Joshi, 2024a). Recent advances in GIS and RS have improved soil erosion assessment by integrating terrain, land use/land cover, rainfall, and vegetation parameters (Panhalkar and Pawar, 2011; Chandniha and Kansal, 2017). Several empirical and process-based models, including

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the Revised Universal Soil Loss Equation (RUSLE), have been widely applied to estimate soil erosion and sediment yield (Biswas and Pani, 2015). In this context, the present study employs the Watershed Erosion Response Model (WERM), which allows for the spatially explicit integration of key erosion controlling factors such as slope, rainfall, LULC, and vegetation within a GIS framework. By assigning weights to these key erosion controlling factors, the model enables spatial assessment and prioritization of erosion prone areas, supporting sustainable watershed management in this ecologically sensitive Himalayan region.

2. Study Area

The study area is located between latitudes $30^{\circ} 10' 0''$ N and $30^{\circ} 50' 0''$ N, and longitudes $78^{\circ} 50' 0''$ E and $79^{\circ} 20' 0''$ E. The watershed is located in the Rudraprayag district of Uttarakhand and covers an area of approximately 1645 km². The major area of the Mandakini watershed primarily lies in the Rudraprayag district of Uttarakhand, India (Fig. 1). The elevation of the study area ranges from 586 to 6970 m (Fig.1). The region features a mostly sloping landscape, with gradients ranging from 0° to 17° in some areas, and 18° to 26° in others. A moderate slope has observed in a larger portion of the watershed, while the northern part has a very steep slope. The average annual rainfall in 2022 was 1867 mm (IMD, Pune). The maximum temperatures range from 30° to 35° °C, and the minimum temperatures range from 0° to 8° °C.

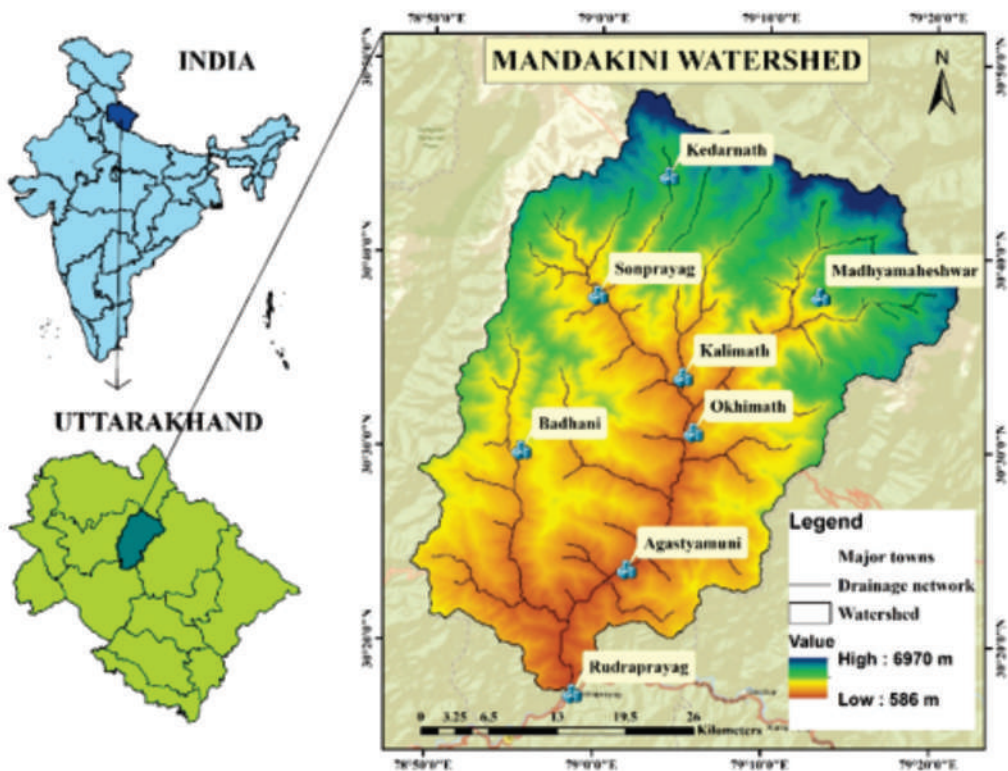


FIGURE 1 Map of the Mandakini watershed

3. Materials and Methods

The WERM is an index-based model used to evaluate soil erosion vulnerability. It incorporates key factors contributing to soil erosion, including rainfall intensity, soil characteristics, vegetation cover, and the topographic and morphological attributes of the watershed (Fig. 2) (Panhalkar and Pawar, 2011; Bohat and Joshi, 2024b). These factors collectively influence the spatial variability and severity of erosion processes.

The rainfall data (1982-2022) used in this study was derived from the gridded datasets of the India Meteorological Department, Pune, at a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$ (accessible at <https://www.imdpune.gov.in/cmpg/Griddata/Rainfall>). For erosion analysis, the data were reclassified into five equal interval classes. A weighted scoring system (1-5) was assigned in ascending order of rainfall magnitude to reflect increasing erosivity (Table 1). The highest rainfall class (1397.60-1468.61 mm) was assigned a weight of 5 due to its greater contribution to runoff and soil detachment, whereas the lowest class (1166.80-1243.73 mm) was assigned a weight of 1, indicating minimal erosive impact. This approach ensures systematic incorporation of rainfall erosivity into the erosion susceptibility model and aligns with established methodologies (Panhalkar and Pawar, 2011; Panwar and Singh, 2014).

The slope map was generated from the ALOS PALSAR DEM, acquired from the Alaska Satellite Facility (<https://search.asf.alaska.edu>). Radiometrically terrain-corrected tiles (ALPSRP235820600 and ALPSRP235820590) with 12.5 m spatial resolution were processed to derive slope map. The resulting slope values were classified into standard categories (nearly level to very steep) based on their control on flow velocity (Table 2) and associated soil erosion potential (Panwar and Singh, 2014).

Satellite data from Landsat 9 with 30 m spatial resolution were used to derive land use/land cover (LULC) and vegetation maps (Table 3). The analysis utilized Level-2 Surface Reflectance data (Product ID: LC09_L2SP_146039_20221208), obtained from USGS Earth Explorer (<https://earthexplorer.usgs.gov>).



FIGURE 2 Flow chart illustrating the methodology for delineation of priority zones

TABLE 1 Classification of rainfall and corresponding weights

Class	Rainfall Range (mm)	Weight
1	1,166.80-1,243.73	1
2	1,243.73-1,308.83	2
3	1,308.83-1,352.62	3
4	1,352.62-1,397.60	4
5	1,397.60-1,468.61	5

TABLE 2 Classification of slope and corresponding weights

Slope class	Slope (%)	Assigned weight
Nearly level	0-1%	1
Very gentle	1-3%	2
Gentle	3-5%	3
Moderate	5-10%	4
Strong	10-15%	5
Steep	15-35%	6
Very steep	> 35%	7

TABLE 3 Classification of vegetation and corresponding weights

Vegetation class	Assigned weight
Very dense vegetation	1
Dense vegetation	2
Sparse vegetation	3
Poor vegetation	4
No vegetation	5

The LULC classification was performed using the supervised classification technique (maximum likelihood classification algorithm). Representative training samples were selected to classify the imagery into discrete classes, namely dense forest, open forest, agriculture, urban areas, water bodies, barren land, and snow cover. Accuracy assessment was carried out using ground truth data, high-resolution imagery from Google Earth Pro, and standard statistical measures including the Kappa coefficient. The classification achieved an overall accuracy of 93.42%, indicating high reliability of the LULC dataset for subsequent analysis

The study employed a knowledge-based weighted overlay approach to assign weights to LULC classes, consistent with standard GIS-based watershed erosion assessment techniques. Weights were allocated based on the relative influence of each land cover type on soil detachment, runoff generation, and sediment transport, following established methodologies (Panhalkar and Pawar, 2011; Panwar and Singh, 2014). Dense forest was assigned the lowest weight due to its canopy cover and root network, which reduce raindrop impact and enhance soil stability (Table 4). Agricultural land received higher weights, as exposed soil during ploughing and early crop stages increases susceptibility to erosion. Open forest was assigned relatively high weights due to sparse vegetation cover. Snow-covered areas were given moderate weights, as

they protect soil during winter but contribute to increased runoff and sediment transport during snowmelt and monsoon periods (Kumar and Hole, 2021). Urban areas were assigned high weights due to impervious surfaces that enhance surface runoff. Barren land received the highest weight owing to direct exposure to rainfall and high erosion potential. Water bodies, though low in erosion, were included to account for sediment deposition and bank erosion processes.

The assigned weights were validated through comparison with previous GIS-based erosion modeling and watershed prioritization studies (Panhalkar and Pawar, 2011). The weighted overlay analysis integrated all thematic layers to delineate erosion-prone zones within the Mandakini watershed.

TABLE 4 Weight allocation for LULC classes

LULC class	Assigned weight
Dense Forest	1
Open Forest	2
Water body	Restricted
Snow cover	3
Urban Areas	4
Agriculture	5
Barren Land	6

4. Results and Discussion

The study aimed to identify soil erosion susceptibility zones within the Mandakini watershed using a weighted overlay analysis that integrated four key factors: rainfall, vegetation, slope, and LULC (Fig. 3).

The analysis was conducted using the Watershed Erosion Responsive Model (WERM) model, which provided a comprehensive understanding of soil erosion vulnerability across the study area. The analysis results are categorized into five classes of erosion susceptibility, where 1 represents the least susceptible and 5 represents the highest susceptible zones (Fig. 4).

The analysis delineates soil erosion

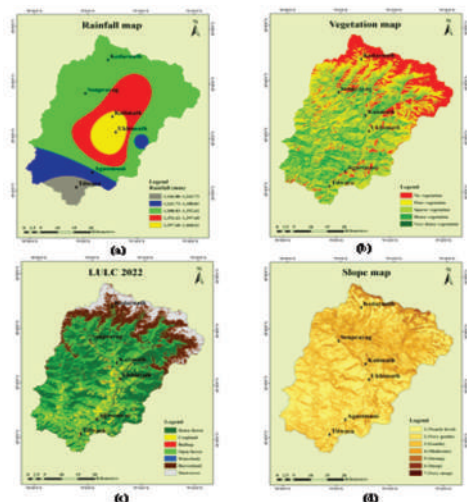


FIGURE 3 Thematic maps of the Mandakini watershed - (a) Rainfall, (b) Vegetation, (c) LULC-2022, and (d) Slope

susceptibility across the Mandakini watershed into five classes (Table 5). Class 1 (very low susceptibility) occupies 7.52% of the area and is characterized by dense vegetation, gentle slopes, and low rainfall, promoting soil stability. Class 2 (low susceptibility), covering 25.58%, reflects moderate vegetation and gentle terrain, limiting soil detachment. The Class 3 (moderate susceptibility) dominates the watershed with 48.24% of the area, where intermediate conditions-moderate slopes, rainfall, and vegetation cover contribute to noticeable erosion risk. Class 4 (high susceptibility), comprising 16.49%, includes areas with steep slopes, sparse vegetation, and high rainfall, resulting in enhanced runoff and sediment transport (Rai *et al.*, 2017). The Okhimath region, in particular, is highly vulnerable due to its steep terrain and intense precipitation, increasing both erosion and landslide risk.

Class 5 (very high susceptibility) accounts for 1.17% of the area and represents zones with extreme conditions such as barren land, steep gradients, and heavy rainfall, making them most prone to severe soil loss. These findings are consistent with previous studies emphasizing the dominant role of slope and vegetation in controlling erosion processes (Kumar and Hole, 2021; Bohat and Joshi, 2024a).

The results highlight the need for targeted soil conservation measures in high and very high susceptibility zones. Mechanical interventions such as contour bunding, terracing, and check dams can effectively reduce runoff and sediment transport, while vegetative measures including afforestation, grass cover enhancement, and agro-forestry can improve soil stability and minimize erosion.

5. Limitations of the Study

The weights included in the model are based on existing literature and expert opinion, which may introduce a degree of subjectivity. The present study is based on previously cited research and established methodology. The model does not have enough testing and calibration in the field, which might affect the results. The use of medium resolution satellite data may also make it hard to show small-scale changes in land use and

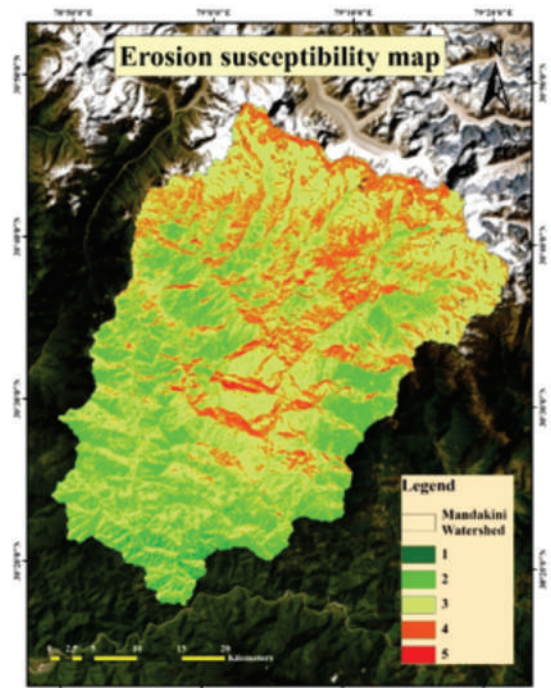


FIGURE 4 Soil erosion susceptibility map of the Mandakini watershed

TABLE 5 Soil erosion susceptibility map of the Mandakini watershed

Class	Soil erosion susceptibility	Area (%)
1	Very low	7.52
2	Low	25.58
3	Moderate	49.24
4	High	16.49
5	Very high	1.17

topography. Furthermore, temporal variations such as seasonal changes in vegetation and rainfall intensity are not explicitly accounted for in the analysis.

Conclusions

The Mandakini watershed, located in the fragile Himalayan ecosystem, is highly susceptible to soil erosion due to steep slopes, intense rainfall, and anthropogenic activities such as deforestation

and unplanned land use. The analysis indicates that most of the watershed falls under moderate susceptibility, while a notable portion lies in high to very high susceptibility zones requiring immediate attention. These vulnerable areas are typically associated with sparse vegetation, steep terrain, and exposed surfaces, which accelerate runoff and soil loss. The study highlights the critical role of land use, topography, and vegetation in controlling erosion processes and emphasizes the need for targeted conservation measures such as afforestation, terracing, and runoff management. The findings provide a scientific basis for prioritizing watershed management and sustainable land-use planning, with future research focusing on field validation and higher resolution temporal analysis to improve model accuracy.

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Healing the Bleeding Himalaya: Shivalik's Path to Land Resilience

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1. Introduction

The Shivaliks have always been a challenging landscape. Stretching nearly 2,400 km from the Indus River to eastern Nepal and covering more than 3 million hectares across the states of Jammu and Kashmir, Himachal Pradesh, Punjab, Haryana, Uttarakhand, Uttar Pradesh, and Assam (Yadav *et al.*, 2015). The Shivalik hills form the outermost range of the Himalayas and support millions of people through agriculture, forestry, and ecosystem services (Tiwari and Bhatt, 2018). Composed of loose, unconsolidated sediments deposited millions of years ago, these hills are highly susceptible to erosion (Sharma *et al.*, 2022). Although nature initially created this fragility, human activities have significantly intensified the risk. Deforestation, overgrazing, unplanned settlements, and intensive agricultural practices have removed the protective vegetation cover that once stabilized these hills (Yadav *et al.*, 2005). Climate change has further aggravated the situation by increasing the intensity and unpredictability of monsoon rainfall, resulting in more frequent flash floods, landslides, and cloudburst events across the region (IPCC, 2019). The consequences are alarming. In some parts of the Shivaliks, annual soil loss exceeds 80 tonnes per hectare enough to bury a cricket pitch knee-deep in sediment during a single monsoon season (Sharma, 2004). At the national scale, nearly 120 million hectares of land, an area larger than South Africa, are categorized as degraded (NAAS, 2010), with water erosion alone affecting approximately 82.6 million hectares. The economic implications are equally severe, with productivity losses estimated at about ₹4,631 per

hectare annually (Panwar *et al.*, 2023), contributing to global land degradation costs of nearly USD 18–20 trillion each year (UNCCD, 2019).

2. Current Scenario of Shivaliks hills

The warning signs are becoming increasingly frequent and severe. In April 2025, a devastating landslide in Ramban district of Jammu and Kashmir, triggered by intense rainfall, fragile geological conditions, and long-standing ecological degradation, destroyed homes and livelihoods within hours (Sharma *et al.*, 2025). Himachal Pradesh experienced consecutive monsoon disasters in 2023 and 2025, with districts such as Shimla (17%), Mandi (16%), Solan (16%), Sirmour (15%), and Chamba (14%) accounting for a substantial share of flood and landslide damage across the state (Kashyap *et al.*, 2021; Chandel, 2025). Similarly, extreme rainfall during October 2021 triggered widespread debris flows throughout the Kumaun and Garhwal regions of Uttarakhand, leaving lasting environmental and socioeconomic impacts from which many communities are still recovering (Thapliyal and Singh, 2024). The August 2025 floods in Punjab, among the most destructive in recent decades, submerged more than 1,400 villages, uprooted nearly 500,000 trees, and damaged approximately 176,000 hectares of agricultural land. The loss of vegetation that once anchored the soil accelerated erosion and led to extensive sediment deposition across farmlands and drainage channels. These disasters are not isolated events; rather, they represent interconnected manifestations of a rapidly changing and increasingly vulnerable mountain ecosystem. Together, they serve as an urgent warning from the Shivaliks.

3. Interventions for healing Shivalik Hills

Over the past several decades, scientists, engineers, and local communities across the

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region have developed and refined a range of effective, affordable, and landscape-compatible solutions for soil and water conservation. These interventions work with natural processes rather than against them and can be broadly grouped into three categories: Mechanical, Biological, and Bioengineering techniques.

3.1 Building with Earth: Mechanical Measures

The oldest trick in the conservation book is reshaping the land itself to slow water down.

3.1.1 Graded Bunds: Graded bunds reduce slope length and channel excess water away from fields, minimizing erosion and enhancing moisture conservation. When reinforced with vegetative hedges and grasses such as napier, they significantly reduce both runoff and overall soil loss (Mane *et al.*, 2009; Belayneh *et al.*, 2020). Simple to build and maintain, they remain one of the most widely adopted conservation structures across the Shivalik.



Graded bunds

3.1.2 Bench Terraces: Bench terracing converts steep slopes into broad, level steps, each with a channel that collects runoff and guides it to a safe outlet at reduced velocity. By decreasing both slope gradient and slope length simultaneously, bench terraces minimize runoff velocity, dramatically reduce erosion and improve water infiltration (Gachene *et al.*, 2019). In the western Himalayan region, conservation bench terracing has been shown to reduce runoff from 36.3% to just 7.4% and soil loss from 10.1 t ha⁻¹ to 1.19 t ha⁻¹ compared to conventional farming systems (Choudhury *et al.*, 2022). Contour bench terracing takes this further, achieving runoff reductions of 80% and soil loss reductions of 88% over the long term (Sharda *et al.*, 2013).



Bench terracing

3.1.3 Contour Bunding: By constructing bunds along the natural contours of a hillside, this technique acts like a series of speed bumps for rainwater slowing flow, spreading water across the slope and allowing it to percolate into the soil rather than run off. Studies show that contour field bunds maintain a runoff coefficient of just 0.126, meaning that as much as 87% of annual rainfall is conserved in situ (Rao *et al.*, 2022). This is transformational for rainfed farming on degraded slopes.



Contour bunding

3.1.4 Loose Boulder Check Dams: These low-cost structures built across gullies using locally quarried stone control runoff, trap sediment and stabilize gully beds and stream banks. They also support groundwater recharge by slowing stormwater flows (Garg *et al.*, 2011). A single loose-boulder check-dam structure can retain up to 146 m³ of sediment, with an average trap efficiency of 22.9%, thereby preventing nearly a quarter of the incoming sediment load from reaching the downstream plains (Adhikary *et al.*, 2024).



Loose boulder check dam

3.1.5 Geo-textiles: Biodegradable jute geo-textiles laid over bare or freshly planted slopes are highly effective during the critical establishment period. They reduce soil loss by up to 75% while conserving 46–62% of essential nutrients, demonstrating strong soil-binding capacity (Manivannan *et al.*, 2018). Agro-geo-textiles made from *Arundo donax* (giant reed) reduce runoff by 24% and limit soil loss to $8.22 \text{ t ha}^{-1} \text{ yr}^{-1}$ compared to conventional conditions (Singh *et al.*, 2019). When combined with legumes and conservation tillage, they also enhance soil carbon sequestration, improving climate resilience in fragile landscapes (Roy *et al.*, 2023).



Geo-textiles

3.1.6 Trenches and Micro-catchments: Trenches, pits or micro-catchments cut into hillslopes intercept and store runoff, promoting infiltration and limiting downslope flow. They also trap silt effectively. Trenches have been reported to reduce runoff losses by 8–10% and keep soil loss below 10 t ha^{-1} (Madhu & Jinger, 2025). In continuous-slope systems, a combination of trenches has achieved runoff reductions of 16–34% and soil loss reductions of 15–25% compared to untreated slopes (Kumar *et al.*, 2021).

3.2 Growing the Solution: Biological Measures



Staggered trenching

Plants are the Shivalik's original engineers, and restoring plant cover remains the most powerful and enduring tool in the rehabilitation toolkit.

3.2.1 Agroforestry: Integrating trees, shrubs, and crops on the same land does remarkable things for degraded soil. Species such as *Acacia nilotica*, *Butea monosperma*, and fruit trees like mango, ber, and citrus improve soil physical properties while simultaneously diversifying farm incomes (Bhatt & Kukal, 2017). Studies from the western India show that agroforestry reduces soil loss by 37.7% and runoff by 19.1% compared to sole cropping (Jinger *et al.*, 2022). Mulberry-based systems with active canopy management boost nutrient retention, soil carbon stocks and crop productivity making them especially well-suited to land rehabilitation in the hill districts (Kaushal *et al.*, 2024). Pasture and horti-pasture systems dominated by *Cenchrus ciliaris* have achieved some of the lowest recorded sediment losses in the region just $4.83\text{--}5.07 \text{ t ha}^{-1} \text{ yr}^{-1}$ while maintaining low runoff coefficients of 20–25% (Meena *et al.*, 2023). Mixed plantations of *Chrysopogon fulvus*, *Albizia lebbek*, *Grewia optiva*, *Bauhinia purpurea* and *Leucaena leucocephala* have demonstrated additional benefits in both erosion control and local livelihood improvement (Jinger *et al.*, 2023).



Agroforestry

3.2.2 Cover Crops: Fast-growing cover crops are among the simplest and most farmer-friendly tools available. By intercepting raindrops before they strike bare soil, they protect surface structure, enhance infiltration, and reduce runoff. Greengram and cluster bean reduce soil loss by 77% and 73%, respectively, compared to fallow land (Machiwal *et al.*, 2021). Beyond erosion control, cover crops contribute to carbon sequestration at a mean annual rate of 0.32 ± 0.08 Mg ha⁻¹ yr⁻¹, with an average maximum carbon increase of 16.7 Mg ha⁻¹ over time (Singhal *et al.*, 2020).



Cover crops

3.2.3 Vegetative Barriers: Densely planted grass strips along the contours of sloping fields act as living barriers against runoff an effective and low-cost alternative to earthen bunds on gently sloping lands. Grasses such as *Vetiveria zizanioides* (vetiver), *Panicum maximum* (Guinea grass), *Eucalyptus tereticornis* and *Eulaliopsis binata* (bhabar) reduce runoff and soil loss by 30–34% (Ghosh *et al.*, 2012). Pigeonpea (*Cajanus cajan*), with its exceptionally dense canopy cover of 95–98%, reduces runoff by 28–29% while also yielding a food crop (Bhattacharyya *et al.*, 2015). Aromatic plants including lemongrass (*Cymbopogon flexuosus*), citronella (*C. winterianus*), palmarosa (*C. martini*) and lavender (*Lavandula vera*) add a particularly attractive dimension: they reduce soil loss by 30–54% and runoff by 60–80% while sequestering 5.38–15.2 t ha⁻¹ of carbon (Tomar *et al.*, 2025). Their strong soil-binding root systems (binding capacity > 200) keep soil particles intact even under intense rainfall (Lal *et al.*, 2004; Jinger *et al.*, 2025), and their essential oil yield makes conservation directly profitable.



Vegetative barriers

3.2.4 Bamboo Live Check Dams: Bamboo is perhaps the Shivalik's greatest unsung hero. *Dendrocalamus strictus*, in particular, is widely recognized for its adaptability and hydrological suitability to ravine and gully lands (Rao *et al.*, 2012). Planted in staggered double rows along gully beds and slopes, bamboo roots dramatically increase water infiltration, reduce runoff velocity and bind loose soil, preventing further deepening or widening of gullies. Research by Singh *et al.*, (2015) demonstrated that such bamboo barriers reduced runoff from 9.65% to 1.81% and soil loss from 4.2 Mg ha⁻¹ yr⁻¹ to 0.6 Mg ha⁻¹ yr⁻¹. In silvopasture systems where bamboo is integrated with grasses and livestock management, more than 80% of rainfall is effectively utilized through plant uptake or deep percolation, contributing substantially to groundwater recharge. Soil loss in such systems falls to less than 1 Mg ha⁻¹ yr⁻¹ compared to 20 Mg ha⁻¹ yr⁻¹ recorded in untreated, degraded landscapes (Soni *et al.*, 2018). Bamboo also lends itself to allometric biomass estimation, making it a useful tool in quantifying carbon stocks for climate finance mechanisms (Kaushal *et al.*, 2022).



Bamboo live check dam

3.3 Bioengineering Measures

This often effective approach combines structural

engineering with living vegetation.

3.3.1 Bamboo + Bori-Bund Structures: The combination of live bamboo check dams with bori-bund structures (reinforced earthen check dams, often filled with local soil in jute bags) has proven highly effective at slowing runoff velocity and trapping sediment (Singh *et al.*, 2020, 2021). The bamboo's extensive root system anchors the structure from within, while the bori-bund provides external resistance. Together they facilitate silt trapping, enhance moisture retention, and promote groundwater recharge and unlike purely engineered structures, they strengthen rather than weaken over time as the bamboo matures.



Bamboo + boribund structure

3.3.2 Bench Terracing + Agroforestry: Integrating bench terracing with agroforestry bio-filter strips is one of the most comprehensively effective combinations documented in the Shivalik region. Guinea grass (*Megathyrsus maximus*) filter strips between terrace steps have been reported to reduce sediment concentration, soil loss by 66%, nutrient loss by 69%, and soil organic carbon loss by 65%, while improving soil nutrient content by 42% and conserving 79% of rainwater in situ (Rao *et al.*, 2022). This means a farmer simultaneously gets better yields, healthier soil, and a dramatically reduced erosion footprint all from the same intervention.



Bench terracing + agroforestry

3.3.3 Loose Boulder / Gabion + Bamboo Plantations: The integration of gabion walls and loose boulder check dams with bamboo plantations and suitable native vegetation has demonstrated remarkable results in rehabilitating severely degraded lands. In a Shivalik foothill project, this combination facilitated the restoration of approximately 43 hectares of degraded land while reducing downstream sediment deposition from 0.09–81.0 t to 0.07–16.7 t and upstream deposition from 1.0–72.0 t to 0.37–13.1 t (Kumar *et al.*, 2013). The vegetative components especially bamboo enhanced structural strength by anchoring soil, reduced gully expansion and improved the overall hydrological balance of the treated watershed. When combined with conservation agriculture and agroforestry at the landscape scale, bioengineering systems contribute significantly to long-term soil health and climate adaptation (Teng *et al.*, 2024; Ram *et al.*, 2025). Studies demonstrate that such integrated systems enhance carbon sequestration, improve water and energy use efficiency and strengthen overall ecological resilience (Singh *et al.*, 2025).



Gabion structure + bamboo

4. The Way Forward

The Shivalik hills face severe land degradation due to fragile geology, intense rainfall, climate variability and unsustainable human activities. Healing the Shivalik is not a single intervention. It is a conversation between science, community and landscape, sustained over decades. The tools and knowledge exists but what is needed now is the scale, speed and institutional will. That means deploying techniques such as remote sensing, GIS, drones and artificial intelligence to identify which slopes need treatment most urgently and which interventions will deliver the greatest ecological and economic return (Suresh Ramanan *et al.*, 2024). It requires investing in community training

so that farmers and panchayats become agents of restoration rather than passive recipients of government schemes. It also require designing financial mechanisms such as carbon credits, payments for ecosystem services, carbon finance etc. that make conservation profitable enough to compete with extractive land use. Further, the UN's Sustainable Development Goal 15.3 sets a global target of achieving land degradation neutrality by 2030 (FAO, 2015). The clock is ticking. The Shivalik has a reservoir of proven science, committed institutions like ICAR-IISWC, and communities with deep knowledge of their own hilly terrains that forms a sound foundation for restoration and resilience of the region.

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Throwing Seeds at the Problem: The Case for Seed Balls in Watershed Restoration

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1. Introduction

Walk across a degraded Rajasthan hillslope after the monsoon. Topsoil is moving toward the nearest nala, and only about one in five saplings planted last June remains, having succumbed to drought, goats, or compaction. The slope struggles against gravity. Now, imagine if just before the rains, a light broadcast of clay-coated seed balls, each with *Acacia tortilis* or *Ziziphus mauritiana* seeds wrapped in compost, had been spread. No pits, no irrigation, just tossing. With the onset of rains, the clay coating softens, allowing the seeds to absorb moisture and, under favourable conditions, germinate. Over time, successful establishment of vegetation can help stabilize the soil and initiate ecological restoration. This seed ball technique, though not new, remains underutilized in many of India's degraded dryland landscapes where conventional planting is often difficult and costly.

1.1 Technique With Deep Roots

The formal origin of seed balls is traced to Masanobu Fukuoka, the Japanese farmer-philosopher who, in the 1970s, advocated a "do-nothing" farming philosophy rooted in working with, not against, natural processes. His seed balls were simple pellets of clay, compost, and seed, broadcast over land without tilling. The clay protected the seed from birds and insects and from drying out; the compost gave the emerging seedling its first nutritional footing; and the rain did the rest. What Fukuoka designed for grain was later adapted, particularly across sub-Saharan Africa and dryland India, for trees. In both contexts, the fundamental insight holds: nature already knows how to plant seeds, it just needs help getting them past the gauntlet of predation, desiccation, and soil crust that stands between a

seed and a seedling.

2. Why Seed Balls Suit Degraded Watersheds

This is the connection that most seed ball literature underemphasises, but it matters enormously for watershed practitioners. In degraded catchments, overgrazed, deforested, or eroded, two interlinked problems prevent natural regeneration. First, the soil surface is often compacted or crusted, making it nearly impossible for broadcast seed to penetrate and maintain contact with moist soil. Second, moisture availability is feast-or-famine: intense monsoon runoff followed by rapid drying. Conventional seedling planting, which depends on a window of good soil moisture and requires protection from grazing, rarely survives both constraints. Seed balls sidestep the first problem by encasing the seed in a matrix that, when it softens and breaks down in rain, creates a localised pocket of moist, organic-rich material around the seed- a micro-nursery, in effect. The clay slows moisture loss, buying the germinating seedling time even as the surface dries between rainfall events.

The implications for watershed management go further. Once established, vegetation from seed ball broadcasts, especially leguminous pioneer species like *Albizia lebbeck*, *Acacia spp.*, and *Sesbania grandiflora*, begins the process of improving soil organic matter, enhancing aggregate stability, and increasing infiltration rates. The same hillslope that was losing topsoil starts, gradually, to hold water. What begins as a reforestation technique becomes, over two to three monsoons, a soil-water conservation intervention.

3. What Goes Into a Seed Ball

The materials are few and the method is forgiving. The core mix is sieved clay soil, compost or vermicompost, and seeds- typically in a 5:3:1 ratio by volume. The clay is the structural and protective

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element. The compost improves the nutritional microenvironment for germination. The seeds are ideally indigenous, drought-tolerant species suited to the local agro-ecological zone. Optional additions strengthen the ball's protective capacity: neem powder or wood ash deters insect and fungal attack; biochar improves water retention; and in trials with *Azadirachta indica*, microbial inoculants such as mycorrhizal fungi have shown measurable improvements in early seedling vigour.

The process takes four steps. Mix the dry materials thoroughly, then add water until the mixture holds a ball without crumbling. Shape into spheres of 2-3 cm diameter, small enough to handle in bulk, large enough to house 1-3 seeds. Sun-dry for 24-48 hours until firm. Store in a cool, dry place until the rains arrive. A group of 20 school children or SHG members working for a day can produce several thousand seed balls. This is not incidental, it is a core feature of the technique's value. However, the development of a seed ball making machine can save time, labour, and resources while ensuring uniformity in seed ball size and composition.

Suitable Species for Dryland Watersheds in India

Acacia tortilis, *Acacia arabica*, *Ziziphus mauritiana*, *Prosopis cineraria*, *Azadirachta indica*, *Albizia lebbek*, *Dalbergia sissoo*, *Butea monosperma* etc., selected for drought tolerance, nitrogen fixation, or soil stabilisation capacity.

4. What the Field Evidence Shows

The honest summary is: seed balls work, with significant variation, and the variation is manageable if it is planned well. Rajasthan has emerged as an important testing ground for seed-ball-based ecological restoration because of its extensive arid and semi-arid landscapes. Native drought-tolerant species such as *Prosopis cineraria*, *Acacia tortilis*, and *Ziziphus mauritiana* have been widely promoted for revegetation and restoration of degraded lands. Forest department led seed-ball campaigns have demonstrated the feasibility of large-scale seed dispersal in difficult-to-access areas, although germination and establishment rates remain highly dependent on rainfall, species selection, and site conditions. On the ground, that translates to measurable improvement in vegetative cover and visible reduction in soil erosion, a meaningful outcome on

landscapes where conventional planting had struggled. Banas Dairy, Gujarat, implemented a large-scale seed-ball campaign in the Jessore Hills of the Aravalli range, dispersing approximately 200,000 seed balls containing more than 600,000 seeds of native tree species, demonstrating the potential of community-led ecological restoration (Parmar, 2023). Similar initiatives in Bengaluru involved nearly 1,000 volunteers and resulted in the establishment of approximately 25,000 trees with about 25% germination. Under the Haritha Haram programme in Telangana, production expanded from 11.8 million seed balls in 2020 to nearly 20 million in 2021, highlighting the scalability of the approach through institutional support and participation of women self-help groups. In Uttarakhand, collaborative restoration efforts involving local communities, NGOs, universities, and government agencies reported establishment success rates of up to 80% under favourable conditions, while also contributing to reduced soil erosion and enhanced vegetation cover (Parmar, 2023). These are not spectacular numbers in isolation. But at scale, half a million seed balls over five years, they represent thousands of established trees at a fraction of the cost of nursery-based planting. Kenya's Seedballs initiative offers the most striking scale data: over 15 million seed balls distributed since 2016 in savannah and degraded rangeland, using a mix of drones, motorcycles, and community groups (Seedballs Kenya, 2023). The species, *Acacia* and *Sesbania*, are well matched to East African drylands. Localized tree establishment and reduced erosion have been reported across rehabilitation sites.

The consistent lesson across these cases is not that seed balls always succeed, but that their failure modes are predictable and preventable. Timing the broadcast to align with the onset of rain, not weeks before, is the single most important factor. Protection from grazing in the first two seasons dramatically improves survival. And using species with known germination behaviour in the target zone outperforms generic species mixes. A broadcast of 10,000 seed balls at 20% germination yields 2,000 germinated seedlings. If 60% of those survive the first monsoon, a conservative estimate with minimal aftercare, that is 1,200 established plants. At a material cost of roughly ₹1 to 2 per seed ball, that is under ₹ 20,000 for 1,200 trees. Nursery-based planting of equivalent stock, including transport, pitting, and first-season care, typically costs 5–10 times more in comparable terrain.

TABLE 1 Key Learnings from different field studies

Region / context	Scale / experiment	Key species / vegetation	Germination / establishment	Outcome	Key learnings	Reference
Native ecosystem restoration trial (New Zealand)	Multi-species experimental trial	11 native species	~20% emergence from seed balls	Potential for large-scale ecological restoration	Seed balls provide protective micro-environment but formulation optimization required for species-specific germination	Griffiths <i>et al.</i> , 2024
Global dryland restoration	Review of seed pellet technology	Grasses, shrubs, trees	Variable	Improved seed protection and establishment in degraded lands	Seed pellets reduce predation risk and improve seed-soil contact in arid ecosystems	Gornish <i>et al.</i> , 2019
Seed coating technology studies (South Carolina, USA)	Multiple species	Crops & native species	Improved germination and protection	Improved emergence under stress conditions	Clay and organic coating improves seed microenvironment and nutrient availability	Schmuck <i>et al.</i> , 2025
Biochar seed coating experiment (Hong Kong, China)	Native species	Improved survival vs uncoated seeds	Reduced predation and improved establishment	Biochar-based coatings improve seed survival in degraded environments	Biochar improves nutrient retention and microbial activity	Nwankwo <i>et al.</i> , 2024
Seed ball formulation research (New Zealand)	Clay-organic matter mixtures	Native plant species	Improved water absorption capacity	Improved structural stability of seed balls	Composition of seed ball affects moisture absorption and germination success	Lord <i>et al.</i> , 2025
Mangrove restoration research (Indonesia)	UAV seed ball dispersal	Mangrove species	Improved seed survival	Improved restoration feasibility in coastal degraded ecosystems	Seed ball coating protects propagules from abiotic stress during aerial seeding	Arifanti <i>et al.</i> , 2022
Tikak Colliery, Margherita (Assam, India)	Coal mine overburden dump restoration through seed balls	9 native species including <i>Crotalaria striata</i> , <i>Mimosa pudica</i> , <i>Indigofera tinctoria</i> , <i>Pongamia pinnata</i>	Germination of leguminous species was 20–35% and survival was 50–60%; soil physicochemical properties improved over time; 26 naturally colonizing species were recorded after 3 years, indicating accelerated succession.	Potential for Coal mine overburden dump	Shows that seed balls can establish early, improve soil condition, and trigger succession on severely degraded substrates;	Hazarika <i>et al.</i> , 2022 & 2023

5. Getting It Right: Design Principles for Practitioners

Seed balls are not infallible, and treating them as a symbolic gesture rather than a designed intervention is the most common way to waste the effort. The following principles reflect what the evidence actually supports.

- **Match species to site with care.** Some species like *Tectona grandis* (teak) and *Butea monosperma* (flame of the forest), have dormancy requirements that a basic clay ball cannot address. Know which species need scarification, soaking, or cold treatment before inclusion in the mix.

- **Time the broadcast to rain, not the calendar** Broadcasting two weeks before the first monsoon shower means sitting through predation and heat without the moisture trigger. Broadcast at or just after the onset of reliable rain.

- **Invest in post-germination protection.** The weakest link in most seed ball campaigns is what happens in months two through five. Fencing a broadcast area, organising a single round of weed removal, and protecting against grazing through community agreements has been shown to double or triple effective seedling survival.

- **Avoid ecologically risky species.** *Prosopis juliflora*, widely used in arid zone planting, is an ecological risk in most Indian landscapes due to its invasive behaviour. Seed selection must go through basic ecological screening, particularly in wildlife corridors or areas near water bodies.

- **Build in monitoring.** A monitoring transect, five fixed 10×10m plots per broadcast area, checked at 30, 90, and 180 days post-broadcast, costs very little and provides the data needed to improve subsequent seasons and to demonstrate outcomes to programme funders.

6. Integrating Seed Balls into Watershed Programmes

The most productive framing for seed balls is not as a standalone afforestation campaign but as one tool in a watershed restoration toolkit- deployed strategically alongside structures, grassland management, and livelihood activities. In a ridge-to-valley watershed treatment sequence, seed ball broadcast on upper slopes and ridge areas makes particular sense: these are often the most degraded, the most inaccessible for conventional planting,

and the areas where early canopy establishment has the greatest impact on reducing runoff velocity and sediment delivery to lower catchment areas. MGNREGA now named as Viksit Bharat-Guarantee for Rozgar and Ajeevika Mission (Gramin) provides a ready vehicle: seed ball production by SHG members as a paid activity, broadcast as part of a monsoon-season workplan, with weed clearing and monitoring in subsequent months. States like Rajasthan and Madhya Pradesh have the policy architecture to do this at district scale. The Green India Mission and CAMPA funds both allow for expenditure on such activities where this is built into district action plans. Drone-based aerial seed dispersal is emerging as a promising tool for ecological restoration, enabling rapid treatment of steep, rocky, degraded, and otherwise inaccessible landscapes that are difficult to reach through conventional ground-based planting programmes. Successful pilot demonstrations in India and other countries have highlighted its potential for large-scale afforestation and landscape restoration. As drone operation costs fall, this becomes increasingly viable even at district programme scale.

Conclusions: Seed Balls — A Friendly Hand to Nature's Own Forestry

Masanobu Fukuoka's original insight was not about seeds or clay. It was about the arrogance of assuming that large-scale mechanical intervention is always superior to working with the conditions nature provides. A seed ball asks almost nothing of the landscape it enters, no pit, no water, no tending, and in return asks only for rain. In a degraded watershed, where years of over-extraction have left the land thin-skinned and fragile, that kind of gentle, distributed, patient intervention may be exactly what the scale of the problem requires. Not instead of structures and bunding and community governance, but alongside them, covering the slopes and ridges and ravines that no planting drive can reach in numbers. Thrown across a hillside by children, distributed by drones across inaccessible terrain, or rolled out by SHG members on a G-RAM-G workday, seed balls carry a straightforward proposition: give a seed a fighting chance, get out of its way, and let the rain decide. Forests do not wait for pit-planting season. Given half a chance, a seed, some moisture, and a season without disturbance, they find their own way back.

The seed ball technique is, at its core, an attempt to give nature that half a chance in landscapes where degradation has tipped the odds too far against natural regeneration.

What makes it genuinely valuable for watershed restoration is not its simplicity alone, but its alignment with how dryland ecosystems actually function. episodically, opportunistically, and at scales no planting programme can fully replicate by hand. Broadcast across a ridge with the onset of monsoon, a few thousand seed balls ask almost nothing of the land and return, quietly, something that conventional restoration struggles to deliver: distributed, self-sustaining vegetation

across the full watershed slope.

The technique is not a substitute for sound watershed management- for structures, for community governance, for soil and water conservation works. But it is a low-cost, community-powered complement that can reach the slopes, gullies, and ridge lines that most programmes leave behind. Adopted thoughtfully, with the right species, timed to the rains, and followed through with basic protection, seed balls offer watershed practitioners a tool that is as close to working with nature as modern restoration science allows.

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Impact of Soil Erosion on Environment and its Mitigation Strategy

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Abstract

The depletion of topsoil through erosion poses a critical threat to the long-term sustainability of ecosystems in contrast, the soil erosion plays an important role in controlling soil carbon dynamics and greenhouse gas emission. By disrupting soil aggregates and redistributing carbon-rich sediments, erosion exposes protected soil organic carbon to mineralisation and alters land-atmosphere CO₂ exchange. But acceleration of soil erosion through water and wind involves preferential removal of soil nutrients along with sediments (silt and clay particles) causing declines in soil fertility, crop productivity, and environmental quality. In India, massive amount of soil and carbon mobilization due to erosion poses a major challenge to sustainable agriculture and climate change mitigation. The present study hypothesises the current evidence on erosion-carbon interactions and highlights effective mitigation strategies. Conservation and regenerative agriculture practices reduce runoff, improve soil structure, and enhance in-situ carbon retention. The horticulture and agroforestry systems are particularly effective, reducing soil loss while increasing carbon sequestration in biomass and soils. Overall, integrating soil and water conservation with agroforestry-based land-use systems can transform erosion-prone landscapes into long-term carbon sinks.

1. Introduction

Soil erosion is a key driver of land and atmospheric interactions, significantly influencing greenhouse gas emissions and climate change by redistributing and destabilising soil carbon and nitrogen pools and promoting the release of carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) from degraded landscapes. Soil erosion by wind and water, followed by desertification, is severe in

semiarid and sub-humid regions (Lal, 2001). Out of the total land degraded globally, water erosion contributes to 1100 mha and wind erosion contributes to 550 mha (Oldeman *et al.*, 1991). According to another assessment (Sharda and Ojasvi, 2016), India experiences a gross erosion rate of 15.59 t ha⁻¹ yr⁻¹, with about 23% of eroded material reaching the oceans, 34% trapped in reservoirs, and roughly 43% redeposited within terrestrial environments. By redistributing soil materials across landscapes, erosion influences the directional allocation of soil carbon stocks and interferes with the net transfer of carbon between soils and the atmosphere as CO₂ (Quine and Van Oost, 2007). Among the global C pools, the oceanic pool is 38000 petagrams (Pg) C, geologic pool (fossil fuel) is 5000 Pg C, soil C pool (soil organic carbon component up to 2m depth is 2450 Pg and soil inorganic carbon component up to 1 m depth is 750 Pg) is 3200 Pg C, atmospheric C pool is 760 Pg C, biotic C pool is 560 Pg C (Batjes, 1996; Schlesinger, 1997; Lal, 2001). The soil C pool is around 4.2 times the atmospheric pool. Water erosion redistributes soil organic carbon across landscapes and influences CO₂ fluxes between terrestrial systems and the atmosphere (Yue *et al.*, 2016). Further aggregate disruption releases protected soil carbon to environmental and microbial processes, accelerating mineralisation (Lal, 2001). There are several opinions towards soil erosion as a source of atmospheric CO₂ due to mineralisation of soil organic matter or as a sink due to deep burial of soil organic matter-loaded sediments during agricultural practices (Kuhn *et al.*, 2009; Yue *et al.*, 2016). Sedimentologists propose that soil erosion may act as a net carbon sink, as substantial amounts of erosion-derived carbon, estimated at 0.6-1.5 Gt C yr⁻¹ can be preserved through sediment deposition and burial. From a soil science and agronomic perspective, erosion-driven disturbance increases mineralisation rates, leading to atmospheric carbon emissions.

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estimated at up to 1 Gt C yr⁻¹

By breaking down soil aggregates, erosion reduces the physical protection of soil carbon, accelerates its decomposition, and ultimately contributes to net CO₂ emissions (Yue *et al.*, 2016). Erosion assessments using Caesium-137 data from ten European and U.S. catchments indicate that contemporary agricultural erosion does not significantly influence atmospheric carbon budgets (Van Oost *et al.*, 2007). Further, a study by Van Oost *et al.*, 2007, observed the soil erosion from world's agricultural landscapes as global sink of 0.12 Pg of carbon yr⁻¹. Among the various techniques for historic soil erosion assessment, tracking the radioactive fallout Cesium-137 is one of them which was generated as result of nuclear weapon testing during mid-1940s to early 1970s (Higgitt, 1995; Lal, 2001). Enhanced erosion by water and wind redistributes carbon-enriched sediments and strongly affects the global carbon cycle as the aggregate breakdown destabilizes soil carbon pools and promotes degradation, leading to emissions of green house gases (GHG) CO₂, CH₄, and N₂O (Lal, 2021). In the present study, there is limited integration between soil erosion and GHG emissions with erosion act as a carbon source or sink. Several studies have been discussed only on short-term and plot-scale, lacking landscape-level and long-term data. According to Novara *et al.*, 2016, erosional redistribution of soil sediments under Mediterranean climates substantially accelerates soil organic carbon mineralisation, with an increase of about 43%. Breakdown of aggregates, high enrichment ratio, transportation of labile carbon, long distance to deposition, severe degradation of eroded soil leads to erosion as a source of carbon emission (Lal, 2021). Estimates indicate that water-induced erosion now mobilizes substantially more sediment worldwide than in the pre-human era, increasing from 14.0 to 36.6 Gt yr⁻¹ when reservoir trapping is not considered '. According to the national scale soil erosion in India, annually mobilizes approximately 4.87 Pg of soil along with 115.36 Tg of C, leading to atmospheric emissions of about 34.61 Tg C.

The purpose of this review is to provide a comprehensive knowledge of soil erosion affecting the soil properties and to evaluate its contribution to GHG emissions. It also focuses on soil nutrient

status and environmental conditions. In addition, this paper aims to examine a range of soil conservation and management practices that can effectively limit erosion, enhance soil functionality and lower GHG emissions, ultimately contributing to sustainable land use and climate change mitigation efforts.

1.1 Impact of Soil Erosion on Soil Nutrient Status

Soil loss-driven land degradation is a major problem worldwide. Loss of soil not only leads to loss of soil particles but also soil organic carbon and other nutrients associated with it. In the process, the top fertile soil gets eroded, leading to a severe decline in crop yield and deterioration of environmental quality. As per the literature, the soil loss varies from 4.71 to 20.8 Mg ha⁻¹ yr⁻¹ in a range of land slope of 2 to 40% (Table 1). In addition to slope, soil loss also varies with different crops. Among the most studied soil nutrients (soil organic carbon, available N, P and K), the highest eroded one is soil organic carbon, which erodes in a range of 106 to 670 Mg ha⁻¹ yr⁻¹ and the least eroded one is available P. The following table summarizes the nutrient loss due to soil erosion under different land slope and crops.

1.2 Impact of Soil Erosion on Environment

Soil is a critical natural resource that sustains essential ecosystem services and underpins progress toward the Sustainable Development Goals (SDGs). Its conservation is imperative in the Indian context to support the vision of a developed India by 2047 and, globally, to ensure sustainable agri-food systems. Healthy soils are fundamental to food and nutritional security and play a key role in mitigating undernourishment. However, in recent years, soil resources have experienced escalating anthropogenic pressures, leading to unprecedented and largely uncontrolled soil erosion. Soil erosion occurs primarily in two forms: water erosion, which is predominant in high rainfall regions, and wind erosion, which is common in arid and semi-arid landscape characterized by high wind velocities. The high kinetic energy of rainfall and the erosive force of strong winds are the key drivers of topsoil detachment and transport. This process induces significant physical, chemical, and biological

alterations in soil properties, thereby degrading soil quality and adversely affecting environmental quality through the continuous soil-atmosphere

continuum. In this section, we tabulate the effects of soil erosion on soil properties and their associated environmental impacts (Table 2).

TABLE 1 Nutrient loss as affected by soil loss under different land slope and crops

Location of study	Land slope (%)	Crop	Impact on soil loss and loss of soil nutrient	Reference
Koraput, Odisha, India	4, 8 and 12 %	Ragi and aromatic grass species	On an average sediment yield was 4.71, 5.94 and 7.07 Mg ha ⁻¹ yr ⁻¹ in 4, 8 and 12% slope, respectively. Loss of organic carbon: 106.2, 119.9 and 130.5 kg ha ⁻¹ yr ⁻¹ in 4, 8 and 12% slope, respectively. Loss of N: 5.71, 6.59 and 7.15 kg ha ⁻¹ yr ⁻¹ in 4, 8 and 12% slope, respectively. Loss of P: 0.43, 0.50 and 0.62 kg ha ⁻¹ yr ⁻¹ in 4, 8 and 12 % slope, respectively. Loss of K: 3.29, 3.76 and 4.39 kg ha ⁻¹ yr ⁻¹ in 4, 8 and 12 % slope, respectively.	Adhikary <i>et al.</i> , 2018
Koraput, Odisha, India	5% and 10 %	Paddy	Soil loss: 10.2 and 12.5 Mg ha ⁻¹ yr ⁻¹ in 5 and 10% slope, respectively. Loss of organic carbon: 143.6 and 167.9 kg ha ⁻¹ yr ⁻¹ in 5 and 10% slope, respectively. Loss of N: 8.1 and 9.9 kg ha ⁻¹ yr ⁻¹ in 5 and 10% slope, respectively. Loss of P: 0.55 and 0.74 kg ha ⁻¹ yr ⁻¹ in 5 and 10% slope, respectively. Loss of K: 4.5 and 5.5 kg ha ⁻¹ yr ⁻¹ in 5 and 10% slope, respectively.	Adhikary <i>et al.</i> , 2017
Koraput, Odisha, India	2-5%	Ragi	Soil loss, Loss of organic carbon, available N, available P and available K were found to be 9.71 Mg ha ⁻¹ yr ⁻¹ , 132.24, 7.35, 0.52 and 4.10 kg ha ⁻¹ yr ⁻¹ .	Lenka <i>et al.</i> , 2012
Umiam, Meghalaya, India	40%	Maize	Soil loss, Loss of organic carbon, available N, available P and available K were found to be 20.8 Mg ha ⁻¹ yr ⁻¹ , 670, 6.85, 2.14 and 7.91 kg ha ⁻¹ yr ⁻¹ .	Lenka <i>et al.</i> , 2017
Dehradun, Uttarakhand, India	9%	Fallow and turmeric	Under fallow condition: Loss of soil, available N, available P and available K were found to be 16.1 Mg ha ⁻¹ yr ⁻¹ , 24.4, 1.05 and 34.4 kg ha ⁻¹ yr ⁻¹ . Under turmeric crop: Loss of soil, available N, available P and available K were found to be 10.0 Mg ha ⁻¹ yr ⁻¹ (approx.), 12.6, 0.73 and 15.3 kg ha ⁻¹ yr ⁻¹ .	Kaushal <i>et al.</i> , 2024

TABLE 2 Impact of soil erosion on environmental factors

Soil parameters	Evidence (Location)	Possible environmental impact
Nutrient availability	4.46% decline in soil fertility from the 1990s–2010s in Northeast China (Xiong <i>et al.</i> , 2024)	Impaired nutrient cycling and reduced soil productivity.
Phenol oxidase activity	Increased enzyme activity (~20–150%) in eroded soils in China (Wei <i>et al.</i> , 2024)	Accelerated SOC decomposition and higher carbon emissions.
Nutrient loss	In the Taihu Lake Basin, annual river inflow delivers approximately 27,234 t yr ⁻¹ of total nitrogen (TN) and 7,032 t yr ⁻¹ of total phosphorus (TP) to the lake, largely from watershed soil erosion and agricultural non-point source pollution. (Lin <i>et al.</i> , 2016)	Eutrophication of aquatic ecosystems.
Soil loss	Soil erosion exports approximately ≈2 kg P ha ⁻¹ yr ⁻¹ in Europe (4–19 kg globally) (Gupta <i>et al.</i> , 2025)	Algal blooms and reduced dissolved oxygen.
Aggregate stability	Soil erosion reduced aggregate stability (MWD) from 1.72 mm to 0.88 mm (~49% decline) in Mollisols, Heilongjiang, China, indicating substantial structural degradation of soil aggregates. (Yang <i>et al.</i> , 2024)	Increased carbon loss and GHG emissions.
Wind erosion (PM _{2.5} , PM ₁₀)	Soil dust emissions contribute 27–40% of atmospheric PM _{2.5} /PM ₁₀ in Ningxia Hui Autonomous Region, China (Tian <i>et al.</i> , 2021)	Air pollution and human health risks.
Wind-derived dust	Wind erosion generated 9.54–40.73 t ha ⁻¹ yr ⁻¹ of soil loss (mean 22.02 t ha ⁻¹ yr ⁻¹) in Arizona, USA (Wu <i>et al.</i> , 2021)	Hazardous air quality and respiratory risks.
Heavy metal release	Wind erosion released Cd: 1.28×10^{-8} – 6.65×10^{-7} g m ⁻² s ⁻¹ , Pb: 5.65×10^{-7} – 9.40×10^{-5} g m ⁻² s ⁻¹ , and Zn: 3.20×10^{-4} – 2.07×10^{-2} g m ⁻² s ⁻¹ into PM _{2.5} –PM ₁₀ fractions in Weining County, China, indicating substantial atmospheric heavy-metal exposure risk. (Zhang <i>et al.</i> , 2025)	Elevated health risks via inhalation and contamination.

2. Mitigation Strategy of Erosion

The study carried out for Indian conditions demonstrated that achievable soil and water conservation technologies in erosion-impacted regions of India may sequester between 19 and 27 Tg C yr⁻¹, potentially mitigating around one-quarter (24.5%) of greenhouse gas emissions from India's agricultural soils. Soil erosion remains one of the most serious challenges to sustainable agriculture in India, particularly in rainfed, hilly, and degraded regions. Several agronomical, horticulture and agroforestry measures as discussed below can be implemented for

successful control of soil erosion.

2.1 Agronomic Measures for Soil Erosion Control

Agronomic measures are cost-effective, farmer-friendly practices primarily adopted on lands with slopes of less than 2 %. The literature consistently demonstrates their effectiveness in reducing soil erosion caused by both water and wind by improving soil cover, enhancing soil structure, and regulating surface runoff. The following agronomic measures are suitable for preventing soil erosion.

2.1.1 Conservation Agriculture (CA)

The CA is based on three core principles: minimal soil disturbance, permanent soil cover, and diversified crop rotation (Hobbs *et al.*, 2008). Reduced soil disturbance limits soil exposure to erosive forces, while permanent soil cover through crop residues or dense crop canopies attenuates raindrop impact and reduces wind velocity at the soil surface. Crop rotation, particularly with legumes, enhances soil organic carbon and aggregate stability, thereby increasing resistance to soil particle detachment by rainfall and runoff.

2.1.2 Regenerative Agriculture (RA)

The RA emphasizes the restoration of soil health through environmentally sound agronomic practices (Schreefel *et al.*, 2020). Increased organic matter inputs improve soil organic carbon, soil structure, and water-holding capacity, leading to enhanced infiltration, reduced runoff, and lower erosion risk.

2.1.3 Mulching

Mulching, using live or dead plant materials, protects the soil surface by dissipating raindrop energy and reducing wind action. It also slows runoff, minimizes soil detachment, and significantly reduces soil loss.

2.1.4 Contour Cropping

Contour cropping involves cultivating crops along contour lines across the slope, thereby interrupting downslope water flow. This practice reduces runoff velocity, enhances infiltration, and limits soil erosion through the stabilizing effect of crop root systems.

2.1.5 Intercropping

Intercropping is the simultaneous cultivation of two or more crops in a defined spatial arrangement. Intercrops provide continuous soil cover, protect the soil from erosive forces, improve resource use efficiency, and enhance system resilience while offering additional economic benefits.

2.1.6 Vegetative Strips on Bunds

Vegetative barriers established on bunds, such as vetiver and perennial grasses, possess deep and dense root systems that stabilize soil, reduce runoff velocity, and enhance soil conservation.

2.1.7 Tied Ridging

Tied ridging creates micro-basins that increase rainwater retention time, promote infiltration, and reduce surface runoff, thereby minimizing soil erosion.

2.1.8 Broad Bed and Furrow (BBF) System

The Broad Bed and Furrow system is widely recommended for black soil regions of India with low infiltration capacity. Raised broad beds facilitate crop growth, while furrows improve drainage and water infiltration, collectively reducing runoff and soil erosion.

2.2 Horticulture and Agroforestry Measures for Controlling Soil Erosion

Horticultural and agroforestry measures are recognized as one of the effective strategies for controlling soil erosion, reducing carbon dioxide (CO₂) emissions, and enhancing carbon sequestration, particularly in tree-based horti-agroforestry models. These systems integrate fruit trees and multipurpose woody species with horticultural or annual crops, creating permanent canopy cover and extensive root networks that significantly reduce soil erosion. Studies from different parts of India have shown that agroforestry and perennial horticultural systems can reduce soil loss by 50-90% compared with conventional annual cropping on sloping lands. Reduced erosion prevents the selective removal of SOC-rich topsoil, thereby lowering erosion-induced CO₂ emissions that arise from accelerated mineralization of displaced organic carbon during transport and deposition processes.

Evidence from long-term research clearly shows that controlling erosion through horticulture and agroforestry has major climate benefits. estimated that the adoption of achievable soil and water conservation practices in erosion-

affected regions of India could sequester between 19 and 27 Tg C per year, which is enough to offset nearly one-quarter (24.5%) of greenhouse gas emissions from agricultural soils in the country. A large share of this mitigation potential comes from perennial systems such as orchards, agroforestry plantations, silvi-horticulture, and boundary tree planting, especially on sloping and marginal lands. Similar conclusions have been drawn by Nair *et al.*, (2010) and Patra *et al.*, (2012), who emphasized that tree-based farming systems store carbon both in woody biomass and in soils while simultaneously reducing land degradation.

Tree-based horti-agroforestry systems also contribute to climate change mitigation by substantially increasing carbon sequestration across multiple carbon pools. Global and regional meta-analyses indicate that agroforestry systems sequester approximately 2-10 t C ha⁻¹ yr⁻¹, equivalent to 7-37 t CO₂ e ha⁻¹ yr⁻¹, depending on climate, species composition, and management intensity. Aboveground woody biomass accounts for a large share of this carbon stock, particularly in fruit trees and timber components, while belowground biomass, litter inputs, and enhanced microbial activity contribute to sustained increases in soil organic carbon.

In addition to direct carbon sequestration, horti-agroforestry systems reduce CO₂ emissions indirectly by improving soil structure, aggregation, and water-holding capacity, which lowers the need for intensive tillage and external inputs such as synthetic fertilizers. Practices such as contour planting, mulching, cover cropping, hedgerows, and shelterbelts slow runoff, trap sediments, and enhance in-situ carbon retention. Reduced sediment transport under agroforestry promotes the physical protection of SOC within soil aggregates, increasing carbon residence time and transforming erosion-prone landscapes from net carbon sources into stable carbon sinks. Consequently, tree-based horti-agroforestry models represent a highly effective land-use option for simultaneous soil conservation, CO₂ emission reduction, and long-term climate change mitigation.

3. Conclusions and Future Prospects

Soil erosion plays a dual role in the climate system

by redistributing soil carbon and influencing greenhouse gas emissions, acting as either a carbon source or sink depending on erosion and deposition processes. Evidence indicates that accelerated erosion, particularly in vulnerable regions, often enhances carbon mineralisation, nutrient loss, and greenhouse gas emissions, thereby exacerbating land degradation and climate change. However, effective soil and water conservation, conservation agriculture, and tree-based horti-agroforestry systems can substantially reduce erosion, stabilise soil carbon, and convert degraded landscapes into long-term carbon sinks, highlighting erosion control as a key climate mitigation strategy. The future research will be focused on integrated studies of soil erosion, carbon dynamics and climate change, which will need to be evaluated and optimised through nature-based and climate-smart practices. Further, application of geospatial tools will be used to expand for accurate monitoring, prediction and management of soil erosion. Along with these, it will also emphasise the role of policy makers and institutional support in promoting sustainable soil management and identify the erosion-prone landscapes into resilient systems, which contribute towards the long-term carbon sequestration and climate change mitigation.

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Climate-Smart Conservation Agriculture: Linking Soil Moisture Retention to Soil Carbon Sequestration

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Abstract

Agricultural production systems around the world are facing unprecedented pressure due to changes in rainfall distribution caused by climate change, rising temperatures, and increasing frequency of drought events. In India, where a significant portion of agriculture is rainfed, the decline in soil moisture availability after receding of the rainy season and depletion of soil organic carbon (SOC) have become critical constraints to sustainable crop production. Conservation Agriculture (CA) has gained global recognition as a climate-smart and resource-efficient production paradigm. It can simultaneously enhance soil moisture retention, SOC sequestration, and reduce greenhouse gas emissions. This article critically synthesizes contemporary scientific evidence on conservation agriculture approaches, with a special emphasis on retaining residue, reducing soil evaporation losses, and building up soil organic carbon. Long-term experiments and meta-analysis suggest that CA-based systems can increase soil moisture availability by 15-30% while reducing water losses from evaporation by 20-40%. They sequestered carbon at rates ranging from 0.3 to 1.0 Mg C ha⁻¹ yr⁻¹, depending on soil type, climate, and management intensity. The article further explains CA's role in enhancing water-use efficiency, yield stability, and ecosystem resilience by contextualizing it in modern climate change mitigation and adaptation frameworks. Adoption challenges, policy implications, and future research needs are also discussed to facilitate the large-scale implementation of conservation agriculture in climate-vulnerable agro-ecosystems.

1. Introduction

Agriculture is facing a growing number of complex and interconnected challenges such as climate change, land degradation, and declining natural resource use efficiency. Many agro-ecosystems are experiencing an increase in soil moisture stress and a depletion of soil organic carbon due to rising global temperatures, erratic rainfall patterns, prolonged dry spells, and extreme weather events. The rainfed nature of 60% of the net cultivated area in India makes agricultural productivity highly sensitive to changes in soil moisture availability. Conventional intensive tillage systems, residue removal or burning, and excessive dependence on synthetic inputs have led to an exacerbation of soil structural degradation, decreased water-holding capacity, and enhanced carbon releases to the atmosphere. Conservation Agriculture (CA) has emerged as an alternative to conventional farming systems that is both scientifically sound and climate-resilient. Minimum soil disturbance, permanent soil cover through crop residues or cover crops, and diversified cropping systems are the three interrelated principles that define CA (Das *et al.*, 2019; Rangappa *et al.*, 2024). The combination of these principles results in soil health restoration, efficient water use, and long-term carbon sequestration. The central role of residue retention is to regulate soil moisture dynamics and enhance soil organic carbon stocks by reducing evaporation, improving infiltration, moderating soil temperature, and stimulating biological activity (Ansari *et al.*, 2022).

2. Methodology for literature synthesis

This article is formulated by analyzing and combining peer-reviewed scientific literature regarding conservation agriculture, residue retention, soil moisture conservation, and soil organic carbon sequestration in climate change scenarios. Scientific databases were utilized to

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collect relevant research articles, review papers, and meta-analyses that were published between 2010 and 2025. These are “Google Scholar”, “Scopus”, “Web of Science”, “Science Direct”, and “Springer Link” using keywords such as “conservation agriculture”, “residue retention”, “soil moisture”, “soil organic carbon sequestration”, “climate-smart agriculture”, and “water-use efficiency”. Long-term field experiments, meta-analytical studies, and region-specific studies from India and other climate-vulnerable agro-ecosystems received the highest priority. Critical analysis and synthesizing of studies reporting quantitative effects on soil moisture retention, evaporation reduction, water-use efficiency, yield stability, and SOC sequestration was conducted. Thematically organized information was used to assess the impact of conservation agriculture on climate change mitigation and adaptation frameworks.

3. Conservation Agriculture and Climate Change: Conceptual Framework

Conservation agriculture (CA) reduces carbon dioxide emissions by minimizing soil disturbance and reducing the oxidation of soil organic matter and fossil fuel consumption associated with repeated tillage operations. The soil surface is protected from erosive forces, temperature extremes are buffered, and direct evaporative losses are reduced by maintaining a permanent soil cover through residue retention (Das *et al.*, 2019; Rangappa *et al.*, 2024). The resilience of the system can be enhanced by crop diversification by improving nutrient cycling, breaking pest and disease cycles, and increasing below-ground carbon inputs. Three major pathways are used by conservation agriculture to reduce the negative impact of climate change. The first thing it enhances is adaptability by enhancing soil moisture storage, infiltration capacity, and drought tolerance. Secondly, it aids in mitigation by boosting soil carbon sequestration and decreasing greenhouse gas emissions caused by tillage and residue burning. The third step in building resilience involves enhancing soil structure, biological activity, and buffering capacity against climatic shocks. In maintaining soil moisture and SOC, CA systems have been consistently demonstrated by long-term studies across tropical, subtropical, and temperate regions to be superior

to conventional tillage systems, particularly in rainfed and semi-arid environments (Lal, 2020; Sharma *et al.*, 2024; Kabato *et al.*, 2025). (Fig. 1) displays a few conservation agricultural practices undertaken in the hill agriculture ecosystem of the Northeastern Himalayan region of India.

4. Residue Retention: Foundation of Soil Moisture Conservation

4.1 Magnitude and Importance of Residue Retention

Residue retention involves leaving crop residues such as cereal straw, maize stover, and legume haulms on the soil surface after harvest, either partially (30–50% soil cover) or fully. Many developing countries, such as India, commonly remove crop residues for fodder, fuel, or burn them *in situ*, leading to a significant loss of organic matter and soil cover. Scientific evidence indicates that even retaining 30–40% of crop residues can significantly alter soil water and carbon dynamics. The physical barrier created by residue mulch serves as a barrier between the soil and atmosphere, intercepting raindrop impact, reducing surface sealing, and enhancing water infiltration. Studies have consistently reported a 15–30% higher soil moisture content in residue-retained systems compared to residue-removed or conventionally tilled systems (Khan *et al.*, 2021; Nunes *et al.*, 2021; Sharma *et al.*, 2024). Increased soil aggregation and macro-porosity under residue-covered soils have resulted in improved infiltration rates of 20–50% (Cherubin *et al.*, 2018; Lal, 2020).

4.2 Residue Retention and Rainfall Use Efficiency

By reducing runoff and promoting uniform water distribution within the soil profile, residue retention improves rainwater use efficiency. Overland flow is slowed down by surface residues, which allows water to infiltrate more, especially in sloping and erosion-prone landscapes. Preventing the loss of nutrient-rich topsoil, which is vital for sustaining long-term productivity under climate variability, is achieved by reducing runoff and erosion, which also conserves water (Lal, 2020; Choudhury *et al.*, 2022; Xing & Wang, 2024).

FIGURE 1 Conservation Agriculture: Zero and minimum tillage with residue retention and mulching in the hill agriculture of Northeastern Himalayan region of India

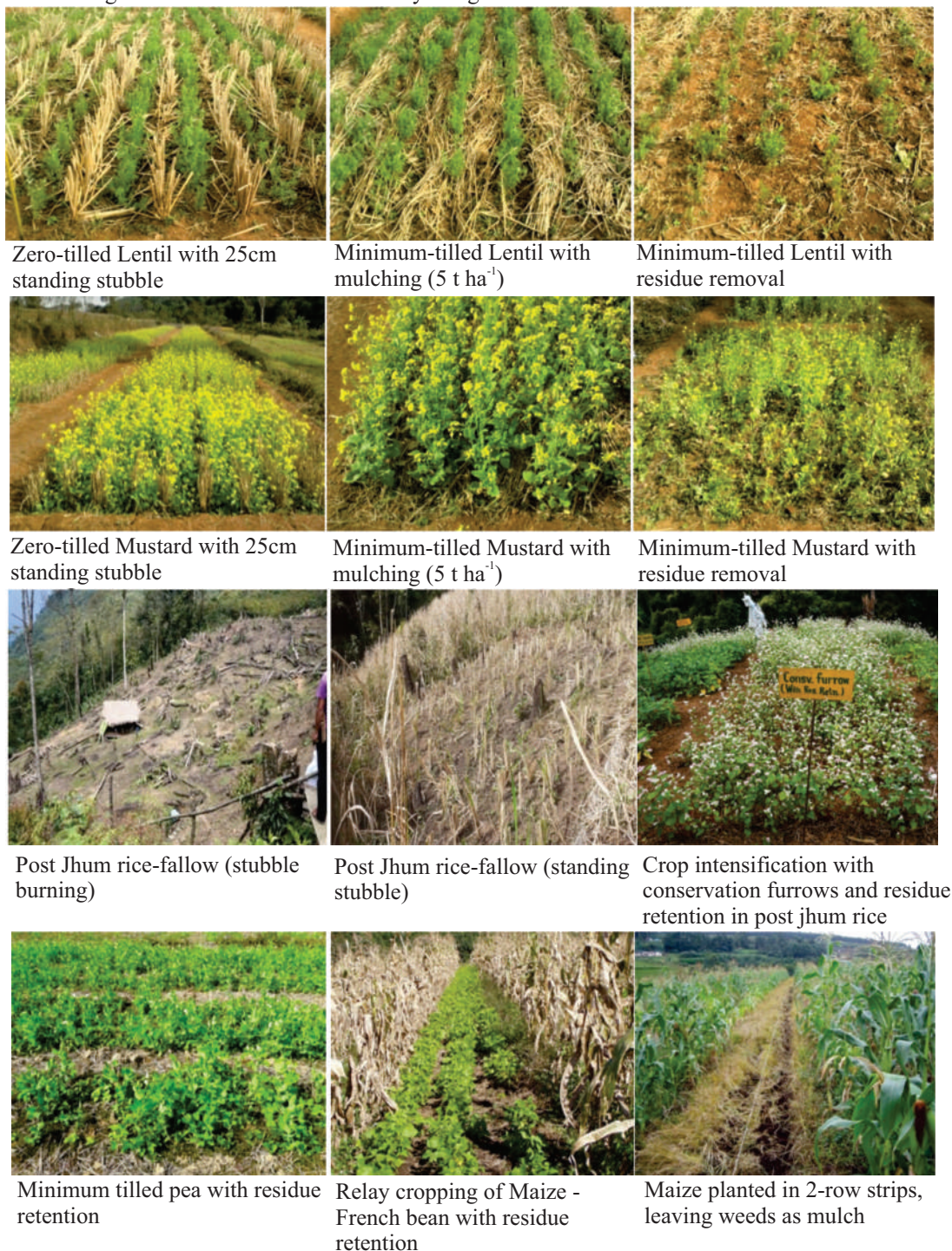


Photo courtesy: ICAR Research Complex for NEH Region, Umiam, Meghalaya

5. Reduced Evaporation Losses under Conservation Agriculture

5.1 Mechanisms of Evaporation Reduction

Conventional agricultural systems lose water through soil evaporation, which is a major non-productive pathway, particularly during fallow periods and early crop growth stages. Conservation agriculture significantly reduces evaporation through the continuous soil cover provided by crop residues (Das *et al.*, 2019). The soil surface is shaded, wind speed decreases at the soil-atmosphere interface, and water flow to the surface is disrupted by residual mulch. Studies suggest that residue mulching can decrease soil evaporation by up to 20%, depending on the thickness of the mulch, the type of residue, the soil texture, and the current climate conditions (Lal, 2020; Nunes *et al.*, 2021; Li *et al.*, 2024). The reductions are especially noticeable in semi-arid and sub-humid regions where there is a high demand for evaporation.

5.2 Soil Temperature Moderation and Microclimate Regulation

By reducing diurnal and seasonal fluctuations, residue cover plays a crucial role in moderating soil temperature. Lowering maximum soil temperatures during hot periods leads to decreased evaporative demand and thermal stress for soil biota, but higher minimum temperatures during cooler periods are favorable for microbial activity and nutrient mineralization. Moderation of soil temperature is becoming more important in climate change scenarios that involve rising mean temperatures and more frequent heat-waves.

5.3 Implications for Water-Use Efficiency and Yield Stability

Conservation agriculture enhances water-use efficiency (WUE) by conserving soil moisture and decreasing evaporation losses. The use of residue-retained zero-tillage systems has shown long-term experiments to improve WUE by 10 to 25% compared to conventional tillage (Cherubin *et al.*, 2018; Sharma *et al.*, 2024) (Table 1). In moisture-limited environments, yield stability is directly impacted by enhanced WUE and cropping systems

vulnerability to intermittent drought stress is reduced.

6. Soil Organic Carbon Build-up under Conservation Agriculture

6.1 Processes Governing Carbon Sequestration

The balance between carbon inputs and losses determines the accumulation of organic carbon in soil in conservation agriculture. Carbon inputs are increased by residue retention through above-ground biomass and root residues, and carbon losses are reduced by limiting oxidation of organic matter with minimal soil disturbance (Rangappa *et al.*, 2024). Furthermore, carbon from residues is gradually incorporated into soil aggregates, where it is shielded from microbial decomposition.

6.2 Magnitude and Distribution of SOC Sequestration

Long-term field studies and meta-analyses indicate that SOC sequestration rates of 0.3–1.0 Mg C ha⁻¹ yr⁻¹ are observed under conservation agriculture systems, with the highest accumulation occurring in the surface soil layers (0–15 cm) (Lal, 2020; Nunes *et al.*, 2021; Li *et al.*, 2024). In Indian agro-ecosystems, CA practices have been reported to increase SOC stocks by 10–25% within a decade, particularly in maize- and wheat-based cropping systems (Sharma *et al.*, 2024; Kabato *et al.*, 2025) (Table 1).

6.3 Role of Soil Biology in Carbon Stabilization

Residue retention stimulates carbon retention in microbial biomass, enzymatic activity, and fungal dominance, all of which play a crucial role in carbon stabilization (Ansari *et al.*, 2022; Sangma *et al.*, 2025). The vertical movement of organic carbon is facilitated by increased earthworm activity and root proliferation, which enhance its incorporation into deeper soil layers and improve long-term sequestration potential. Soil structure is strengthened, porosity is improved, and the positive feedback between soil moisture retention and carbon storage is reinforced by these biological processes.

TABLE 1 How residue management affects soil hydraulic properties, carbon, and water use efficiency

Experimental Treatments	Soil Moisture / Evaporation Impact	Water-Use Efficiency / Yield Impact	SOC / Carbon Impact	Reference
CT + residue removal vs. ZT + 50% residue retention	Soil moisture increased by 18–26% under residue retention compared to CT	WUE improved by 14–22%; higher yield stability under dry spells	SOC stock increased by 0.42 Mg C ha ⁻¹ yr ⁻¹	Das <i>et al.</i> , 2019
ZT without residue vs. ZT + full rice residue mulch	Surface soil moisture (0–15 cm) higher by 23–30%	Grain yield increased by 8–15% under moisture stress	SOC increased by 12–20% after 8–10 years	Sharma <i>et al.</i> , 2024
Residue removal (0%) vs. partial (30%) vs. full (≥60%) residue retention	Soil evaporation reduced by 20–35% with ≥60% residue cover	WUE increased by 10–18% in maize systems	SOC sequestration rate: 0.3–0.6 Mg C ha ⁻¹ yr ⁻¹	Nunes <i>et al.</i> , 2021
Conventional tillage vs. CA with residue mulch	Infiltration rate increased by 35–50%, reducing runoff losses	Yield variability reduced by ~20% across seasons	SOC accumulation of 0.5–0.8 Mg C ha ⁻¹ yr ⁻¹	Cherubin <i>et al.</i> , 2018
Straw removal vs. straw returning (mulch)	Soil evaporation reduced by 25–40%; cooler soil surface	Improved WUE and crop biomass by 12–25%	SOC increased by 15–28% in surface soil	Li <i>et al.</i> , 2024
Residue incorporation + minimal tillage vs. residue removal	Soil moisture retention improved by 17–24%	Better crop resilience under terminal drought	SOC stock improved by 10–18% in 5–7 years	Ansari <i>et al.</i> , 2022
Conventional tillage vs. CA with residue retention	Mean soil moisture increase of 15–30%	WUE improvement of 10–25%	SOC sequestration: 0.3–1.0 Mg C ha ⁻¹ yr ⁻¹	Lal, 2020
Residue-retained CA vs. CT systems	Reduced evaporative losses via soil temperature moderation	Improved physiological stress tolerance of succeeding crops	Enhanced microbial biomass C and aggregate-associated SOC	Rangappa <i>et al.</i> , 2024

7. Residue Management and System Productivity under Conservation Agriculture

The experimental evidence summarized in (Table 2) clearly demonstrates that residue management is a key driver of system productivity across diverse agro-ecological regions and cropping systems. Retention or incorporation of crop resid-

ues under con-servation agriculture consistently enhanced overall system productivity by 8–25% compared to conventional systems where residues were removed or burnt. These gains were observed in major cereal-based systems such as rice–wheat, maize–wheat–mungbean, and cereal–legume rotations, as well as in diversified hill farming systems of the Eastern Himalayas. The improvement in system productivity is

primarily attributed to better soil moisture conservation, reduced evaporative losses, moderated soil temperature, and enhanced soil organic carbon status, which collectively improve crop growth and yield stability across seasons. Long-term residue retention further contributes to sustained productivity by improving soil structure, nutrient cycling, and biological activity, thereby

reducing yield variability under moisture stress conditions. Overall, residue management emerges as a central component of climate-smart conservation agriculture, enabling higher and more stable system productivity while simultaneously enhancing soil health and resilience to climatic variability.

TABLE 2 Effect of residue management on system productivity

Study / Region	Cropping System	Experimental Treatments	System Productivity / Yield Response	Key Outcome on System Productivity	Reference
Indo-Gangetic Plains, India	Rice–wheat	CT without residue vs. ZT + rice residue retention	System yield increased by 8–15% under ZT + residue retention	Residue retention enhanced productivity of both rice and wheat, improving overall system output	Sharma <i>et al.</i> , 2024
Eastern Himalaya, India	Rice–vegetable systems	Conventional tillage vs. CA with residue retention	Combined system productivity improved by 12–20%	Residue retention improved soil moisture and yield stability across crops	Rangappa <i>et al.</i> , 2024
Semi-arid India	Maize–wheat–mungbean	ZT without residue vs. ZT + crop residue retention	Maize-equivalent yield increased by ~15–18% with residue	Residue retention enhanced total system productivity in cereal–pulse rotation	Lal, 2020
Tropical Brazil	Multiple cropping systems	Conventional tillage vs. CA with surface residue mulch	System productivity increased by 10–22% over conventional systems	Long-term residue mulching stabilized yields and improved productivity	Cherubin <i>et al.</i> , 2018
China (Loess Plateau)	Cereal-based systems	Straw removal vs. straw returning (mulch)	Crop-equivalent yield increased by 12–25% with straw return	Residue return improved biomass production and system productivity	Li <i>et al.</i> , 2024
NE India (acid soils)	Cereal–legume systems	Residue incorporation vs. residue removal	System productivity increased by 10–18% within 5–7 years	Residue inputs enhanced soil fertility and sustained productivity	Ansari <i>et al.</i> , 2022
Global (meta-analysis)	Diverse cropping systems	Conventional tillage vs. CA with residue retention	Mean system productivity gain of 10–20%	Residue retention identified as a key driver of productivity gains	Lal, 2020

Continued on next page

Table 2 continued

Study / Region	Cropping System	Experimental Treatments	System Productivity / Yield Response	Key Outcome on System Productivity	Reference
North-western Himalayan Region, India	Maize–pea–wheat	Conservation tillage with <i>Arundo donax</i> agro-geotextiles (5–10 cm thickness; 0.5–1.0 m vertical interval) vs. conventional practice	Wheat-equivalent yield increased to 12.0–13.6 t ha ⁻¹ yr ⁻¹ with higher profitability under residue-based agro-geotextile systems	Residue recycling (6.0–7.1 t ha ⁻¹), improved soil moisture retention, reduced soil erosion by 80–90%, and SOC build-up (1.16–1.20%) enhanced long-term system productivity	Singh <i>et al.</i> , (2025)
North-western Himalayan Region, India	Conservation-tilled maize on sloping lands	Conservation tillage with <i>Arundo donax</i> agro-geotextiles vs. conservation tillage without agro-geotextiles	Agro-geotextile systems reduced runoff losses and maintained higher soil moisture under extreme rainfall conditions, supporting improved crop sustainability	Runoff reduced by ~29–75% and soil erosion by ~24–94%; AGT systems retained more rainwater and improved resilience of sloping rainfed systems	Singh <i>et al.</i> , (2024)
North-western Himalayan Region, India	Conservation Agriculture (CA) practices in rainfed sloping (2%) arable lands involving maize–wheat and direct-seeded paddy–wheat rotations.	Conservation Agriculture (CA) practices are being evaluated in rainfed sloping (2%) arable lands to evaluate the impacts of tillage and cropping system diversification on residue retention, soil erosion, nutrient losses, yield performance, and soil properties in maize–wheat and direct-seeded paddy–wheat rotations.	Transition from conventional (Maize–Wheat: >10t/ha; Paddy–wheat: <7.2t/ha) to zero tillage reduced overall system productivity. Zero tillage with diversified rotation decreased runoff (35–91%), soil erosion, (52–97%) and nutrient losses. Zero tillage and legume rotations enhanced surface soil SOC (1.35–1.37%) and decreased bulk density to 1.3 Mg/ha. Maize–wheat was superior in nutrient retention, yield stability, and SOC enhancement than paddy–wheat.	Overall, Maize–Wheat demonstrated superior nutrient conservation and yield stability, while Paddy–Wheat provided stronger erosion and residue management benefits. Integrating zero tillage with legume-based diversified cropping and in situ residue management improves soil health, reduces erosion and nutrient loss, and stabilizes yields, demonstrating a viable pathway toward climate-resilient CA in sloping rainfed arable lands.	Singh <i>et al.</i> , (2026)

8. Conservation Agriculture for Climate Change Mitigation

Conservation agriculture is one of the mechanisms that can be utilized to mitigate climate change. Reduced tillage reduces fuel consumption and associated CO₂ emissions, while avoiding residue burning prevents the direct release of CO₂, CH₄, N₂O, and particulate matter into the atmosphere. The long-term carbon sink of enhanced SOC stocks in CA partially offsets emissions from agricultural activities. According to integrated assessments, adopting conservation agriculture on a large scale could reduce approximately 5-10% of greenhouse gas emissions from the agricultural sector, while also improving productivity and resource-use efficiency (Lal, 2020; Xing & Wang, 2024). CA is a method that is both practical and scalable for mitigating climate change in both national and global climate action strategies.

9. Adoption Constraints and Policy Perspectives

Despite strong scientific evidence supporting conservation agriculture, adoption remains constrained by several biophysical and socio-economic factors. Farmers are often deterred from adopting CA practices due to competing uses of crop residues, limited access to appropriate machinery, knowledge gaps, and short-term economic considerations. Accelerating adoption requires policy interventions such as machinery subsidies, residue management incentives, carbon credit mechanisms, and targeted extension programs.

10. Future Research Needs

Long-term assessments of carbon stabilization beyond surface soil layers, integrating conservation agriculture with biochar, cover crops, and precision soil moisture monitoring should be prioritized in future research (Ansari *et al.*, 2022; Das *et al.*, 2023). The current situation necessitates the development of CA packages that are specific to regions for rainfed and hill agro-ecosystems. To scale conservation agriculture in diverse farming contexts, it is crucial to conduct socioeconomic studies that evaluate incentive-based adoption models.

Conclusions

The intertwined challenges of soil moisture stress, soil carbon depletion, and climate change can be addressed with a robust and science-based framework provided by conservation agriculture. The core mechanisms for CA to enhance productivity, resilience, and environmental sustainability are “Residue retention”, reduced evaporation losses, and soil organic carbon build-up. Ensuring long-term food security while contributing to global climate change mitigation efforts can be achieved by mainstreaming conservation agriculture into climate-smart agricultural policies and development programs.

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Napier Grass: A Sustainable Forage and Conservation Solution for Hilly Areas

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1. Introduction

India possesses the world's largest livestock population, yet availability of quality fodder remains a major constraint to livestock productivity. National assessments indicate deficits of approximately 11.2% in green fodder, 23.4% in dry fodder, and 28.9% in concentrate feeds, adversely affecting milk production and animal health (DAHD, 2022; ICAR-IGFRI, 2019). Simultaneously, land degradation has emerged as a serious environmental challenge, with nearly 96.4 million hectares (29.3% of the geographical area) affected by various forms of degradation, particularly water erosion and vegetation loss (ISRO, 2021). These problems are especially acute in hilly and mountainous regions where steep slopes, fragile soils, and intense rainfall accelerate runoff and soil erosion (Dagar *et al.*, 2020). Therefore, perennial forage species capable of simultaneously providing fodder, restoring degraded lands, and enhancing ecosystem services are increasingly important for sustainable rural development. Against this backdrop, Napier grass (*Cenchrus purpureus* (Schumach.) Morrone), formerly known as *Pennisetum purpureum* Schumach.-a high-yielding, fast-growing perennial forage grass-emerges as a climate-resilient and multifunctional resource with immense potential for improving fodder availability and supporting sustainable land use in hilly areas. Napier grass is one such multipurpose perennial grass with exceptional biomass production potential and adaptability across diverse agro-ecological conditions (Heuzé *et al.*, 2017). Owing to its vigorous growth, deep root system, and high biomass accumulation, Napier grass contributes not only to fodder security but also to soil conservation, carbon sequestration, watershed management, and renewable energy production.

In addition to its primary role in fodder production and erosion control, Napier grass also contributes to ecosystem services such as carbon sequestration, biodiversity enhancement, and habitat provision for beneficial organisms. The grass's vigorous vegetative growth captures atmospheric carbon, improves soil organic matter, and enriches degraded soils with biomass inputs. Its ability to thrive with limited external inputs makes it a cost-effective, low-risk option for resource-poor farmers and community-based conservation programs. Moreover, Napier grass is gaining attention for its potential as a bioenergy crop. Its high biomass yield and lignocellulosic content make it suitable for producing biofuels such as biogas, bioethanol, and briquettes. Integrating Napier into bioenergy value chains offers dual benefits of rural energy security and income diversification while reducing dependency on fossil fuels. This aligns well with national and global priorities on clean energy, climate mitigation, and sustainable rural development.

Given its multi-functionality, Napier grass can be a strategic intervention in climate-resilient agriculture (CRA), especially in rainfed, marginal, and hilly zones where both fodder and natural resource degradation are critical issues. Yet, despite its demonstrated benefits, the adoption of Napier grass remains limited due to constraints such as lack of quality planting material, poor extension outreach, and inadequate integration into government programs.

This article explores the diverse roles of Napier grass in hilly agro-ecosystems, emphasizing its contributions to fodder security, soil and water conservation, ecosystem health, and renewable energy. It also discusses key challenges in its adoption and offers actionable policy and programmatic recommendations for scaling its benefits across vulnerable rural landscapes.

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2. Need of Napier Grass in Hills

Hilly and mountainous areas often suffer from:

- Scarce arable land
- Steep slopes prone to erosion
- Low soil fertility and moisture retention
- Seasonal fodder shortages for livestock

Napier grass can grow on marginal and sloping lands, providing multiple benefits beyond green fodder—such as soil stabilization, rainwater retention, biodiversity support, and clean energy feedstock.

3. Key Benefits of Napier Grass in Hilly Areas

3.1 Provisioning Services

Napier grass provides a continuous supply of nutritious green fodder throughout most of the year, thereby supporting livestock productivity and reducing dependence on external feed resources (ILRI, 2013; Hassen *et al.*, 2017). In addition, production and sale of planting material offers supplementary income opportunities for rural households. Napier grass exhibits exceptional potential as a renewable bioenergy feedstock because of its rapid growth rate and high biomass production. Under favourable management conditions, fresh biomass yields of 200–300 t ha⁻¹ year⁻¹ and dry matter yields of 30–40 t ha⁻¹ year⁻¹ have been reported (Heuzé *et al.*, 2017). Such productivity makes it a promising feedstock for biogas, briquettes, and lignocellulosic bioethanol production (Chamoli *et al.*, 2024).

However, in fodder-deficit regions, utilization of Napier grass for energy production should not compromise livestock feed security. Therefore, biomass allocation strategies should prioritize fodder requirements, while surplus biomass, mature stems, and material produced on marginal lands can be diverted towards bioenergy production (FAO, 2018).

3.2 Regulating Services

The extensive root system of Napier grass effectively stabilizes soil aggregates and reduces susceptibility to erosion on sloping lands. When planted along contour lines and terrace risers, it

decreases runoff velocity, enhances infiltration, and improves soil moisture conservation (ICAR-IGFRI, 2019; Dagar *et al.*, 2020). Its substantial biomass production also contributes to atmospheric carbon sequestration and climate-change mitigation by increasing soil organic carbon stocks (FAO, 2018).

3.3 Supporting Services

Napier grass improves nutrient cycling through root turnover and litter deposition, resulting in enhanced soil organic matter and improved soil biological activity. Dense vegetation cover provides habitat for beneficial insects, pollinators, and small fauna while contributing to restoration of degraded landscapes and watershed ecosystems (FAO, 2018; Dagar *et al.*, 2020).

4 Agronomic Management for Hilly Areas

4.1 Site Selection

Napier grass is highly suitable for cultivation in hilly and undulating landscapes where fodder scarcity, soil erosion, and land degradation are major concerns. The crop performs best on moderately sloping or terraced lands that receive adequate sunlight and are free from prolonged waterlogging. In hill agriculture, Napier grass is ideally established along terrace risers, contour bunds, field boundaries, and erosion-prone gullies, where it provides both high-quality fodder and effective soil and water conservation benefits (ICAR-IGFRI, 2019). Well-drained loam to clay loam soils with a pH ranging from 5.5 to 7.5 are considered most suitable for optimum growth and biomass production.

4.2 Land Preparation

Proper land preparation is essential for rapid establishment and sustained productivity of Napier grass. The field should be ploughed and leveled to create a fine tilth, particularly on terraces and gently sloping lands. Incorporation of 10–15 t ha⁻¹ of well-decomposed farmyard manure (FYM) during land preparation is recommended to improve soil organic matter content, enhance moisture retention, and promote early root development. In erosion-prone

locations, contour furrows or staggered trenches may be prepared to reduce runoff and increase rainwater infiltration (Dagar *et al.*, 2020)

4.3 Planting Material and Planting Time

Napier grass is propagated vegetatively through rooted slips or stem cuttings. Healthy stem cuttings containing 2–3 viable nodes or well-developed rooted slips should be used for planting to ensure rapid establishment and uniform crop growth. Planting is preferably undertaken at the onset of the monsoon season, typically from June to July, when adequate soil moisture is available. Stem cuttings should be planted with at least one node inserted into the soil to facilitate rooting and sprouting. Contour planting is particularly advantageous in hilly areas as it minimizes runoff losses and improves soil moisture conservation.

4.4 Spacing

Appropriate spacing is important for maximizing fodder yield while maintaining adequate aeration and ease of harvesting. Under hill conditions, a spacing of 75–90 cm between rows and 30–50 cm between plants is generally recommended. Wider spacing may be adopted on shallow soils or moisture-limited sites, whereas closer spacing can be used under fertile conditions with adequate moisture availability (ICAR-IGFRI, 2019).

4.5 Nutrient Management

Napier grass is a heavy nutrient feeder owing to its high biomass production potential. Application of 100–150 kg N ha⁻¹ year⁻¹, split into three to four equal doses after each harvest, is recommended to sustain vigorous growth and rapid regrowth. A basal application of 40–60 kg P₂O₅ ha⁻¹ and 40–50 kg K₂O ha⁻¹ should also be provided to support root development, tillering, and stem strength. In environmentally sensitive hill ecosystems, integrated nutrient management involving FYM, compost, crop residues, and biofertilizers should be encouraged to improve nutrient-use efficiency, maintain soil fertility, and minimize nutrient losses through runoff (FAO, 2018; ICAR-IGFRI, 2019).

4.6 Irrigation and Moisture Management

Although Napier grass is predominantly cultivated under rainfed conditions in hilly regions, supplemental irrigation during prolonged dry spells and the establishment phase can significantly enhance plant survival and biomass production. Moisture conservation practices such as mulching, contour cultivation, and intercropping with legumes such as cowpea (*Vigna unguiculata*) or lucerne (*Medicago sativa*) help reduce evaporation losses, improve soil fertility, and enhance overall system productivity. These practices are particularly beneficial in areas characterized by erratic rainfall and limited irrigation facilities.

4.7 Harvesting and Crop Management

The first harvest of Napier grass can generally be taken 60–75 days after planting, followed by subsequent harvests at intervals of 45–60 days depending on climatic conditions and growth rate. Harvesting should be carried out at a height of 5–10 cm above ground level to encourage tillering and prevent damage to the crown. Timely harvesting improves forage quality, digestibility, and crude protein content, thereby enhancing livestock performance and milk production (Hassen *et al.*, 2017). Napier grass is relatively tolerant to pests and diseases; however, occasional infestations of stem borers or leaf spot diseases may occur under humid conditions. These can be effectively managed through timely harvesting, field sanitation, removal of infected plant parts, and avoidance of over-aged stands. The crop generally remains productive for three to four years, after which productivity declines and replanting or field rejuvenation is recommended to maintain optimum yields.

4.8 Varieties Suitable for Hill Regions

Several Napier grass varieties have shown excellent adaptability to hilly and semi-arid environments. Among the most widely recommended cultivars are CO-3 and CO-4, which are characterized by profuse tillering, rapid growth, succulent stems, and high fodder yield. These varieties are particularly suitable for intensive fodder production systems requiring frequent harvesting. NB-21 is another promising cultivar known for its hardiness and ability to establish successfully under moderate moisture

stress and low-fertility conditions, making it suitable for sloping and rainfed landscapes. In addition, IGFR Hybrid Napier, developed by the Indian Grassland and Fodder Research Institute (IGFRI), Jhansi, exhibits superior regrowth ability, high biomass productivity, and resilience to climatic variability. Collectively, these varieties provide suitable options for integrating fodder production, soil conservation, and climate-resilient farming strategies in hill agro-ecosystems (ICAR-IGFRI, 2019; Heuzé et al., 2017).

5. Livestock and Livelihood Benefits

Napier grass serves as a foundational component of livestock production systems in hilly regions. With crude protein content ranging between 8 and 14 percent and good digestibility when harvested at the right time, it significantly enhances milk yield in dairy cattle and promotes weight gain in small ruminants and draft animals (Table 1). This is especially beneficial in regions where low-quality dry fodder dominates during lean periods. In the hills, where free grazing is often restricted due to forest conservation policies and fragmented landholdings, Napier supports the widely practiced stall-feeding or cut-and-carry system. Once established, it can be harvested six to seven times annually, offering a consistent supply of green fodder even in dry spells. The biomass can also be preserved as silage, ensuring availability during winter dormancy or periods of prolonged drought.

Napier not only meets fodder needs but also presents opportunities for rural income diversification. Farmers can sell green fodder to neighboring farms or supply root slips to fodder nurseries. This makes Napier cultivation a potential source of supplementary income, particularly for women and youth engaged in livestock rearing. It reduces reliance on external feed inputs, lowering production costs and improving profitability. In many hilly areas, Napier grass is integrated into homestead farming systems, acting as a protective barrier around horticultural crops and bunds while also serving as a bio-fence. It is often intercropped with legumes, which enhance protein quality in the forage mix and contribute to nitrogen enrichment in the soil. Backyard dairy units, goatery, and mixed farming systems in upland regions derive immense benefit from Napier, making it a cornerstone of sustainable, climate-resilient livelihoods.

Moreover, Napier grass cultivation has proven to be a gender-inclusive activity. Women, who traditionally manage livestock in hill regions, often take the lead in planting, harvesting, and processing fodder. This contributes to household food and nutritional security and empowers women economically through their active role in fodder-based value chains.

6. Challenges and Management

Problem	Cause	Management Solution
Winter dormancy and seasonal fodder shortage	Low temperatures and frost during winter reduce or stop vegetative growth, particularly in high-altitude regions	Integrate Napier with leguminous fodders such as cowpea and lucerne; conserve surplus fodder as silage or hay during peak production periods to ensure year-round feed availability (Hassen <i>et al.</i> , 2017)
Declining productivity after 3–4 years	Root systems become overcrowded and woody, reducing tillering and regenerative capacity	Rejuvenate stands through root division, replanting, and incorporation of organic manures to maintain vigour and biomass production (ICAR-IGFRI, 2019)

continued on next page

Table continue

Problem	Cause	Management Solution
Poor establishment under moisture stress	Inadequate soil moisture during establishment and prolonged dry spells limit rooting and early growth	Plant at the onset of monsoon, adopt mulching, contour planting, and provide supplemental irrigation during critical growth stages (Dagar et al., 2020)
Waterlogging and root rot	Poor drainage and prolonged soil saturation during heavy rainfall	Avoid cultivation in low-lying areas; establish raised beds and drainage channels; plant along gentle slopes to facilitate runoff (ICAR-IGFRI, 2019)
Soil erosion on steep slopes	Heavy rainfall and surface runoff remove topsoil and destabilize planting areas	Establish Napier along contour bunds, terrace risers, and vegetative barriers to reduce runoff velocity and improve soil conservation
Limited availability of quality planting material	Lack of organized multiplication and distribution systems in remote hill regions	Establish community nurseries, fodder banks, and decentralized slip production units through extension programmes and farmer groups (DAHD, 2022)
Low farmer awareness and adoption	Insufficient extension support and limited demonstration of benefits	Conduct training programmes, field demonstrations, and integration with watershed and livestock development programmes (ICAR-IGFRI, 2019)
Nutrient depletion under intensive harvesting	High biomass removal results in continuous nutrient extraction from soil	Apply recommended doses of N, P and K along with FYM, compost, and biofertilizers through integrated nutrient management practices (FAO, 2018)
Pest and disease incidence under humid conditions	High humidity favours stem borers and leaf spot diseases	Adopt timely harvesting, field sanitation, removal of infected plant parts, and avoid over-aged stands (ICAR-IGFRI, 2019)
Weak integration with development programmes	Fodder cultivation often receives limited policy attention in hill development projects	Promote Napier grass under the National Livestock Mission (NLM), watershed development programmes, and agroforestry-based interventions to enhance fodder security and ecosystem restoration (DAHD, 2022)

7. Policy and Programmatic Implications

To fully harness the potential of Napier grass in hilly regions, its promotion should be integrated into ongoing rural development, livestock development, watershed management, and climate-resilient agriculture programmes. Inclusion of Napier grass plantations under the Viksit Bharat - Guarantee for Rozgar and Aajeevika Mission (Gramin) (VB-G RAM G) can support

slope stabilization, soil conservation, and the establishment of decentralized fodder banks while generating rural employment and restoring degraded landscapes.

The National Livestock Mission (NLM) offers a suitable platform for scaling up Napier grass cultivation through fodder development initiatives, establishment of community nurseries, production and distribution of quality

planting material, fodder banks, and farmer capacity-building programmes. Such interventions can improve year-round fodder availability, reduce pressure on natural grazing lands and forests, enhance livestock productivity, and strengthen livelihood security in fodder-deficit hill regions (DAHD, 2022).

Napier grass also aligns closely with the objectives of the National Agroforestry Policy Govt. of India 2014; Chavan *et al.*, 2015. Its suitability for planting along terrace risers, contour bunds, field boundaries, and within silvopastoral systems makes it an ideal component of agroforestry-based land-use systems. Integration of Napier grass with fruit trees, fodder trees, and multipurpose woody perennials can enhance biomass production, improve nutrient cycling, increase carbon sequestration, diversify farm income, and strengthen climate resilience while conserving fragile hill ecosystems (Dagar *et al.*, 2020).

Effective scaling pathways should include the establishment of village-level fodder nurseries, promotion of community fodder banks, integration of Napier grass into watershed treatment plans, and dissemination through self-help groups (SHGs), farmer producer organizations (FPOs), and extension networks. Demonstration plots, farmer training programmes, and inclusion of Napier-based forage systems in climate-smart agriculture initiatives can accelerate adoption and awareness among hill farmers.

Policy incentives such as subsidized planting material, financial assistance for fodder nurseries and silage units, incentives for silvopastoral and agroforestry systems, and convergence of schemes under NLM, VB-G RAM G, watershed development programmes, and state livestock missions can further encourage large-scale adoption. Such coordinated policy support can transform Napier grass into a key intervention for enhancing fodder security, restoring degraded lands, improving ecosystem services, and building climate-resilient livelihoods in hilly regions.

8. Success Story

A successful example of Napier grass adoption in hill agriculture has been reported from Kharakh

et village, Vikasnagar tehsil, Dehradun district, Uttarakhand, where the ICAR–Indian Institute of Soil and Water Conservation (ICAR-IISWC), Dehradun, through its watershed and silvopastoral research programme, evaluated hybrid Napier grass (CO-3) on degraded rainfed lands under a silvopastoral system. The grass recorded a survival rate of approximately 84% and exhibited superior sprouting ability compared with Guinea grass, demonstrating its adaptability to degraded hill environments. The intervention improved fodder availability, reduced pressure on natural grazing resources, and enhanced the sustainability of livestock-based farming systems. The study highlighted Napier grass as a promising component of silvopastoral interventions for improving fodder security and land productivity in the Himalayan foothills of Uttarakhand (Singh *et al.*, 2016) (Fig. 1).

Conclusions

Napier grass is not just a fodder crop—it is a multifunctional asset for hilly landscapes. It supports livestock systems, improves degraded lands, sequesters carbon, and serves as a renewable energy source. Its strategic use in soil and water conservation, bioenergy, and climate resilience makes it an ideal candidate for scaling up under rural development and sustainable land management programs.



FIGURE 1 Napier grass planted around the field bund

TABLE 1 Nutritional Composition of Napier Grass (Dry Matter Basis)

Nutrient Parameter	Typical Range	Remarks	Citation
Dry Matter (DM, %)	20-25	At harvest; varies with cutting interval	Heuzé <i>et al.</i> , (2017); ILRI (2013)
Crude Protein (CP, %)	8-14	Decreases with plant maturity	ILRI (2013); Hassen <i>et al.</i> , (2017)
Neutral Detergent Fiber (NDF, %)	60-70	High fiber limits digestibility if mature	Hassen <i>et al.</i> , (2017); Kizilsimsek <i>et al.</i> , (2021)
Acid Detergent Fiber (ADF, %)	35-45	Correlates with lignin content	Heuzé <i>et al.</i> , (2017); ILRI (2013)
Lignin (% of DM)	4-8	Increases with maturity	Kizilsimsek <i>et al.</i> , (2021)
Total Digestible Nutrients (TDN, %)	55-60	Indicator of energy content	ILRI (2013); NRC (2001)
Metabolizable Energy (ME, MJ/kg DM)	7.5-9.0	Energy availability for ruminants	Heuzé <i>et al.</i> , (2017); NRC (2001)
Calcium (Ca, %)	0.3-0.5	Sufficient for most livestock	Hassen <i>et al.</i> , (2017)
Phosphorus (P, %)	0.20-0.35	Often needs supplementation	ILRI (2013); NRC (2001)

Box 1. Do's and Don'ts for Successful Napier Grass Cultivation in Hilly Areas

Do's

- Plant Napier grass at the onset of the monsoon (June–July) to ensure good establishment.
- Use healthy rooted slips or stem cuttings with 2–3 viable nodes.
- Plant along contour bunds, terrace risers, field boundaries, and gully edges to maximize soil and water conservation benefits.
- Apply 10–15 t ha⁻¹ of FYM or compost during land preparation.
- Follow recommended spacing (75–90 cm × 30–50 cm) for optimum growth and fodder yield.
- Apply nitrogen fertilizer in split doses after each harvest to maintain vigorous regrowth.
- Practice mulching and integrate legumes such as cowpea or lucerne to conserve moisture and improve forage quality.
- Harvest at 45–60 day intervals and maintain a cutting height of 5–10 cm above ground level.
- Preserve surplus fodder as silage or hay for use during winter and drought periods.
- Replant or rejuvenate stands after 3–4 years to sustain productivity.

Don't

- Do not plant in waterlogged or poorly drained areas, as Napier is sensitive to prolonged water stagnation.
- Do not use diseased, over-aged, or damaged planting material.
- Do not delay harvesting excessively, as mature forage has lower protein content and digestibility.
- Do not allow uncontrolled grazing on newly established plantations.
- Do not remove all crop residues or neglect organic manure application, which can reduce soil fertility over time.
- Do not apply excessive nitrogen fertilizer in a single dose, as it may increase nutrient losses and lodging.
- Do not ignore weed control during the establishment phase.
- Do not retain old and unproductive clumps beyond their productive life without rejuvenation.
- Do not cultivate Napier on highly unstable slopes without adequate soil conservation measures
- Do not depend solely on Napier fodder; combine with legumes and balanced feed supplementation for improved livestock nutrition.

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Bringing Tanks Back to Life: Strategic Desiltation for Water and Livelihood Security in Southern India

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1. Introduction - A Tank in Trouble

Picture a village tank in Vellore district on a dry April morning. Where water once stood waist-deep, a cracked grey floor stretches to the bund. Borewells in surrounding farms are stuttering. Paddy sowing is delayed. Families debate whether it is worth staying. This is not an isolated scene. Across the semi-arid tracts of Tamil Nadu, Karnataka, Telangana, and Andhra Pradesh, thousands of village tanks - some centuries old - are silently losing the battle against silt. Every monsoon, eroded topsoil from degraded catchments flows in; every dry season, a little more storage capacity disappears.

The tragedy is not that it happens, but that it is entirely reversible. Tank desiltation — the removal of accumulated sediment to restore storage capacity — is among the most direct and impactful watershed interventions available to planners, communities, and field practitioners. Yet it remains underutilised, often viewed narrowly as a high-cost engineering activity rather than what it truly is: a long-term investment in water security, agricultural productivity, and rural resilience.

2. Why Tanks Silt Up: The Upstream Story

The silt choking a tank tells a story that begins far upstream. Declining forest cover — driven by encroachment, fuelwood extraction, and urban sprawl — strips the land of its natural sponge. Bare slopes and overgrazed patches lose their capacity to absorb rainfall, generating high-velocity runoff that picks up topsoil and carries it into tank beds season after season.

Compounding this ecological degradation is an institutional vacuum. Soil and water conservation structures - check dams, contour bunds, silt traps - have either not been built or fallen into disrepair. Community participation in catchment management has weakened as tanks have come to be perceived as government assets rather than shared village resources. Fragmented departmental approaches and poor inter-agency coordination leave the problem unaddressed across administrative boundaries.

Without upstream treatment, desiltation becomes a recurring cost rather than a lasting investment. The consequences cascade predictably - reduced tank storage, falling groundwater, declining crop yields, lower land values, and ultimately, rural out-migration. A silted tank is not merely an engineering problem; it is a social one.

3. What Desiltation Restores

When a tank is properly desilted, its storage capacity is physically recovered. But the benefits extend well beyond the tank bed. Enhanced water retention increases percolation to the water table, recharging the shallow aquifers on which millions of domestic wells and irrigation borewells depend. Drought resilience improves as tanks hold more water through dry spells and moderate the impact of erratic monsoons.

Evidence from across southern India confirms these gains are real and measurable. In Vellore district, desiltation of five village tanks raised groundwater levels by 0.5 to 1.2 metres within two years - directly improving drinking water availability and enabling a 15-20% increase in paddy yields. In Tumkur district, Karnataka, community-led desiltation under MGNREGS raised groundwater by 0.4-0.8 metres within 18

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months and improved ragi productivity significantly. In Dharmapuri, a cluster approach stabilised borewell irrigation and measurably reduced seasonal migration from villages (Table 1).

4. Silt as a Resource, Not a Waste

One of the most underappreciated aspects of tank desiltation is what comes out of the tank. Desilted material is typically enriched with organic carbon, plant-available nitrogen, phosphorus, and potassium - accumulated over years of biological activity and catchment runoff. When applied to

agricultural fields, this silt functions as a slow-release multi-nutrient amendment that improves soil structure, moisture retention, and crop performance.

Farmers in Karnataka reported a 25% reduction in fertilizer costs after applying tank silt to ragi fields - a direct agronomic dividend from what is commonly dismissed as spoil. In sandy soils, silt application improves moisture retention; in compacted clay soils, it improves aeration and workability. The silt also contributes to soil organic carbon, with modest but meaningful implications for climate mitigation at the farm scale (Table 2).

TABLE 1 Groundwater Response to Tank Desiltation — Field Evidence

Location	Tank Cluster	Groundwater Rise (m)	Timeframe	Key Outcome*
Vellore, TN	Village tanks (5 nos.)	0.5 – 1.2	2 years	15–20% paddy yield increase
Tumkur, KA	MGNREGS-supported tanks	0.4 – 0.8	18 months	Reduced fertilizer cost by 25%
Dharmapuri, TN	NGO-led cluster tanks	0.6 – 1.0	3 years	Stabilised borewells, reduced migration

TABLE 2 Nutrient Profile of Tank Silt (Tamil Nadu & Karnataka)

Parameter	Range Observed	Agronomic Significance
Organic Carbon (%)	0.4 – 1.2	Improves soil fertility and carbon sequestration
Available Nitrogen (kg ha ⁻¹)	250 – 400	Enhances crop growth, reduces fertilizer demand
Available Phosphorus (kg ha ⁻¹)	20 – 45	Boosts root development and grain yield
Available Potassium (kg ha ⁻¹)	150 – 300	Improves drought tolerance and crop resilience
Zinc (ppm)	1.2 – 2.5	Corrects micronutrient deficiency in soils

Silt quality should always be tested before field application, and the bottom 0.3–0.5 m of the tank bed should be retained to preserve structural integrity.

5. Selecting the Right Tanks: A Strategic Lens

Not every tank merits immediate investment. Indiscriminate desiltation without strategic prioritisation dilutes resources and limits impact. Priority should go to tanks that:

- Serve multiple purposes-irrigation, drinking water, and groundwater recharge;
- Are located in identified recharge zones with permeable substrates;
- Have treatable catchments with scope for complementary soil and water conservation

works;

- Demonstrate community willingness and institutional support through active Water Users Associations; and
- Are structural sound and free from sewage or industrial contamination.

Clustering several tanks within a micro-watershed for simultaneous or phased treatment amplifies both hydrological and social outcomes - groundwater recharge is additive across a landscape, and community institutions are strengthened by collective action.

6. Embedding Desiltation in the Watershed: What Makes it Sustainable

The most common failure mode in tank desiltation programmes is treating the tank in isolation. Without addressing the catchment that feeds it, the tank begins re-silting within a few monsoon seasons, negating the investment. Sustainable desiltation must therefore be embedded within a broader watershed development framework.

Catchment treatment works - silt traps, percolation ponds, contour bunds, and vegetative barriers - must either precede or accompany the desiltation. Foreshore areas should be afforested with multi-purpose native species that stabilise banks, reduce runoff velocity, and provide fodder and fuel to local communities. Hydrological monitoring should track recharge efficiency and inform future interventions.

Institutionally, state departments, rural development agencies, and gram panchayats must coordinate on planning and funding - a step that requires deliberate inter-departmental mechanisms rather than ad hoc collaboration. Linking desiltation with MGNREGS provides the

labour architecture and financial sustainability to operate at scale. Large tanks are best phased over 5–6 years for operational efficiency, and Water Users Associations should be constituted early as the governance backbone for long-term maintenance.

7. The Equity Dimension

There is a dimension to tank desiltation that rarely appears in cost-benefit analyses but is no less real. In many villages, the tank is the last common resource accessible to small and marginal farmers who lack the capital to drill borewells or install pump sets. As groundwater tables fall and private irrigation infrastructure becomes more expensive, the gap between those who can access water and those who cannot widens.

Restoring a tank's function is, in effect, an act of equity - ensuring that water security is not the exclusive privilege of those who can afford to drill deeper. The social case for desiltation is as compelling as the hydrological one, and policies that treat it primarily as an engineering expenditure miss this dimension entirely (Fig.1).

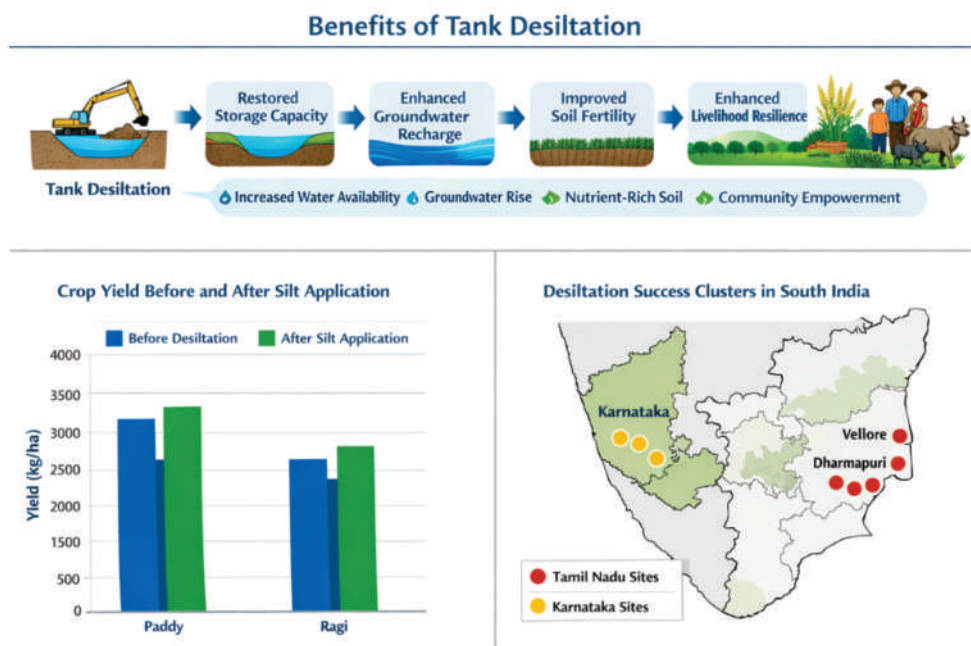


FIGURE 1 Conceptual framework of tank desiltation impacts

8. Conclusions: From Engineering Task to Generational Investment

Tank desiltation in southern India is not a relic of traditional water management-it is a climate-resilient strategy for the future. As rainfall becomes more erratic, groundwater tables continue to fall, and rural livelihoods come under mounting pressure, restored tanks serve as critical buffers for both agriculture and drinking water security.

But the shift in thinking must go further than the technical. When communities manage their tanks as shared ecological assets - when desiltation is planned, executed, and maintained collectively - the intervention transforms from a one-time engineering event into a rolling, self-reinforcing cycle of watershed renewal.

The evidence is clear. The tools exist. The

institutional pathways through MGNREGS, watershed programmes, and community governance structures are available. What is needed now is the long view - the same long view that the communities who originally built these tanks brought to the task of securing water for generations they would never meet.

9. Key Takeaways

Desiltation restores groundwater by 0.4–1.2 m within 1-3 years across documented sites in southern India.

Tank silt is a natural fertilizer-field application cuts farmer fertilizer costs by up to 25%.

Always treat the catchment alongside the tank; desiltation without upstream intervention is short-lived.

Link desiltation to MGNREGS for labour; phase large tanks over 5–6 years.

Constitute Water Users Associations early-governance is as critical as the engineering.



Including Soil Biodiversity in Soil Erosion Modelling: Can it change our calculations?

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1. Introduction

Soil is often comprehended as THE most essential resource for the sustenance of human life and to ensure climate as well as food security (Amundson *et al.*, 2015, Alwell *et al.*, 2019). But most of the world soil resources are in a state of fair, poor or very poor condition, with the availability of good quality soil becoming a scarce phenomenon (FAO, 2015). Various forms of land degradation impact the soil's capacity to perform different functions which are essential for sustainability of the entire ecosystem. Water mediated soil erosion is one of the prime degrading agents, and as early as 1990's almost 56 % of the world soils were affected by water erosion to different extent (Oldeman, 1992). Almost 90% of the land surface could face the problem of water erosion by 2050 (FAO & ITPS, 2015), and the predicted economic losses (total real Gross Domestic Product Loss) under different climate change scenarios during 2015-2070 is projected somewhere between 216 billion US\$ to 625 billion US\$ (European Commission 2024). The projections are chilling and paints an uncertain future for nations particularly vulnerable to the impacts of climate change. Regions dotted across Africa and the tropics are likely to be more severely affected by the water erosion process, setting the targets of achieving the Sustainable Development Goals haywire (European Commission, 2024). The list of most severely affected countries also include India along with South Africa, China and Indonesia, putting us on alert mode.

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To manage soil erosion and prioritize the different conservation measure implementation, comprehensive database on soil erosion is required. Till date such a database is lacking at a global scale, which may result in the exclusion of soil erosion from major environmental and agricultural policies (Alwell *et al.*, 2019). Studies on soil erosion monitoring, measurement and prediction over a given land scape started as early as 1930's. Since then several soil erosion models have been framed and utilized for measuring soil erosion. The most commonly used soil erosion prediction models are the Universal Soil Loss Equation (USLE), Revised Universal Soil Loss Equation (RUSLE), the Water Erosion Prediction Project (WEPP), the European Soil Erosion Model (EUROSEM), the Soil and Water Assessment Tool (SWAT), the Water and Tillage Erosion and Sediment Model (Watem), the Agricultural non-point Source Erosion Model (AGNPS), the Chinese Soil Loss Equation (CSLE) etc. (Alwell *et al.*, 2019). Among the different soil erosion models, USLE/RUSLE is the most widely used because of its wider applicability under varied conditions and diverse scenarios across the globe (Risse *et al.*, 1993).

2. Limitations of Soil Erosion Models (USLE/RUSLE)

The USLE originated with Wischemeir and Smith (1965) which attempted to measure the soil erosion process in terms of some measureable parameters which put together yielded a quantifiable output. The mathematical algorithm representing USLE is

$$A = R * K * L * S * C * P$$

Where,

A is soil loss in Mg ha⁻¹ year⁻¹

R is the rainfall runoff erosivity factor

K is the soil erodibility factor

L&S are slope length and slope steepness

respectively

C is the land cover and management factor

P is the soil conservation and prevention practices

USLE was used by a wide range of users in different conditions under different landscapes, however, the more empirical nature of USLE and constraints in its application to non-agricultural scenarios such as rangelands, pastures etc. resulted in the formulation of the Revised Universal Soil Loss Equation (RUSLE) by Renard *et al.*, (1991, 1997). The modification in the RUSLE included alterations in the calculation of erosivity. Changes in the soil erodibility values taking into account the seasonality, modified L and S values, revised P values for rangeland etc. The RUSLE have found wide application as an erosion model for predicting erosion at different spatial scales from large watersheds to country level. However, the model does not take into account the activity of the soil macro and micro flora and fauna which has varied impact on soil erosion. This leaves a scope for modification of the RUSLE further by incorporating soil biodiversity as a component to measure and predict soil erosion at various scales.

3. How soil biodiversity affects soil erosion

The process of soil erosion is defined in three steps of detachment, transportation and deposition is a complex process. Besides the physical forces of rainfall, slope and topographic conditions, soil structure, vegetation and human management, the soil biological forces also actively influence the soil erosion process. Soil erosion process and biodiversity follows a reciprocal relationship (Orgiazzi and Panagos, 2018). The soil flora and fauna have a multitude of impact on the soil processes. The activity of soil microbes may enhance structural stability, aggregate formation, soil porosity, thereby resulting in improved water movement through soil profile (Roy *et al.*, 2021). The increased stability of soil aggregates reduces the soil loss by water erosion (Burri *et al.*, 2013). Surface runoff reduction by inclusion of mycorrhizal inoculum have been reported by Mardhiah *et al.*, (2016). On the contrary, the large soil macrofauna causing burrowing activities in the soil may result in weakening of soil structure and exacerbate the soil erosion process (Reichman and Seabloom, 2002).

Organisms like earthworm may have dual impact on soil erosion. The burrowing activity creates macropores, channels and pathways which causes rapid water movement down the soil profile and better infiltration rates (Shuster *et al.*, 2002; Blanchart *et al.*, 2004). However, these “ecosystem engineers” have been identified to increase soil erosion rates as well through formation of unconsolidated casts on the soil surface. Chen *et al.*, (2022) reported 42 and 46 % increase in soil erosion rates in a 10 degree and 15-degree slope in contrast to the control plots due to activity of earthworms. The effect of earthworm casts on soil erosion losses have been reported to be positive by Joquet *et al.*, (2008). The casts produced by *Amyntus khami* enhanced soil water infiltration rates than the free biogenic aggregates or physiogenic aggregates. Thus, the prominent influence of soil biodiversity on soil erosion necessitates the of expressing it in some quantitative form to include it in the quantification of soil erosion (Orgiazzi and Panagos, 2018).

4. Quantifying soil biodiversity into soil erosion: the Earthworm Factor

There is absolutely no dilemma in accepting the role of soil biodiversity in maintaining the several soil functions and their role in manipulating soil erosion (Wieder *et al.*, 2015). The soil equation model till date acknowledges the biodiversity factor to an extent by the C-factor, though the living organisms present below ground remains completely unaccounted for (Kinell, 2010). Though the below ground biodiversity modifies the soil erosion rates in several ways, its inclusion in the soil loss estimation is overlooked. It is stated that for more accurate estimation of soil erosion, inclusion of biodiversity is essential. Since, the role of biodiversity in impacting soil erosion process is bidirectional, the inclusion of the factor needs critical evaluation and exercise before incorporation into the model (Blouin *et al.*, 2013). The existing K factor includes the soil texture, organic matter content, soil structure, permeability and stoniness. If we critically evaluate the organic matter content, soil structure, porosity etc. the soil biodiversity plays an important role in manipulating these soil properties. The soil organic matter accumulation is related to the activity of the soil microbes. The soil aggregation and structural stability is greatly influenced by

fungi and the exudates/ extracellular enzymes of the microbes which help in binding the soil particles. All these in turn influence the soil bulk density, porosity and soil water movement. Thus, Orgiazzi and Panagos (2018), explored the inclusion of soil biodiversity factor as a component of the K-factor. They opine the introduction of ET-factor (the Earthworm factor) in the K-factor would enhance the prediction of soil erosion estimates.

The ET factor is a combination of the earthworm abundance and richness in the soil system.

$$ET_{AR} = 1 - R + (R/(A+1)) \dots\dots\dots \text{Eq. 1}$$

Where, A = abundance of earthworms (no. of individuals /m² in the soil) normalized to a 0-1 index

R = species richness (number of taxa per m², normalized to 0-1)

The ET factor has a value ranging from 0.5 to 1.0, thus, modifying the final K-factor by 50 % (Blouin *et al.*, 2013).

The modified K-factor in the soil loss equation is as follows

$$K_{ET} = K * ET_{AR} \dots\dots\dots \text{Eq. 2}$$

This equation was given by Panagos *et al.*, (2014). At highest value of ET=1, the K_{ET} = K, while ET=0.5, K_{ET} = 0.5 K (half of the actual erodibility), thus, reducing the soil erodibility due to the increase in the richness or abundance of the earthworms. This would finally imply a reduction in the actually estimated soil erosion loss from any catchment due to the presence of the earthworms.

The soil biodiversity is not only limited to the earthworms. However, as an inception since this macro-fauna is easy to account for, it was included in the K-factor. Besides this the fungal biodiversity, bacterial biodiversity, other meso and macro fauna can be included in the K-factor.

Conclusions

Though conceptually the inclusion of soil

biodiversity is rationale and result in better soil erosion estimation, but the practical approach of its inclusion is tedious. One of the major constraints in inclusion of the soil biodiversity is the availability of large spatial scale database on soil biodiversity. Though effort towards mapping of soil biodiversity is scarce in India, the European Union has ongoing projects for the large scale assessment of earthworm distribution (Cameron *et al.*, 2016). The Global Soil Biodiversity Atlas map by Orgiazzi *et al* (2016) which uses soil microbial biomass C as a proxy of the microbial diversity can serve as the base data for initiation of large scale studies. Additionally, tracking down the impacts of soil erosion on soil biodiversity, in terms of migration, invasion, rebuilding, functional effect should be quantified at laboratory and large scale to understand their impact on each other. The inclusion of soil biodiversity gives an opportunity to address the loss of ecosystem services through erosion and how biodiversity can play a critical role to address it. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) framework which highlights the role of biodiversity in preserving land degradation, also supports such kind of inclusion and can play a pivotal role for identifying how soil biodiversity regulates the soil erosion process, and design measures for its preservation to help manage the soil sustainably.

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Nano Nitrogen Fertilizer: Minimizing Nitrogen Leaching and Environmental Impact

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1. Introduction

Modern agriculture greatly benefits from nanotechnology's increased productivity, sustainability, and efficiency. Nanotechnology (NT) is a cutting-edge field that involves manipulating materials at the nanoscale, typically ranging from 1 to 100 nanometers (nm) (Parisi *et al.*, 2015). Materials of this scale have distinct physical, chemical, and biological characteristics compared to their bulk counterparts, which allows for breakthroughs in various industries. Nanomaterials (NM) differ from conventional materials in that they have a specific composition with unique properties such as small particle size with high surface area, high reactivity and catalytic activity (Das *et al.*, 2025).

Nanotechnology supports agriculture by improving crop productivity, soil health, and resource efficiency through advanced applications like nano fertilizers (NF), nano pesticides, and precision farming. Nano fertilizers utilize nanotechnology to enhance nutrient delivery, absorption, and efficiency in plants. Unlike conventional fertilizers, NF allow better nutrient uptake, reduced environmental impact, and improved crop yield. Additionally, NT aids in soil and water purification, ensuring better resource management. By increasing efficiency, reducing input costs, and minimizing environmental impact, NT plays a crucial role in sustainable and modern agriculture (Lowry *et al.*, 2019).

Traditional fertilizers and NF differ significantly in their formulation, nutrient delivery

mechanisms, and environmental impact. Traditional fertilizers are typically composed of macroscopic particles in granular, liquid, or powdered forms, containing essential nutrients like nitrogen, phosphorus, and potassium and often required at larger rates due to their less precise nutrient delivery, leading to potential nutrient losses through leaching and runoff, which can harm the environment. In contrast, NF utilize nanoparticles, allowing for more efficient penetration into plant cells, improved nutrient absorption and substantial reduction in losses through leaching, runoff, fixation or volatilization (Manjunatha *et al.*, 2016; Mejias *et al.*, 2021) thereby minimizing environmental pollution. However, it's important to note that NF are a relatively new technology, and their long-term effects on soil health and ecosystems are still under investigation.

Current agricultural practices are heavily dependent on synthetic fertilizers with maximum dependency on nitrogenous fertilizers, leading to significant environmental issues. One of the most pressing concerns is nitrogen (N) leaching, which results in groundwater contamination, eutrophication, and greenhouse gas emissions. Conventional nitrogen fertilizers, such as urea and ammonium nitrate, have low nutrient-use efficiency (NUE), leading to nutrient loss through leaching, volatilization, and runoff. The shift from traditional fertilizers like urea to NFs like nano urea opens up newer vistas of crop production, which would help to sustain soil health while ensuring high productivity. (Shang *et al.*, 2019). This article tries to explore the benefits of NFs in agriculture and their positive impact on the environment and crop production.

2. Understanding Nitrogen Leaching and its Environmental Impact

Nitrogen is an essential nutrient for plant growth and a key component of fertilizers used in

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agriculture. Conventional nitrogen fertilizers, such as urea and ammonium nitrate, have low NUE, with less than 50% of the applied nitrogen absorbed by plants. The remaining nitrogen is either lost to the atmosphere through volatilization and denitrification or leached into water bodies. Nitrogen leaching occurs when water-soluble nitrates move with percolating water through the soil profile, eventually reaching groundwater sources. This process is accelerated by excessive rainfall or over-irrigation, particularly in sandy and well-drained soils.

Nitrogen leaching has several negative consequences. First, it contaminates groundwater, making drinking water unsafe and increasing the risk of health issues such as methemoglobinemia (blue baby syndrome). Second, it contributes to eutrophication in freshwater and marine ecosystems, causing algal blooms that deplete oxygen levels, kill aquatic life, and disrupt biodiversity. Third, nitrogen losses from agriculture contribute to climate change by increasing nitrous oxide (N_2O) emissions, a potent greenhouse gas. These environmental and health risks highlight the urgent need for innovative strategies to minimize nitrogen leaching while maintaining agricultural productivity. Understanding nitrogen leaching and its causes and consequences is crucial for developing sustainable agricultural practices and protecting ecosystems.

3. How Nano Fertilizers Help Reduce Nitrogen Leaching and Pollution

NF offer a sustainable solution to nitrogen leaching and pollution by enhancing nutrient use efficiency, reducing runoff, and minimizing greenhouse gas emissions. Traditional nitrogen fertilizers, such as urea and ammonium nitrate, are often applied in large quantities, but plants absorb only a fraction of the nutrients. The excess nitrogen leaches into groundwater or washes into rivers and lakes, causing water pollution, eutrophication, and ecosystem imbalances. Additionally, nitrogen volatilization releases ammonia and nitrous oxide, contributing to air pollution and climate change.

Jovzi *et al.* (2023) observed a 35.72 % reduction in nitrate leaching from potato fields due

to applying nano-nitrogen chelate compared to conventional urea. Alimohammadi *et al.*, (2020) observed similar trends with nano-nitrogen fertilizers recording the least leaching losses of nitrate, while increased doses of conventional urea led to increased nitrate concentration. The synchronization of nutrient release from the NFs with the plant growth plays a key role in regulating the nitrate concentration in soil and subsequent leaching losses (Verma *et al.*, 2023). Traditional nitrogen fertilizers, such as urea and ammonium nitrate, are highly soluble and often lead to excessive nitrogen loss through leaching, volatilization, and runoff. This contributes to groundwater contamination, eutrophication of water bodies, and increased greenhouse gas emissions (Zulfiqar *et al.*, 2019). With respect to nano urea (NU) launched by Indian Farmer's Fertilizer Cooperative Limited (IFFCO), the application is done through foliar spray, thereby reducing the chances of losses to a greater extent.

Moreover, the NF has higher absorption efficiency due to its nanoscale size and increased surface area. It penetrates plant roots and leaves more effectively, allowing plants to utilize nutrients more efficiently. This improved absorption means that lower quantities of fertilizers are needed, reducing the overall environmental impact (Raliya *et al.*, 2017).

By reducing nitrogen losses through volatilization and runoff, NF also help decrease greenhouse gas emissions. Traditional nitrogen fertilizers contribute to air pollution by releasing nitrous oxide (N_2O), a potent greenhouse gas that accelerates global warming. NF minimize these emissions by keeping nitrogen stable in the soil for a longer period, ensuring a gradual and controlled release to plants. NF also promote soil health by preventing the accumulation of excess salts and heavy metals, which are common with conventional fertilizers. Healthier soils enhance microbial activity, further aiding in nitrogen retention and reducing pollution.

Additionally, NF exhibit superior soil retention and reduced susceptibility to environmental factors such as rainfall and temperature fluctuations, further limiting nitrogen leaching (Kah *et al.*, 2018). Research suggests that nano-encapsulated nitrogen fertilizers can

decrease nitrate accumulation in soil and water, effectively reducing pollution levels and promoting environmental sustainability (Liu *et al.*, 2015).

The absorption mechanism of the NFs also plays a crucial role in minimizing the losses of N and mitigating pollution. The NFs are absorbed by plants through multiple pathways, including foliar and root uptake, due to their ultra-small size, high surface area, and enhanced reactivity (Elemike *et al.*, 2019). NFs penetrate root cell walls via apoplastic or symplastic pathways when applied to the soil. In the apoplastic route, nanoparticles move through the cell walls and intercellular spaces until they reach the endodermis, crossing into the vascular system. The symplastic pathway involves direct entry into root cells through plasmodesmata, allowing transport via the cytoplasm. The nanoparticles may dissolve in the soil solution and provide nutrients as soluble ions to be absorbed by plants, which is similar to what happens with conventional fertilizers, however, nanoparticle solubility rate and amount coming into the soil solution were higher than for traditional compounds because of their small size (in nm range) that enlarges surface area (Nagula *et al.*, 2016). Additionally, NFs can be absorbed through foliar application, where they adhere to the leaf surface, dissolve in moisture, and enter the plant through stomata, cuticles, or trichomes. Once inside the plant, nanoparticles either release nutrients in a controlled manner or degrade into ionic forms, ensuring efficient nutrient utilization. Their interaction with root exudates and soil microbes can further enhance solubility and uptake. These absorption mechanisms provide better opportunity for utilization of NFs and reduce their environmental impact.

4. Impact of Shifting to Nano Fertilizers

Shifting to NF offers significant advantages over traditional fertilizers across multiple dimensions, including input reduction, loss mitigation, nutrient uptake efficiency, and economic and environmental benefits.

4.1 Input Reduction

Nano-urea, which contains 4% nitrogen, has emerged as an innovative solution to reduce

reliance on conventional urea, containing 46% nitrogen. The smaller particle size of nano-urea allows for better foliar penetration and utilization, significantly lowering the required application rate. Studies show that applying nano-urea at 30–50% of the conventional dose can achieve comparable or even superior crop yields. This is due to higher nitrogen use efficiency (NUE) and reduced wastage. For instance, an application of 150 kg N ha⁻¹ using nano-urea has shown equivalent productivity to 225 kg N ha⁻¹ using traditional urea (Kumar *et al.*, 2024). Such reductions also translate into lower fertilizer costs and environmental burden.

4.2 Loss Mitigation

One of the key advantages of NF is their ability to minimize nitrogen losses through leaching, volatilization, and denitrification. Traditional urea often results in significant nitrogen loss up to 50–60% due to its rapid solubility and conversion into gaseous or mobile forms. NF, on the other hand, offer controlled and targeted nutrient release, which significantly reduces these losses.

Research by Upadhyay *et al.*, (2023) reported that nitrogen losses can be reduced by 24–43 kg ha⁻¹ when nano urea is used in place of conventional urea, thanks to slower nutrient release and stronger binding in the root zone. Additionally, nano-fertilizers improve nitrogen use efficiency (NUE) by 10–20%, which is beneficial for crop productivity and environmental conservation. Reduced nitrogen losses help prevent nitrate leaching into groundwater, a common cause of contamination in intensive farming areas.

4.3 Higher Efficiency

NF significantly improve nutrient uptake efficiency due to their ultrafine particle size and high surface area, which enhance nutrient availability and mobility within the plant system. These fertilizers bypass conventional barriers such as soil fixation and pH-induced precipitation, allowing more nutrients to be absorbed through the leaves or root epidermis. For instance, foliar application of nano-urea or nano-Zn results in quicker assimilation compared to bulk fertilizers. Research shows a 5–15% increase in nutrient uptake, leading to better chlorophyll formation,

enzymatic activity, and overall plant vigour. In a field study, substituting 33% of the nitrogen requirement with nano-urea increased grain yield in wheat and maize by 0.5–1.2% over full-dose conventional urea, emphasizing improved efficiency and performance (Rathour *et al.*, 2024).

4.4 Economic and Environmental Benefits

The adoption of NF offers dual advantages: economic profitability and environmental sustainability. Economically, nano-fertilizers reduce the quantity of fertilizer required due to their higher efficiency and precision targeting. This significantly cuts down fertilizer input costs without compromising crop yields. A comparative study by Sharma *et al.*, (2023) found that mustard cultivation using nano-N and nano-Zn yielded a net return of 1,209 USD ha⁻¹, as compared to 1,071 USD ha⁻¹ with conventional fertilizer, primarily due to reduced fertilizer expenses and equivalent yield output.

Environmentally, NF mitigate the adverse impacts associated with traditional fertilizers. They reduce nitrate accumulation in soil, thereby minimizing nitrate leaching into groundwater—a major cause of water pollution and health hazards like methemoglobinemia ("blue baby syndrome"). Furthermore, lower nitrogen loss also means decreased nitrous oxide emissions, a potent greenhouse gas contributing to climate change. Overall, the transition to NF aligns with sustainable agriculture goals by improving resource use efficiency, reducing environmental footprint, and enhancing farmers' income.

5. Future Prospects of Nano Fertilizers

NF have promising prospects, aligning with global sustainability goals by minimizing chemical inputs and reducing environmental pollution. Their enhanced nutrient efficiency improves crop yields without increasing fertilizer use but supporting food security. Although initial production costs are high, long-term benefits such as reduced fertilizer consumption and increased productivity make them economically viable. Additionally, NF can be integrated into smart agriculture through precision farming technologies like the Internet of Things (IoT) sensors and drones, enabling real-time monitoring

of soil nutrient levels and optimized fertilizer application. This integration enhances resource efficiency, reducing waste and environmental impact. As agriculture moves towards more sustainable and high-tech solutions, NF are expected to play a crucial role in improving soil health, maximizing productivity, and ensuring long-term food security while minimizing ecological harm. Their adoption will likely increase as research and technological advancements make them more accessible and cost-effective for farmers worldwide.

In India, the launch of Nano Urea paints a bright scenario for reducing dependency on synthetic nitrogen fertilizers like urea. However, the fundamental mechanisms, mass balance, actual efficacy and mode of action of NF require extensive investigation to conclusively establish their effectiveness and accelerate widespread adoption.

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Accomplishments of IASWC members



Dr Basudev Behera, Professor & Head, Department of Agronomy, **Institute of Agricultural Sciences**, Siksha 'O' Anusandhan (Deemed to be) University, Bhubaneswar- 751 029 (Odisha) and **life member of IASWC, Dehradun** was inducted as Fellow of Indian Society of Agronomy, New Delhi on **24 November 2025** on the occasion of Sixth International Agronomy Congress held at New Delhi during **24-26 November 2025**. Dr Behera also worked as Member, QRT, IISWC, Dehradun for the period **2012-2017**.



Dr Subhash Chand received the SCSI-Book Award 2024 in the national conference held during **8-10 December 2025 at PAU-Ludhiana**.



Dr. Omvir Singh, Professor, Department of Geography, Kurukshetra University, Kurukshetra-136119, Haryana, India. **Attended 35th International Geographical Congress on Celebrating a World of Difference (2024)** held at **Dublin City University, Dublin, Ireland. August 24-30**.

Accomplishments of IASWC members



33rd National Conference on “Land and Water Management for Ecological Restoration and Agricultural Sustainability,” at Punjab Agricultural University Ludhiana w.e.f. 8-10 December, 2025

Soil Conservation Society of India in cooperation with Punjab Agricultural University, Ludhiana organized 33rd National Conference on “Land and Water Management for Ecological Restoration and Agricultural Sustainability,” at Punjab Agricultural University Ludhiana w.e.f. 8-10 December, 2025. The scientists, researchers, academicians, extension professionals, policymakers and stakeholders from 20 states and Union Territories participated in this conference and shared research findings on sustainable approaches and suggested innovative strategies for the long-term management of land and water resources.

The conference was attended by 275 registered delegates. The discussions were held under six themes. The conference successfully addressed critical national priorities related to sustainable land and water management, ecological restoration, and agricultural sustainability through six well-defined thematic areas.

In the inaugural function, Dr B.R. Kamboj, Vice-Chancellor, Choudhary Charan Singh Haryana Agricultural University, Hisar was the chief guest. The function was presided over by Dr S.S. Gosal, Vice-Chancellor, PAU, Ludhiana and Guest of Honour of the function was Dr. T.B.S. Rajput, President, SCSI, New Delhi. The technical session began with the Prof. J.S. Bali Memorial Lecture by Dr Jagdish Prasad, Former Principal Scientist, Division of Soil Resource Studies, ICAR-NBSSLUP, Nagpur. The session was chaired by Dr. T.B.S. Rajput, President, SCSI and co-chaired by Er. Shamsher Singh and Dr. J.P. Singh.

On the second day of National Conference, a special panel discussion was conducted on the topic Rehabilitation of Flood Affected Soils. The panel discussion was chaired by Dr. Satbir Singh Gosal PAU Vice-Chancellor. Dr. JK Singh and Dr. Ajmer Singh Dhatt were the special guests in the discussion. During this, experts including Dr Manmohanjit Singh, Dr. TBS Rajput, Dr. Rakesh Sarada, Dr. Rajiv Sikka, Dr. JP Sharma and Dr. Arya stressed on restoring the fertility and water-holding capacity of the land as well as advocated the importance of soil testing to check the correct status of soil carbon and nutrients. The experts stressed on working for early warning systems to identify flood-prone areas and urged farmers to adopt soil restoration techniques. On third day of the conference the field visits were organized to Amritsar, Kandi region of Punjab and to various facilities developed at PAU.

CONTRIBUTING TO WATERSHED BULLETIN

AIMS AND SCOPE

Watershed Bulletin, an annual publication of the Indian Association of Soil and Water Conservation, offers a unique platform for researchers and field functionaries in sustainable land and water resource management. It serves as a hub for interdisciplinary dialogue, bridging research-practice gaps, showcasing emerging trends, case studies, and national and international news on soil and water resource conservation and management. The bulletin's mission is to foster a comprehensive forum for stakeholders in natural resource management to exchange knowledge, share experiences, and contribute to sustainable practices that uphold environmental integrity and human well-being.

The bulletin seeks contributions on a wide range of topics related to sustainable natural resource management, including innovative approaches and technologies, critical gaps in policy and practice, emerging trends and challenges, inspiring case studies and field initiatives, news updates on environmental policies and events, reviews and analyses of key issues shaping the future of sustainable land and water resource use, and discussions on socio-economic factors influencing the adoption and effectiveness of conservation strategies. Manuscripts for the bulletin should revolve around a central idea of interest to the targeted audience. Unlike typical research papers, articles for the bulletin should not be data-intensive. Authors are encouraged to list the key takeaways of their manuscripts.

MANUSCRIPT PREPARATION GUIDELINES

Authors submitting to the Watershed Bulletin are advised to follow the general guidelines for manuscript preparation recommended by the Indian Journal of Soil Conservation. However, please omit the 'Methods and Material' and 'Results' sections. You have the flexibility to structure your manuscript as per your content's needs. However, it should include a title page with authors' affiliations and contact details, key takeaways in bullet form, an introduction, the main body of the article with suitable headings supported by tables, charts, photographs, a conclusion, and references.

SUGGESTED FORMAT FOR DEVELOPING A SUCCESS STORY

For: Watershed / NRM / Livelihood Projects:

1. Introduction:

- Describe context and the environmental and socio-economic challenges faced by the community prior to the project.
- Highlight the significance of watershed management in addressing these challenges, such as soil erosion, water scarcity, or livelihood insecurity (baseline information).
- Extent of area and beneficiary groups represented by project area.

2. Project Description:

- Provide a brief overview of the watershed development project, including its objectives, location, and duration.
- Detail the strategies, methodologies, and interventions employed during the project implementation phase.
- Discuss the involvement of stakeholders, including local communities, government agencies, NGOs, and other partners. Highlight any innovative approaches or technologies utilized.
- Outline the significant milestones reached throughout the project timeline.

3. Key Achievements:

- Quantify the impact achieved in terms of improved water availability, increased agricultural productivity, biodiversity conservation, and socio-economic empowerment.
- Include before-and-after statistics, such as changes in water quality, land use, crop productivity, or household income.
- Share individual or community success stories that illustrate the tangible benefits of the project. Include quotes or testimonials from beneficiaries, project staff, or local leaders to add authenticity and human interest.
- Incorporate photographs, maps, infographics, to illustrate the outcomes.

4. Sustainability and Scalability:

- Reflect on the sustainability of project outcomes beyond the implementation phase.
- Discuss capacity-building efforts, community ownership, and institutional support to ensure the long-term success of watershed management practices.
- Explore opportunities for replicating or scaling up the project model in other similar contexts.

5. Challenges and Lessons Learned:

- Acknowledge the challenges faced during project implementation and how they were addressed.
- Reflect on key lessons learned, including what worked well and areas for improvement in future projects.

6. Conclusion:

- Summarize the overall impact and significance of the watershed development project.
- Emphasize its contribution to environmental conservation, sustainable livelihoods, and community resilience.
- Conclude with a forward-looking statement about the project's legacy and future implications.

7. Additional Resources:

- Provide links or references to relevant reports, publications, or supplementary materials for further reading.

For Innovative SWC Technologies:

1. Introduction:

- Briefly introduce the target area and targeted problems. Intended objectives of the SWC technology.

2. Technology Description:

- Describe the theory and applied aspects of the SWC technology and methodology of its field execution.
- Highlight any initial challenges faced during implementation.

3. Impact and Achievements:

- Showcase the intended and measurable benefits of the technology (e.g., increased water savings, reduced soil erosion, improved soil health, higher crop yields).
- Use quantifiable data (e.g., percentage increase in yield, water use reduction) and visuals like charts or before-and-after photos to illustrate the impact.
- Include a quote from the beneficiary expressing their perspective on the technology's benefits.
- Consider discussing any unintended broader environmental benefits achieved through the technology (e.g., improved land quality, water table levels, reduced pollution).

4. Sustainability and Scalability:

- Describe how the farmer plans to maintain the technology and its benefits for the long term (e.g., maintenance plans, knowledge sharing with other farmers).
- Briefly mention the potential for scaling up the technology to other farms in the region.

5. Conclusion (A Lasting Impression):

- Briefly summarize the key takeaways of the success story.
- Emphasize the effectiveness of the technology in promoting soil and water conservation, leading to environmental and economic benefits.

6. Additional Tips:

- Keep in mind targeted audience, which are researchers and field practitioners in the field of land and water management, and tailor the language accordingly.
- Choose a title that grabs attention and reflects the success of the technology.
- Use a clear and engaging writing style to showcase the story's impact. Include references to data sources (e.g., yield reports, soil health tests) and any organizations involved in implementing the technology.

For further details and clarifications, please contact:

Dr Rajive K. Singh

Chief Editor

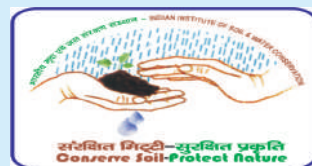
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“Save Soil Campaign”



“Upon this handful of soil our survival depends. Husband it and it will grow our food, our fuel, and our shelter and surround us with beauty. Abuse it and the soil will collapse and die, taking humanity with it”

From Atharvavedas (Sanskrit Scripture) – 1500 BC

“I pledge to intensify our endeavours to protect and improve soil resources that surround us in order to restore and maintain a sound ecological balance in land, air, and water. I commit myself to promoting public awareness and education on the “Save Soil Campaign” as well as the public reporting of the environmental impact of various activities being taking place on the thin layer of SOIL. I believe it is our responsibility to take care of soil and land resources so that it remains available in good condition to my children and grand children (for generations). I also pledge to continue promoting the benefits of soil conservation for the sake of human's well being”.

Facts and Popular quotes about the importance of soil resources

- ☐ It can take more than 1,000 years to form a centimeter of topsoil
- ☐ In a handful of fertile soil, there are more individual organisms than the total number of human beings that have ever existed
- ☐ There are over 100,000 different types of soil in the world
- ☐ Five tonnes of animal life can live on one hectare of soil
- ☐ SOIL is “Soul of infinite life”
- ☐ Listen to soil, if you have ears - Jesus
- ☐ Take good care of me or else, when I get hold of you, I shall never let your soul go - Kipsigis proverb cites soil as saying to man
- ☐ We know more about the movement of celestial bodies than about the soil underfoot - Leonardo da Vinci
- ☐ Soil is a storehouse of Carbon to mitigate Climate change
- ☐ A land without a Farmer becomes barren
- ☐ Agriculture connects Farmer, Land and Nature
- ☐ Soil sustains all life on the Earth
- ☐ Farmers are the Human factors in soil Management
- ☐ Farmers first in soil and water conservation: Beginning the Journey towards a new vision
- ☐ Farmers heal the land

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