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ORIGINAL ARTICLE

Indian Journal of Soil Conservation

Living with nature: A cultural and scientific perspective

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ABSTRACT

Human society, in its dual role, significantly influences both the destruction and protection of Earth's systems. As societal values, priorities, and perceptions evolve under the influence of scientific and technological developments, there exists a critical opportunity to redirect these dynamics toward fostering a more harmonious relationship between humans and nature. The continuous development of science, coupled with art forms that express ecological concerns, provides a powerful means to influence cultural narratives and reinforce environmental protection efforts. This paper explores how traditional and emerging cultural elements can support environmental stewardship and how advancements in science and creative disciplines can further strengthen these efforts. By weaving together cultural threads that favour ecological balance and sustainable practices, this study suggests strategies for leveraging human ingenuity to safeguard natural resources while acknowledging the inherent responsibility of humanity in both the degradation and preservation of natural ecosystems.

HIGHLIGHTS

- Human behaviour is crucial in damaging and restoring the earth's systems.
- Cultural values and practices are constantly evolving under the influence of advancements in science and art forms.
- There is a need and scope to realign societal frameworks with ecological principles.

1 | INTRODUCTION

The world is currently grappling with a severe environmental crisis, marked by widespread degradation and unsustainable consumption of resources. This not only poses a threat to our current livelihoods but also endangers the prospects of future generations. As the global population continues to grow, the increasing demands for agriculture, urbanization, and industrial development have led to the widespread conversion of natural landscapes. Approximately 75% of terrestrial ecosystems have been significantly altered by human actions, primarily through deforestation, land-use change, and unsustainable agricultural practices (IPBES, 2019). In India, 29.3% of the total land area, about 96.4 M ha, is undergoing desertification, largely due to over-cultivation, deforestation, and improper land management (ISRO, 2016). India, as the largest user of groundwater, extracts 251 billion cubic m/year, with 60% of its districts facing critical groundwater depletion (CGWB, 2020). Pollution from industrial effluents, agricultural runoff, and untreated sewage further exacerbates water quality issues, with over 351 river stretches in India classified as highly polluted (NGT, 2020). These factors disrupt the hydrological cycle, reduce water availability, and degrade aquatic ecosystems. Over 1 million flora and fauna species are at risk of extinction globally, threatening ecosystem services that support human life, such as pollination, clean air, and fertile soil. In India, the rapid loss of forests, wetlands, and other natural habitats due to human encroachment has placed critical ecosystems like the Western Ghats and the Sundarbans under severe stress. Additionally, the loss of biodiversity and ecosystem services can lead to ecosystem collapse, directly affecting agriculture, livelihoods, and climate resilience (IPBES, 2019). Recognizing the urgent need to mitigate the adverse effects of human activity on the planet's ecosystems, the Sustainable Development Goals (SDGs) were established by the United Nations in 2015. These goals emphasize that economic growth, social inclusion, and environmental protection must go hand in hand to achieve long-term development.

The potential impact of technology, infrastructure, policy support, and government initiatives is inherently limited unless individuals, communities, and organizations have a collective prioritization and unwavering commitment to environmental conservation. This requires a concerted effort to integrate sustainable practices into daily operations, promote eco-friendly behaviours, and advocate for policies that prioritize environmental protection and preservation. To make environmental awareness a people's movement, there is a need and scope to carefully analyse and manoeuvre cultural perceptions and values towards a harmonized coexistence of man and nature. Cultures of diverse human societies are ever-evolving under the influence of scientific advancements, changing lifestyles, and shifting perceptions and sensibilities towards nature and art forms. A harmonious blend of art, science, and culture can provide practical tools to mobilise communities in this direction. While science provides analytical tools and methodologies, art brings creativity and emotion, and culture instils values and traditions that guide our actions. This article explores how the intersection of art, science, and culture plays a pivotal role in conserving our precious natural resources.

2 | The Interplay of Science, Art and Culture in Natural Resource Conservation

The threesome of Science, Art, and Culture (SAC) play a crucial role in our constantly changing society that resonates through time (Table 1). Culture helps us stay grounded, while science and art propel us forward. While these pursuits are often seen as separate, they have a fascinating interplay that influences and shapes each other in an ongoing loop, driving the story of human evolution (Benton and Jane, 2005). With its relentless quest for knowledge, science provides the foundation upon which much of art and culture are built. Artistic interpretations of scientific discoveries, like the celestial imagery inspired by astronomy or the intricate sculptures reflecting the human form revealed by anatomy,

TABLE 1 The Elements of Art Science and Culture

	Art: a diverse range of human activities and creations that express ideas, emotions, and experiences	**Science:** systematic enterprise that builds and organizes knowledge	**Culture:** shared beliefs, values, customs, traditions, behaviours, and artefacts
Purpose (Over-arching reason)	To enrich human experience and foster cultural identity. To inspire, entertain, and provoke dialogue. To document history, culture, and human expression.	To advance human understanding and knowledge, solve complex problems and challenges, improve the quality of life and address societal needs.	To strengthen social cohesion and solidarity. To celebrate human creativity and ingenuity. To promote tolerance, diversity, and inclusivity. Transmit knowledge and values across generations.
Aims (overall goals)	To express emotions, ideas, and perspectives. To evoke thought, emotion, and connection. To provide a platform for creativity and innovation.	To understand the natural world and its phenomena. To explain and predict observations through empirical evidence. To develop theories and models that expand human knowledge.	To preserve and transmit shared beliefs, values, and practices. To foster a sense of identity and belonging. To promote cross-cultural understanding and appreciation.
Objective (specific time-bound targets)	To create works that communicate messages or narratives. To evoke aesthetic experiences and appreciation. To challenge societal norms and provoke critical thinking.	To conduct research & experimentation, test hypotheses and theories, & develop practical applications and technologies.	To promote cultural heritage and diversity. To facilitate intercultural dialogue and exchange. To address issues of cultural identity and representation.
Scope	Visual arts (painting, sculpture, photography, etc.). Performing arts (music, dance, theatre, etc.). Literary arts (poetry, prose, literature, etc.). Applied arts (architecture, design, fashion, etc.).	Natural sciences (physics, chemistry, biology, etc.). Social sciences (psychology, sociology, economics, etc.). Formal sciences (mathematics, logic, computer science, etc.).	Material culture (artefacts, architecture, monuments, etc.). Intangible culture (language, traditions, rituals, etc.). Popular culture (music, film, fashion, etc.).
Core Values	Creativity and innovation. Expression and communication. Aesthetic appreciation and interpretation.	Skepticism, critical thinking, and the pursuit of knowledge. Empiricism and objectivity. Intellectual rigour and accuracy. Collaboration and peer review.	Tradition and innovation. Respect and inclusivity. Heritage and identity preservation. adaptation to changing environments.
Focus	Creativity, expression, and communication through various mediums, such as visual arts, performing arts, literature, and more. Emphasizes subjective interpretation, aesthetics, emotion, and personal expression. It explores human experiences, perspectives, and ideas.	Understanding the natural world, exploring phenomena, and generating knowledge through systematic observation, experimentation, and analysis. Emphasizes objectivity, empirical evidence, logic, and scientific methods.	Shared beliefs, values, customs, traditions, and practices define and shape human societies and communities. Emphasizes identity, diversity, heritage, and social interaction.
Drivers	Personal expression and exploration. Cultural and societal influences. Technological advancements and new mediums.	Curiosity & exploration. Technological advancements and tools. Societal needs and challenges.	Historical legacies and traditions. Intergenerational continuity. Globalization and cultural exchange. Social movements and activism.
Impact	Inspires creativity, fosters empathy, challenges perceptions, and contributes to cultural identity and social change.	Drives technological innovation, improves quality of life, addresses global challenges, and shapes public policy and decision-making.	Shapes individual and collective identities, fosters cross-cultural understanding, influences social norms and behaviors, and preserves heritage and traditions.

bridge the gap between the objective and the subjective (Duncan, 2007). Art forms ignite scientific curiosity through nature depictions and thought-provoking installations that challenge assumptions and inspire new questions (Malina, 2015). The influence of technology on the creation and sharing of art goes beyond just providing inspiration. Science and technology have transformed the way art is made and experienced. From digital tools used for visual arts to the global reach of social media for performance arts, technology plays a crucial role in shaping the world of art (Kramsch, 2010). Similarly, art can inform scientific communication. Compelling data visualizations and captivating documentaries translate complex scientific concepts into a language accessible to a broader audience, fostering scientific literacy and public engagement (Dunbar, 2018).

Culture is the bedrock upon which both science and art flourish, providing the social context and framework within which they operate. Cultural beliefs, traditions, and practices influence scientific inquiry, shaping research priorities, methodologies, and interpretations. For instance, indigenous cultures have developed complex knowledge systems about their surroundings, which are often reflected in their traditions and art. These can provide valuable insights for scientific research and inspire new perspectives for understanding the world (Agrawal, 2000). The interplay between SACs is dynamic and reciprocal, driving societal progress and transformation. The impact of interconnectedness is evident in our constantly evolving society. As science advances, our understanding of the world changes, and art reflects these new realities, sparking discussions about important issues such as climate change and artificial intelligence. Culture also evolves, incorporating these ideas and concerns into social norms and traditions.

In the context of human and nature interaction, science serves as the foundation for understanding the intricacies of our ecosystems. Scientific pursuit provides essential data to identify environmental challenges and formulate effective conservation strategies. Understanding the impacts of human activities on climate change, ecosystem processes, and the quality of the natural resource base is crucial for sustainable management. In recent years, technological advancements in remote sensing, Geographic Information Systems (GIS), and data analytics have propelled environmental science forward and helped inform conservation efforts decision-making. Art forms are vital in communicating environmental issues to a broader audience. Through paintings, sculptures, music, and literature, artists evoke emotions that resonate with people on a visceral level. This emotional connection often serves as a catalyst for change. Public art installations focused on environmental themes, for instance, can transform urban spaces into platforms for environmental awareness. Street art depicting endangered species or thought-provoking sculptures made from recycled materials are potent reminders of the need for conservation. Art can transcend language barriers, making it a universal medium to inspire action. To embed and strengthen conservation in cultural value systems, we need to gain insight into how societies interact with their environment. Indigenous knowledge, traditional practices, and cultural rituals often hold profound wisdom for sustainable living. Many cultures worldwide have long-standing traditions of living in harmony with nature, emphasizing the interconnectedness of all living things. Preserving cultural practices that promote conservation is crucial. From sustainable farming techniques to water management practices passed down through generations, cultural values can inform modern conservation strategies. Recognizing and respecting diverse cultural perspectives fosters collaboration and ensures that conservation efforts are inclusive and culturally sensitive.

The synergy of SAC in natural resource conservation efforts is evident in various initiatives worldwide. Collaborative projects bring together scientists, artists, and local communities to address environmental challenges creatively. Murals depicting local ecosystems, scientific discoveries presented through storytelling, and community-led conservation projects showcase the potential of this interdisciplinary approach. One notable example is the "BioArt" movement, where artists collaborate with scientists to create living artworks using biological materials (Kac, 2007). These projects generate public interest and highlight the beauty and fragility of the natural world. Through this fusion of art and science, a deeper understanding of the environment emerges, fostering a sense of responsibility for its preservation.

3 | Cultural Threads in Support of Environmental Protection

Cultural threads linked with environmental protection refer to the interconnected values, beliefs, traditions, and practices within societies that contribute to a collective commitment to safeguarding the environment. These cultural elements play a crucial role in shaping attitudes, behaviours, and policies related to environmental conservation. Over the centuries of their civilized existence, communities have developed rich knowledge systems, cultural values, traditions, and religious beliefs to live in harmony with nature in India's highly diverse agroclimatic landscapes.

3.1 | Indigenous Wisdom and Traditional Knowledge

India boasts a rich tapestry of cultures, each with unique practices and beliefs deeply intertwined with nature. Traditional wisdom, passed down through generations, emphasizes harmony with the environment, recognizing the interconnectedness of all living beings. India's diverse landscape and long history of agriculture have fostered a wealth of traditional practices that promote environmental sustainability. Indigenous communities across the country possess invaluable insights into local ecosystems and sustainable resource utilization. Their traditional knowledge, rooted in centuries-old practices, offers holistic approaches to environmental stewardship. Here is a deeper look at some of these time-tested methods:

3.1.1 | Cropping Patterns: Farmers have traditionally been planting time-tested crops based on specific seasons and rainfall patterns (FAO, 2011; Kumar and Purohit, 2015). This optimizes water usage and ensures crops mature during the most favourable conditions. Specific crop combinations are chosen for their beneficial interactions. Crop diversification in mixed cropping, intercropping, agroforestry, or multiple cropping systems has been done by indigenous and time-tested farming systems in different parts of India. Some examples of traditional cropping patterns in India include:

- **Crop Rotation:** In the Deccan Plateau region, farmers traditionally practice a crop rotation cycle involving bajra or pearl millet (*Pennisetum glaucum*), pulses like lentils (*Lens culinaris*), and oilseeds like sesame (*Sesamum indicum* L.). Bajra is a drought-resistant crop that helps fix loose soil due to its fibrous roots and extended culums, while pulses replenish nitrogen through biological nitrogen fixation. Sesame thrives in the loosened soil and adds oilseed diversity. In the Karnataka region, farmers rotate crops such as paddy (*Oryza sativa*), finger millet (*Eleusine coracana*), pigeon pea (*Cajanus cajan*), and groundnut (*Arachis hypogaea*) in the same field seasonally. In the Indo-Gangetic plains and other irrigated areas, a traditional cropping pattern involves the rotation of paddy and wheat crops. Farmers rarely integrate leguminous crops in this rotation; besides, there is much evidence of the usefulness of legumes in the rotation (Singh *et al.,* 2018). This practice is against the law of nature to become less dependent on external inputs and against nature's ecosystem services like fixing atmospheric nitrogen through biological activities, destroying soil structure due to soil puddling for growing paddy, and increasing reliance on external inputs like chemical fertilizers.
- **Mixed Cropping in Dryland Farming:** In many regions of India, especially in the semi-arid tropics, farmers traditionally cultivate a mix of millets such as sorghum (*Sorghum bicolor*), pearl millet, and finger millet along with pulses like pigeon pea, chickpea (*Cicer arietinum*), and green gram. Additionally, they may include oilseeds such as groundnut or sesame. This diversification ensures food security and enhances soil fertility and resilience to climate variability. Companion planting practices in traditional home gardens of Tamil Nadu, where vegetables like tomato (*Solanum lycopersicum*), brinjal (*Solanum melongena*), and chilli (*Capsicum annuum*) are interplanted with aromatic herbs like basil (*Ocimum basilicum*) and mint (*Mentha*). This companion planting deters pests and enhances flavour and aroma in culinary preparations.
- **Agroforestry Systems:** Traditional agroforestry systems in India often involve integrating fruit-bearing trees like mango (*Mangifera indica*), guava (*Psidium guajava*), or jackfruit (*Artocarpus heterophyllus*) with annual or perennial crops such as vegetables, spices, or medicinal plants. This diversification provides multiple benefits, including enhanced biodiversity, soil conservation, and supplementary income for farmers.
- **Terrace Farming with Multiple Crops:** In hilly regions such as Uttarakhand and Himachal Pradesh, farmers practice terrace farming, where they grow a variety of crops such as millets, rice, wheat, maize, potatoes, and vegetables on terraced slopes. This diversification optimizes land use, minimizes soil erosion, and ensures food security in mountainous areas.

3.1.2 | Water Management Systems: In the monsoon-based hydrological cycle of India, water scarcity has always been a major concern in many parts of the country. This has motivated communities to develop ingenious methods to capture, store and recycle rainwater in ingenious ways. Some of the surface and sub-surface rainwater harvesting systems are listed here:

- **Ahni System:** This intricate network of underground channels in the Himalayan foothills captures rainwater runoff from mountain slopes. The water is then channelled towards agricultural fields for irrigation.
- **Kattas:** These are trenches dug across fields in southern India. Rainwater collects in these trenches and slowly infiltrates the soil, increasing soil moisture and groundwater recharge.
- **Eris (lakes):** In Tamil Nadu, there are elaborate networks of channels for distribution.
- Bandhis (reservoirs) in Rajasthan are often built near hills to collect rainwater flowing down slopes.
- **Tankas:** These are unique underground structures built in Rajasthan's Thar desert. They consist of a cylindrical well with an inverted earthen cone-shaped roof. Rainwater entering the tank percolates through the sandy soil, replenishing groundwater reserves.
- **Paar System:** A sub-surface community water harvesting system in western Rajasthan where rainwater is collected under the desert's sandy soil over an impervious sub-surface bed. The local community retrieves the collected water through specially designed multiple cylindrical wells (Kuis), generally 5-12 m deep.
- **Khadin:** Harvesting rainwater on farmland for subsequent use for crop production during post-monsoon season.

- **Zabo system:** A bamboo channel network that diverts rainwater from hillsides to terraced rice paddies in Nagaland. This ingenious system minimizes water loss and irrigates crops efficiently.
- **Rooftop harvesting:** Some communities traditionally collected rainwater from rooftops. This practice is gaining renewed interest due to urbanization. In some regions, houses were designed with sloping roofs to direct rainwater into storage tanks. The courtyards were designed to channel water into underground storage.
- **Johad:** These crescent-shaped earthen embankment-type structures collect rainwater for groundwater recharge and community consumption. These are quite popular in Rajasthan and adjoining states.

3.1.3 | Traditional seed Saving: Traditional seed saving is an eco-friendly practice deeply rooted in India's agricultural heritage. Indian farmers save seeds from one harvest to the next, selecting those well-suited to local conditions. This practice preserves agricultural biodiversity, reduces reliance on commercial seeds and agrochemicals, and supports agroecosystems. It empowers small farmers, preserves unique varieties, and promotes sustainable farming practices and ecological balance in India.

3.1.4 | Composting: Culturally, Indian farmers prefer waste recycling. After composting, soil nutrients from farm waste and animal dung are generally returned to farm fields. There is a scope for minimizing nutrient losses with more scientific composting methods. In the Western Ghats, farmers use a traditional practice called "**Jeevamrutha.**" which involves fermenting cow dung, urine, jaggery (unrefined cane sugar), and local flours. The resulting liquid is used as a natural fertilizer and soil conditioner, promoting microbial activity and nutrient availability. Another ancient practice, **Panchagavya**, involves a five-element concoction using cow dung, urine, milk, ghee, and curd. Used as a natural fertilizer and pest repellent, Panchagavya promotes soil fertility and reduces reliance on chemical inputs.

3.1.5 | Pest management: Traditional methods of pest control were a selection of crop varieties naturally resistant to pests prevalent in their region and the use of natural pesticides such as Neem leaves, turmeric, and chilli peppers in organic concoctions to repel insects and other pests. Also, farmers practised creating sites for birds that prey on insects, promoting natural pest control. Farmers in parts of Tamil Nadu plant marigolds (tagetes) around their cotton crops. The marigolds add colour and deter harmful nematodes (roundworms) that attack cotton roots. They also attract ladybugs, natural predators of other destructive insects. Traditional rice farmers in Andhra Pradesh use natural predators such as frogs and ducks to control pests like rice leafhoppers and rice borers.

These indigenous traditional practices generally rely on locally available resources, minimizing dependence on expensive chemical inputs, reducing the cost of cultivation, and promoting self-sufficiency. These organic practices promote healthy soil ecosystems, increasing fertility and crop yields. Diverse cropping patterns and avoiding pesticides create habitats for beneficial insects and pollinators. Traditional water management techniques and drought-resistant crop varieties enhance resilience to climate change. Revising and integrating these practices with modern scientific advancements can create a more sustainable and secure agricultural future for India.

3.2 | Spiritual and Religious Beliefs

Several religious and spiritual traditions incorporate teachings that highlight the sacredness of nature and the responsibility to be stewards of the Earth. These beliefs can inspire environmental ethics and a sense of reverence for the natural world. All religious faiths of Indian origin have particular reverence for nature, viewing it as divine and sacred. Hinduism holds nature in high regard, viewing it as sacred and divine. The concept of "*Vasudhaiva Kutumbakam*" (the whole world is one family) emphasizes interconnectedness and the duty to protect all life forms. Hindus often worship various elements of nature, including rivers, trees, and animals, considering them manifestations of deities. Sikhism emphasizes the interconnectedness of all creation and the duty to serve humanity and nature. Buddhist teachings advocate living in harmony with nature and practicing mindfulness daily. Concepts like "*Ahimsa*" (non-violence) extend to environmental ethics, encouraging individuals to minimize harm to the environment and all living creatures. Jains are known for their strict adherence to vegetarianism and practices aimed at minimizing harm to living beings, including environmental conservation efforts such as water and energy conservation. India's other indigenous communities, such as the *Adivasis* and tribal groups, possess rich spiritual traditions closely tied to nature. Their animistic beliefs regard natural elements as sacred, and their spiritual practices often revolve around maintaining balance and harmony with the environment. In the context of environmental protection, vital elements of Indian religious faiths are:

3.2.1 | Reverence for Nature: The ancient Hindu scriptures contain hymns praising the elements of nature, such as rivers, mountains, and forests, highlighting their importance in sustaining life. By respecting and protecting the earth and its resources, individuals uphold their religious duty and contribute to the well-being of all living beings. The Bhagavad Gita (Chapter 3, Verse 14) says that all living beings subsist on food grains from rain. Rain is produced by performing yajna (sacrifice), and yajna is born of prescribed duties (अन्नाद् भवन्ति भूतानि पर्जन्याद् अन्न सम्भवः। यज्ञाद् भवति

पर्जन्यो यज्ञः कर्म समुद्भवः ॥). Further, to emphasize our dependence on nature for sustenance, the Atharvaveda (12.1.3) says that the earth is the mother, the sky is the father, and the rain is the womb. By that (rain), all this universe is pervaded; it moves therein (पृथिवी माता धरणी धर्या पर्जन्यो योनिः सूर्यः पितां । तेनेदं विश्वं विभजन्ति सधस्थाद् अप इति विश्वम् ॥). Another shloka that highlights the religious importance of land, water, and the ecosystem is from the Rigveda: अपो वा इव देव्यो यथा रस्यो अमृता भुवनानि विश्वां । यो वै भूमा तत्सुखं तेन मा नो भूमि विश्वायाः कर्तव्या ॥ Which means "Just as the divine waters, like nectar, pervade the entire world, so does that which is vast bring happiness. Therefore, let us not harm the earth, the source of sustenance for all beings." These hymns underscore the sacredness and life-sustaining nature of water and the earth. It emphasizes the interconnectedness of all beings with the land, water, and ecosystem, urging humans to treat the environment with reverence and care.

3.2.2 | *Ahimsa* (Non-violence): Ahimsa is a fundamental tenet of Hindu, Jain, and Buddhist religions, advocating non-violence toward all living beings. This principle extends to environmental ethics, promoting the conservation of natural resources and minimizing harm to ecosystems.

3.2.3 | Sacred Rivers: Rivers hold a special significance in Hinduism, with the Ganges, Yamuna, and other rivers considered sacred. Hindus perform rituals and ceremonies along riverbanks, emphasizing the importance of water purity and conservation. Initiatives like river clean-up drives and campaigns to protect these rivers align with Hindu beliefs.

3.2.4 | Sacred plants: Trees are revered in Hinduism, symbolizing life, fertility, and prosperity. The Banyan, Peepal, and Neem trees hold particular significance and are often worshipped. Hindu festivals like Vat Purnima and Vana Mahotsava celebrate the importance of trees and promote afforestation efforts (Table 2).

TABLE 2 Some sacred plants of India with their ecological and cultural significance

S.No.	Plants	Ecological significance	Cultural significance	Suitable agro-eco condition
1	Tulsi (*Ocimum sanctum*)	Attract pollinators such as bees and butterflies, contributing to ecosystem biodiversity. They also emit volatile compounds that can repel pests, reducing the need for chemical pesticides.	Considered the embodiment of the goddess Lakshmi. Planted in households and temples to purify the surroundings and ward off negative energies. Medicinal properties (respiratory disorders, fever, and digestive issues.	Warm and humid tropical climates Well-drained loamy soils rich in organic matter
2	Peepal, Bodhi tree (*Ficus religiosa*)	Provide habitat and food for various birds, insects, and small mammals. Their large canopy helps regulate temperature, reduce soil erosion, and improve air quality.	Holds significance in Hinduism, Buddhism, and Jainism; considered sacred symbol of wisdom and longevity	Tropical and subtropical climates with ample sunlight Well-drained soils with medium fertility
3	Banyan (*Ficus benghalensis*)	Support a diverse ecosystem by providing shelter and food for birds, bats, & epiphytic plants. Their aerial roots help stabilize soil and prevent erosion in riparian areas.	Associated with the Trimurti - Brahma, Vishnu & Shiva. It symbolizes eternal life and the interconnectedness of all living beings and is often associated with spiritual wisdom and enlightenment.	Tropical and subtropical climates with high humidity Deep, well-drained soils with good water-holding capacity
4	Neem (*Azadirachta indica*)	Have allelopathic properties, meaning they release chemicals that inhibit the growth of competing vegetation. This can help control weed growth and maintain biodiversity in ecosystems where neem trees are present.	Sacred in Hinduism for its medicinal properties and is associated with the goddess Sitala, believed to ward off evil spirits and is used in various religious rituals.	Thrives in hot and dry tropical climates. Adaptable to various soil types but prefers well-drained sandy
5	Ashoka (*Saraca asoca*)	Provide shade, enhance aesthetic appeal, and support urban biodiversity by attracting pollinators.	Revered in Hinduism and Buddhism for its association with love, compassion, and fertility. It is often planted in temple courtyards and is considered auspicious for weddings	Subtropical to tropical climates with moderate rainfall Well-drained, fertile soils with good moisture retention
6	Amla (*Phyllanthus emblica*) or Indian Gooseberry	Produce small, greenish-yellow flowers that attract pollinators like bees and butterflies. They also provide food for birds and other wildlife, contributing to ecosystem biodiversity.	Considered sacred in Hinduism and is associated with the goddess Lakshmi. It is used in religious rituals and is believed to have medicinal & rejuvenating properties. Rich in vitamin C and antioxidants	Subtropical to tropical climates with hot summers: Well-drained loamy soils with slightly acidic pH
7	Mango (*Mangifera indica*)	Valuable for agroforestry systems, providing shade, soil stabilization, and habitat for birds and insects. Fruits are consumed by various wildlife species, contributing to ecosystem food chains.	Prosperity & fertility symbol in Hinduism; Leaves used in religious ceremonies, and the tree is considered auspicious in many Indian households	Tropical climates with distinct dry and wet seasons Well-drained, deep soils with good aeration
8	Bel, Bilva (*Aegle marmelos*)	Well adapted to dry, tropical climates and can help mitigate soil erosion and desertification. Provide shelter and food for wildlife and contribute to the regeneration of degraded landscapes.	Sacred to Lord Shiva in Hinduism. Its leaves, fruit, and roots are used in religious rituals and offerings to Lord Shiva.	Subtropical to tropical climates with moderate rainfall. Well-drained sandy loams or loamy soils
9	Coconut (*Cocos nucifera*)	Important coastal species that stabilize dunes, prevent erosion & protect coastal habitats from storms & high tides. They also provide nesting sites for seabirds and turtles.	Associated with purity and prosperity. Used in various religious ceremonies and offerings to deities. Breaking a coconut is a common practice to symbolize the breaking of the ego and offering oneself to the divine.	Tropical coastal climates with high humidity Sandy soils with good drainage and ample moisture

TABLE 2 Continued...

S.No.	Plants	Ecological significance	Cultural significance	Suitable agro-eco condition
10	Sandalwood (*Santalum album*)	Hemiparasitic, meaning they obtain some of their nutrients from host plants. Regulating host plant populations and contributing to the diversity of forest ecosystems.	Revered in Hinduism for its fragrance and cooling properties. Sandalwood paste is believed to have spiritual significance.	Subtropical to tropical climates with distinct dry and wet seasons Well-drained sandy loams or lateritic soils.
11	Kadamba (*Neolamarckia cadamba*)	Fast-growing species that provide shade and habitat for birds and small mammals. Their fruits are consumed by wildlife, contributing to seed dispersal and regeneration in forest ecosystems.	Associated with Lord Krishna in Hindu mythology and is often mentioned in religious texts and poetry. Its flowers are offered to Lord Krishna in worship.	Tropical climates with high humidity and moderate rainfall Moist, well-drained soils with good organic content.
12	Lotus (*Nelumbo nucifera*)	Aquatic perennials that provide habitat and food for fish, amphibians, and waterfowl. They help improve water quality by absorbing nutrients and pollutants from aquatic environments.	Symbolizes purity, enlightenment, and spiritual growth associated with deities like Lakshmi, Saraswati, and Buddha	Thrives in warm temperate to tropical climates Muddy or silty soils with shallow water, such as ponds or marshes.
13	Jasmine (*Jasminum sambac*)	Attract pollinators such as bees, butterflies, and moths, enhancing biodiversity in gardens and natural habitats. Their fragrance can also deter pests, reducing the need for chemical pesticides.	Associated with various Hindu deities, including Vishnu and Shiva.	Warm tropical to subtropical climates with ample sunlight Well-drained loamy soils with good fertility
14	Shankhpushpi (*Clitoria ternatea*)	Valued for their nitrogen-fixing abilities, enriching soil fertility and supporting plant growth in agricultural and natural ecosystems. They also attract pollinators and beneficial insects.	Associated with Lord Vishnu in Hindu mythology. It is used in traditional medicine for its memory-enhancing and calming properties.	Warm tropical climates with moderate rainfall Well-drained sandy loams or loamy soils.
15	Rudraksha (*Elæocarpus ganitrus*)	Provide habitat and food for birds and small mammals. Their fruits are eaten by various wildlife species, contributing to seed dispersal and forest regeneration.	Considered sacred in Hinduism and are believed to have spiritual and medicinal properties. They are worn as prayer beads and are associated with Lord Shiva.	Subtropical to tropical climates with moderate rainfall Well-drained sandy loams with good moisture retention.
16	Guggul (*Commiphora wightii*)	Small shrubs native to arid regions of India. These shrubs help stabilize soil, prevent erosion, and provide habitat for desert wildlife.	Resin is used in Ayurvedic medicine for its healing properties and is considered sacred in Hindu rituals. It is believed to purify the atmosphere and ward off negative energies.	Arid and semi-arid climates with hot summers, Sandy or rocky soils with good drainage
17	Haritaki (*Terminalia chebula*)	Contribute to biodiversity by providing food and shelter for birds, insects, and mammals. in tropical and subtropical forests	One of the three ingredients of Triphala, a traditional Ayurvedic formulation. It is considered sacred and is believed to promote longevity, good health, and spiritual well-being.	Thrives in warm subtropical to tropical climates Well-drained loamy soils with neutral to slightly acidic pH.
18	Arjuna (*Terminalia arjuna*)	Stabilize soil, prevent erosion, and provide shade for aquatic organisms along river banks and in riparian habitats. Fallen leaves enrich riverbed soils	Bark is used in Ayurvedic medicine for cardiovascular health.	Subtropical to tropical climates with moderate rainfall. Well-drained sandy or loamy soils.
19	Deodar (*Cedrus deodara*)	Provide habitat for mountain wildlife and contribute to watershed protection and soil stabilization in alpine ecosystems.	Associated with Lord Shiva. It is used in religious ceremonies and is believed to have purifying properties.	Cool temperate to sub-tropical climates with ample moisture. well-drained loamy soils with good organic content
20	Turmeric (*Curcuma longa*)	Cultivated in low-light landscapes and home gardens. Their dense foliage helps prevent soil erosion and conserves soil moisture.	Considered sacred in Hindu rituals and ceremonies. Believed to have purifying and healing properties.	Tropical to subtropical climates with well-distributed rainfall. Well-drained sandy loams with good organic matter
21	Brahmi (*Bacopa monnieri*)	Found in wetlands, marshes, and along stream banks. They stabilize soil, filter water, and provide habitat for aquatic organisms and wetland wildlife.	Memory-enhancing and cognitive-boosting properties. Associated with the Hindu goddess Saraswati.	Wetland and marshy habitats in tropical to subtropical climates Moist, fertile soils with high organic content.
22	Kachnar (*Bauhinia variegata*)	Deciduous species found in dry forests and scrublands. Provide food for wildlife and support pollinators, contributing to ecosystem resilience and biodiversity.	Associated with the goddess Parvati. Its flowers are used in religious ceremonies and are believed to have medicinal properties.	Subtropical to tropical climates with distinct dry & wet seasons well-drained sandy loams or loamy soils.
23	Atasi (*Linum usitatissimum*) or Flaxseed	Cultivated for their oil-rich seeds and fibre. Supports pollinators and beneficial insects and can be intercropped with other crops to enhance biodiversity in agricultural landscapes.	Atasi, or Flaxseed, is considered sacred in Hindu rituals and ceremonies. It is used in religious offerings and is believed to have medicinal	Cool temperate to sub-tropical climates with moderate rainfall Well-drained loamy soils with good moisture retention.
24	Shatavari (*Asparagus racemosus*)	Native forest spp. provide food and habitat for wildlife and contribute to soil fertility and moisture retention in their ecosystems.	Rejuvenating and nourishing properties. Used as a tonic for women's health and is associated with the goddess Shakti.	Subtropical to tropical climates with moderate rainfall Moist, well-drained sandy loams with high organic content.

TABLE 2 Continued...

S.No.	Plants	Ecological significance	Cultural significance	Suitable agro-eco condition
25	Parijat (*Nyctanthes arbor-tristis*)	Cultivated for their fragrant flowers, which attract pollinators such as bees & butterflies. They enhance biodiversity in gardens and urban green spaces.	Associated with themes of love, devotion, and longing due to its ethereal nighttime blooming	Tropical to subtropical climates with moderate to heavy rainfall Moist, well-drained loamy soils.

3.2.5 | Sacred Groves: Sacred groves, known as "Devrai" in Maharashtra, "Kans" in Gujarat, "Kavu" in Kerala, "Devara Kadu" in Karnataka, "Sarana" in Tamil Nadu, and by various other names in different regions, are pockets of forested areas that are considered sacred by local communities in India. These groves hold immense cultural, ecological, and spiritual significance and have been preserved for centuries due to religious beliefs and traditional customs. The concept of sacred groves dates back to ancient times when communities revered specific natural spaces as the abode of deities, spirits, or ancestors. These groves were considered sacred sanctuaries where flora, fauna, and natural resources were protected and worshipped. Trees within these groves were often regarded as manifestations of deities, and rituals and offerings were made to honor them. Sacred groves play a crucial role in biodiversity conservation and contribute to the ecological balance by regulating microclimates, maintaining soil fertility, protecting watersheds, and providing ecosystem services such as water purification and soil erosion control. They serve as centers for religious ceremonies, festivals, and cultural practices, fostering a sense of community identity and belonging.

3.2.6 | Conservation Ethics: Hindu scriptures advocate for sustainable living and resource management. The concept of "Yajna" (sacrifice) emphasizes the importance of giving back to nature and maintaining ecological balance. Organic farming, water conservation, and eco-friendly lifestyles align with these teachings.

3.2.7 | Karma and Rebirth: The belief in karma (the law of cause and effect) and reincarnation emphasizes the interconnectedness of all life forms. Hindus recognize the impact of human actions on the environment and strive to protect it for future generations, considering it a part of their spiritual journey.

By drawing upon these aspects of religious faiths, individuals and communities can find inspiration and guidance in their efforts to protect soil, water, and the environment, fostering a harmonious relationship with nature through their religious beliefs.

3.3 | Festivals and Celebrations: Cultural events and festivals can serve as opportunities to celebrate nature, raise awareness about environmental issues, and promote sustainable practices. Some festivals are rooted in agricultural cycles, emphasizing the dependence on a healthy environment. Harvest festivals like Pongal in South India, Makar Sankranti in North India, and Baisakhi in Punjab celebrate nature's bounty and the agricultural cycle. These festivals honour farmers, express gratitude to the land, and promote sustainable farming practices, water conservation, and soil fertility management. Ganesh Chaturthi, celebrated primarily in Maharashtra, involves the worship of Lord Ganesha, the remover of obstacles. In recent years, eco-friendly celebrations have gained popularity, with clay idols, natural dyes, and biodegradable materials replacing materials like plaster of Paris and chemical-based paints. These eco-friendly practices promote environmental sustainability and reduce pollution in water bodies. Similarly, Holi, the festival of colours, the use of synthetic dyes and water wastage are now being replaced by eco-friendly Holi celebrations that encourage the use of natural colours made from plant-based materials and promote water conservation through dry Holi events. These eco-friendly practices reduce pollution and promote environmental consciousness. Now, Earth Day (22nd April), World Environment Day (5th June), and *Van Mahohtsav* (1st week of July) are being celebrated to promote environmental awareness and conservation.

3.4 | Art and Storytelling: Art and storytelling have long been integral to Indian culture, conveying messages, values, and traditions across generations. In environmental conservation, various cultural threads in art and storytelling emphasize the interconnectedness between humans and nature, promote ecological stewardship, and highlight the importance of living in harmony with the environment. Traditional folk art, sacred narratives and myths (Puanas and Jatak tales), traditional music and dance forms, Adivasi folklore and tribal songs and rituals can serve as powerful mediums for raising awareness, fostering empathy, and inspiring action towards environmental conservation in India. By tapping into the rich tapestry of cultural heritage, artists, storytellers, and communities can amplify messages of environmental stewardship.

3.5 | Etheno-medicine: Etheno-medicine relies on a rich diversity of medicinal plants and herbs in India's diverse ecosystems, including forests, grasslands, wetlands, and mountains. Traditional healers, known as vaidyas, have intimate knowledge of local flora and fauna, including their medicinal properties, habitats, and conservation status. By promoting the sustainable use and protection of medicinal plants, etheno-medicine contributes to biodiversity conservation and ecosystem health.

3.6 | Cultural Aesthetics and Nature Appreciation: Cultural aesthetics and nature appreciation play a significant role as cultural threads in India, shaping attitudes, behaviors, and perceptions towards the environment. These cultural elements encompass various forms of artistic expression, cultural practices, and spiritual beliefs that celebrate the beauty, diversity, and sacredness of the natural world. In environmental conservation, cultural aesthetics and nature appreciation are potent tools for raising awareness, fostering empathy, and inspiring action to protect and preserve the environment. India has a rich tradition of artistic expression that draws inspiration from nature's beauty and abundance. From classical dance forms like Bharatanatyam and Odissi, which depict stories of gods and goddesses in natural settings, to visual arts such as painting, sculpture, and photography, artists often portray landscapes, flora, and fauna as sources of inspiration and admiration. Indian literature and poetry are replete with references to nature, landscapes, and ecological themes. From ancient Sanskrit texts like the Vedas and Upanishads to modern works by renowned poets like Rabindranath Tagore and Kalidasa, nature is a recurring motif and metaphor for spiritual truths, human emotions, and existential reflections. Through evocative imagery and lyrical language, literature and poetry evoke a sense of awe, wonder, and reverence for the natural world, nurturing a deeper appreciation for its beauty and significance. India's diverse landscapes, ranging from lush forests and pristine beaches to majestic mountains and arid deserts, offer abundant opportunities for outdoor recreation and ecotourism. Activities such as trekking, wildlife safari, birdwatching, and nature photography allow people to immerse themselves in nature's beauty, appreciate its diversity, and develop a deeper connection with the environment. Through eco-friendly tourism practices, individuals contribute to conservation efforts and sustainable livelihoods for local communities.

3.7 | Cultural Taboos and Prohibitions: Some cultures have taboos or prohibitions against harming certain species or natural features. These cultural restrictions contribute to the protection of specific environments or ecosystems. The cow is considered sacred in Hinduism, leading to taboos against its slaughter and consumption. These cultural attitudes contribute to wildlife conservation and the preservation of biodiversity. The Bishnoi community in Rajasthan follows strict cultural taboos against cutting trees or harming wildlife. These taboos are rooted in the community's belief in the sanctity of all living beings and have led to the creation of Bishnoi-managed conservation areas where hunting and tree felling are prohibited. Many cultural traditions emphasize cleanliness, purity, and respect for the environment, leading to taboos against littering, defiling natural spaces, or polluting water bodies. These cultural attitudes foster environmental stewardship and promote responsible waste disposal and pollution prevention behaviour.

3.8 | Cultural Attitudes Toward Waste and Consumption: Traditional Indian culture emphasizes frugality, thriftiness, and minimalism in resource use and consumption. Many cultural practices, such as repairing and reusing items, sharing resources within communities, and making do with what is available, reflect a mindset of resourcefulness and conservation. Cultural attitudes towards waste and consumption reflect a deep respect for the environment and a recognition of the interconnectedness between humans and nature. This reverence motivates individuals and communities to minimize waste, conserve resources, and protect the natural world for future generations. Community and social norms that govern societal behaviour and interactions influence cultural attitudes towards waste and consumption. In many Indian communities, there is a strong emphasis on collective responsibility, social cohesion, and mutual support, which shape attitudes towards sharing resources, reducing waste, and caring for the environment. Social norms that prioritize cooperation, solidarity, and community well-being foster a culture of environmental conservation and sustainability.

In many Indian households, old clothes are often repurposed into quilts or rugs or used as cleaning cloths instead of being discarded. This cultural practice of reusing textiles reduces waste, preserves resources, and minimizes the environmental impact of clothing production and disposal. In cities like Pune and Bengaluru, informal waste recycling networks known as "*kabadiwalas*" play a crucial role in collecting and recycling waste materials such as paper, plastic, and metal. These community-based recycling systems, rooted in cultural attitudes towards resource conservation and thriftiness, contribute to waste reduction, resource recovery, and environmental sustainability. These examples demonstrate how cultural attitudes towards waste and consumption in India are intertwined with environmental conservation efforts, promoting sustainable practices, resource efficiency, and cultural preservation. By recognizing and embracing these cultural attitudes, communities can harness traditional wisdom and cultural values to address contemporary environmental challenges.

3.9 | Cultural Heritage Preservation: Cultural heritage preservation serves as a significant cultural thread in India, intertwining efforts to conserve cultural traditions, historical artefacts, and architectural marvels with environmental conservation. India's rich cultural heritage, spanning diverse traditions, art forms, and architectural styles, reflects centuries of interaction between human societies and the natural environment. By preserving cultural heritage, communities safeguard their cultural identity and historical legacy and contribute to the protection and sustainable management of natural resources and ecosystems. Cultural heritage preservation in India often involves community engagement, capacity building, and sustainable tourism development that empower local communities and promote cultural vitality. Community-based initiatives for heritage conservation integrate cultural heritage with environmental education, eco-tourism, and livelihood opportunities that enhance community resilience and promote environmental stewardship. Examples include heritage walks in historic neighbourhoods, cultural festivals celebrating local traditions, and eco-friendly tourism initiatives that showcase India's cultural diversity and natural beauty while supporting conservation efforts.

3.10 | Environmental Education and Cultural Transmission: Cultural institutions, including schools and community centres, play a role in transmitting environmental values across generations. Education rooted in cultural contexts fosters a sense of responsibility for the environment. Environmental education is crucial in raising awareness, building knowledge, and fostering attitudes and behaviours that promote environmental conservation. Incorporating environmental education into formal and informal learning settings, such as schools, colleges, community centres, and nature reserves, can empower individuals with the knowledge and skills needed to address environmental challenges. Environmental education programs may include curriculum-based initiatives, outdoor experiential learning activities, citizen science projects, and environmental awareness campaigns that promote ecological literacy, sustainable practices, and environmental stewardship among students, teachers, and the broader community.

3.11 | Social Media: The use of different social media platforms has emerged as a popular culture across all sections of society in India. These platforms offer unprecedented opportunities for information dissemination, community engagement, and advocacy on environmental issues. Leveraging social media channels such as Facebook, Twitter, Instagram, and YouTube can amplify environmental messages, mobilize support, and facilitate dialogue and collaboration among diverse stakeholders. Environmental organizations, grassroots movements, and advocacy groups utilize social media to share educational content, promote eco-friendly initiatives, organize events, and mobilize volunteers for environmental conservation efforts. Hashtag campaigns, viral challenges, and online petitions can galvanize public support and catalyze collective action on pressing environmental issues.

These cultural heritages are dynamic and vary across different societies and communities. Recognizing and leveraging these cultural elements can enhance environmental protection efforts by aligning them with the values and traditions of diverse populations. Integrating cultural perspectives into conservation strategies promotes more inclusive and practical approaches to environmental sustainability. By harnessing the synergies between the above-listed cultural elements, communities can cultivate a culture of environmental consciousness, responsibility, and action that transcends geographical boundaries and generational divides. Through collaborative efforts that leverage the strengths of each platform, individuals and communities can mobilize collective agency and drive transformative change towards a more sustainable and resilient future for people and the planet.

4 | Empowering Cultural Heritages with Science and Arts

Traditional local wisdom and value systems need to be evaluated and validated in the present social and environmental context and further refined by conducting scientific investigations, field experiments, and ecological assessments. This validation helps identify best practices and preserve indigenous wisdom for future generations. Integrating indigenous knowledge with modern scientific understanding can help develop more acceptable hybrid approaches for ecosystem management. By combining traditional ecological knowledge with scientific methodologies, communities can leverage the strengths of both systems to address contemporary environmental challenges while respecting cultural values and traditions.

4.1 | Capacity Building: Modern communication methods and social media can be very effective tools to support capacity-building initiatives that empower local communities with technical skills, scientific literacy, and research methodologies. Training programs, workshops, and knowledge exchange activities facilitate the transfer of scientific knowledge and expertise to traditional practitioners, enabling them to apply innovative techniques and technologies in their conservation efforts. Art-based educational initiatives, such as eco-art workshops, nature-inspired art classes, and environmental storytelling sessions, can raise awareness about environmental issues and inspire empathy for nature. A series of nature-inspired art workshops for children, for instance, could teach them about local ecosystems, biodiversity conservation, and sustainable living practices through hands-on creative activities.

4.2 | Adaptive Management and Resilience Planning: Data-driven insights into ecosystem dynamics, climate change impacts, and socio-economic trends can help well-informed adaptive management strategies and resilience planning. Scientific modelling, monitoring systems, and scenario analysis help communities anticipate and respond to environmental changes, enhancing their adaptive capacity and resilience to future disturbances.

4.3 | Community Engagement: Local communities can be engaged as active participants in research initiatives, participatory monitoring programs, and citizen science projects. By involving community members in data collection, analysis, and decision-making processes, science fosters ownership, collaboration, and co-management of natural resources, strengthening cultural connections to the land and water. Participatory art projects, such as community murals, collaborative installations, and public performances, can mobilize local communities to actively engage in conservation efforts. For example, a community-led mural painting project could transform a barren wall into a vibrant depiction of local ecosystems, sparking conversations about the importance of biodiversity conservation and ecosystem restoration.

4.4 | Policy Support and Collaboration Platforms: Scientific evidence adds value and credibility to conservation technology, facilitating opportunities for interdisciplinary collaboration, cross-cultural exchange, and innovation diffusion, fostering inclusive approaches to sustainable land and water management. It helps promote mutual learning and partnership-building between scientists, traditional practitioners, policymakers, and other stakeholders.

4.5 | Cultural Preservation and Revitalization: Traditional art forms, such as indigenous crafts, music, dance, and storytelling, can be used to celebrate cultural heritage, reinforce community identity, and transmit traditional knowledge about environmental stewardship. For instance, tribal paintings depicting local flora and fauna can serve as visual narratives of ecological relationships and conservation values. Art-based ecotourism experiences, such as guided nature walks, cultural performances, and traditional craft demonstrations, can offer visitors immersive opportunities to learn about local cultures and ecosystems. For example, a guided tour led by indigenous artists and storytellers could provide insights into traditional ecological knowledge, medicinal plants, and sustainable land management practices.

4.6 | Connecting Communities to Nature: Local festivals and events that celebrate the connection between art, culture, and nature can foster a sense of belonging and reverence for the natural world. For example, a nature-inspired music festival could bring together artists, musicians, and environmentalists to showcase the beauty of local landscapes and promote environmental conservation through artistic expression.

5 | CASE STUDIES

5.1 | Participatory Watershed Development Projects: Over a period of about 60 years, the experience on watershed developmental projects implemented and investigated by the Indian Institute of Soil and Water Conservation (ICAR-IISWC) has been a journey of embracing a new approach to watershed management, transitioning from a top-down to a bottom-up, compartmental to integrated and emphasizing increased participation of beneficiary communities at all stages of the project lifecycle. This shift recognizes the importance of local knowledge and cultural values in achieving sustainable watershed management. These projects are good examples of integrating scientific expertise with local preferences and wisdom, to create impactful projects. Scientific principles in hydrology, soil conservation, and sustainable agriculture form the foundation of conservation planning. Research guides the selection of location-specific interventions like rainwater harvesting structures, check dams, and erosion control measures. Traditional knowledge and practices are woven into the project design. The priorities and values of local communities carry a deep understanding of their watershed's unique characteristics and challenges and, therefore, are given due consideration in project planning. The artistic skills of locals are utilized in the process of participatory resource appraisal (PRA) exercises. Communities participate in all stages, from planning and execution to monitoring and evaluation, fostering a sense of ownership and ensuring the project addresses their specific needs and priorities.

5.2 | The Jhabua Grassland Revival Initiative: This project in Madhya Pradesh tackles land degradation through a unique blend of traditional knowledge and modern science. The indigenous Bhil communities possess deep knowledge of grassland management practices. The project incorporates their expertise in grazing control, fire management, and native seed dispersal into scientific restoration plans. Additionally, artists collaborate with the Bhil communities to create murals and performances that celebrate their connection to the grasslands and promote sustainable management practices.

5.3 | Sindhudurg's Community-Managed Marine Protected Area (MPA): This MPA off the coast of Maharashtra showcases successful co-management between the fishing community and the forest department. Traditional fishing knowledge about breeding grounds and seasonal closures informs regulations within the MPA. Additionally, community members participate in patrolling and monitoring activities. Art plays a role in raising awareness about the MPA's importance. Local artists create posters, sculptures, and even performances using recycled materials to educate tourists and the wider community about the value of marine conservation.

5.4 | Tehri Garhwal's Van Panchayats (Forest Councils): This centuries-old system in Uttarakhand empowers local communities to manage their forests. The Van Panchayats enforce traditional rules regarding resource use, protect sacred groves, and promote sustainable forestry practices. Art and cultural celebrations are intertwined with forest management. Villagers organize traditional dance performances and create murals depicting the importance of forests, fostering a deep connection between the community and its natural surroundings.

5.5 | Oli Kadal (meaning "One Earth, One Sea" in Tamil): This project by the Dakshin Foundation uses a combination of scientific research, community engagement, and art installations to conserve Olive Ridley turtles on the Tamil Nadu coast. Scientists track turtle migration patterns, while artists create sculptures and murals to raise awareness about threats to turtles and engage local communities in conservation efforts.

6 | Way Forward: To ensure the realignment of societal frameworks with ecological principles, a multifaceted approach is essential. This approach must integrate policy changes, education reform, cultural transformation, and interdisciplinary collaboration. Here's a way forward:

6.1 | Policy Reform and Global Cooperation: Policymakers must prioritize environmental sustainability as a core aspect of governance. This requires adopting policies that not only promote renewable energy, circular economies, and conservation practices but also ensure that these policies are enforced. Incentives for sustainable farming, waste reduction, and green technologies should be integrated into national and international policy frameworks. International cooperation on climate agreements, such as the Paris Agreement, must be strengthened, with stricter adherence to emissions targets and financial support for developing nations to adopt green practices.

6.2 | Educational Transformation: Education systems must undergo a paradigm shift to embed ecological literacy as a core subject from early schooling. Teaching students about environmental ethics, sustainability, and the consequences of human actions on ecosystems will nurture a generation of eco-conscious citizens. Interdisciplinary learning - where science, arts, and humanities are integrated to provide a holistic understanding of environmental issues- should become the norm. Environmental education should not be confined to classrooms but extended to community engagement, with hands-on learning experiences such as urban farming, tree planting, and waste management workshops.

6.3 Cultural Shifts through Influencers and Media: Cultural influencers, including media figures, artists, and social media personalities, hold immense power to shift public opinion and behavior. Encouraging these figures to promote environmental values can help integrate sustainability into mainstream culture. Campaigns that highlight the importance of sustainable lifestyles - through the use of eco-friendly products, reduced consumption, and support for environmental initiatives - can influence the masses. Additionally, traditional wisdom that promotes harmony with nature, such as indigenous farming practices, should be revitalized and made accessible to modern audiences.

6.4 | Interdisciplinary Collaborations: Promoting collaborations between scientists, artists, and innovators is crucial to fostering creative solutions for environmental challenges. Artists can translate complex scientific concepts into compelling visual, auditory, or performative works that engage the public on an emotional level. For instance, bioartists use living organisms in their creations, encouraging people to rethink their relationship with nature. Similarly, science and technology must be directed toward eco-innovation - whether through biomimicry, sustainable architecture, or clean energy solutions - to solve pressing environmental problems.

6.5 | Platforms for Knowledge Sharing and Innovation: Creating platforms that merge traditional ecological knowledge with modern scientific advancements can generate novel solutions to environmental challenges. Online portals, community forums, and international networks that facilitate the exchange of ideas between indigenous knowledge holders, scientists, artists, and activists can foster a global movement toward sustainability. Moreover, such platforms should be accessible to the public, helping to inform and inspire communities to take action at the grassroots level.

7 | CONCLUSION

The human society is responsible for the degradation of Earth's systems and the potential for their preservation. As human values and priorities shift under the ongoing influence of scientific and technological advancements, a significant opportunity exists to reorient these forces towards nurturing a sustainable and symbiotic relationship between humanity and nature. Cultural traditions that have long supported environmental protection need to be further strengthened with the evolving scientific progress and artistic expression to promote ecological consciousness. There is a need to realign societal frameworks with ecological principles that encourage policymakers, educators, and influencers to foster a cultural shift that integrates sustainability into core value systems. Recommendations include promoting interdisciplinary collaborations between scientists and artists, expanding environmental education, and creating platforms that blend traditional wisdom with modern innovations to inspire a more eco-centric worldview.

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DATA AVAILABILITY

The data presented in this paper are available in the public domain and published literature.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR'S CONTRIBUTIONS

RK Singh: Conceptualization, analysis, and writing of the manuscript; Raman Jeet Singh: Revising indigenous knowledge and traditional wisdom on crop management and editing the manuscript.

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Framing land degradation and restoration policy in India following the IPBES pathway

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Policy

ABSTRACT

In the face of ongoing land resource degradation and climate change challenges, environmental protection has become a global priority. In India, where per capita land availability is already half the world average, about 91.2 million hectares (27.7% of the land area) are degraded. Inadequate scientific data, community engagement, and coordination among planning, research, and implementing agencies hinder the country's land restoration programs. A robust policy and regulatory framework, a central coordinating institution, and interconnected institutional relationships are needed to address these issues. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) offers a policy framework to complement existing governmental policies and to help restore degraded lands by addressing nature, ecosystem services, and the quality of life. The essence of this framework lies in spotlighting its contributions to people while orchestrating land restoration initiatives across different scales. The approach hinges on integrating empirically grounded scientific insights alongside indigenous and local knowledge (ILK). A renewed initiative is recommended for land degradation assessment along with its impact on biodiversity and ecosystem functions following the IPBES pathway. Developed scientific databases, models, and information, including ILK, should be employed to construct an all-encompassing policy that defines the role of all participating institutions, advances ecosystem functions, and positively contributes to nature and human well-being.

HIGHLIGHTS

- Harmonizing natural and anthropogenic factors is crucial for sustainable land management.
- In India, land restoration programs are hindered by inadequate scientific data and community engagement.
- The IPBES framework integrates scientific insight and indigenous knowledge to craft robust land management policies, emphasizing collaboration between various stakeholders in managing biodiversity and ecosystems.

1 | INTRODUCTION

Land degradation is a widespread crisis that impacts all types of terrain due to soil erosion, salinization, draining of peatlands and wetlands, and the deterioration of forests. This degradation process is exacerbated and made more evident by the impacts of climate change, leading to more frequent occurrences of droughts, floods, landslides, forest fires, cyclones, rising sea levels, species extinction, desertification, and biodiversity loss. The degradation significantly disrupts biodiversity and the resulting ecosystem services globally. It has local, national, regional, and international repercussions. The worsening of degradation is compounded by anthropogenic causes such as population growth, government policy inaction, and related issues, among others, in climate change scenarios, which affect the entire ecosystem and living beings. Once land degradation assumes a higher dimension, reversing it to a naturally viable state has substantial economic implications. This revolves around the economics of land degradation (ELD), which decides whether restoring the system to its original state or converting it for alternative land uses promises quicker economic gains. The inclination towards immediate economic gains from land degradation restoration often leads to adverse net economic effects. This invariably results in a change in the green economic account, which often goes unnoticed by policymakers due to its intangible characteristics. This results in insufficient investments in restoring or rehabilitating degraded lands, impacting developed and developing nations equally.

1.1 | Land Degradation in India

In India, degraded land covered about 91.2 M ha, or 27.7% of the country's total land area, in 2015-16 (Sreenivas *et al.,* 2021). Attributing 55.91% of the total land degradation or 15.53% of the country's total geographical area (TGA), water erosion was the primary process causing land degradation. This was followed by wind erosion, accounting for 15.66% of total land degradation or 4.35% of TGA. Salinisation / alkalization (comprising various categories like saline, sodic, saline-sodic, and Rann) accounted for 7.09 % of total land degradation. Acidification accounted for 3.33 % of total land degradation (*ibid*). According to data from the United Nations Convention to Combat Desertification (UNCCD 2019), between 2015 and 2019, India's reported land area experienced further degradation, amounting to 30.51 M ha. As of 2019, 9.45 % of the country's landmass was degraded, up from 4.42 % in 2015, as reported by Centre for Society and Environment (Down to Earth, 2023).

Land degradation impact has several dimensions. The effects percolate to different sectors with cascading effects. About 3.7 M ha suffered from nutrient loss and depletion of organic matter (Sehgal and Abrol, 1994). At the state level, productivity loss in rainfed cereals was observed, ranging from 0.2-10.9 q/ha, for oilseeds 0.1-6.3 q/ha, and for pulses 0.04-4.4 q/ha (Sharda and Dogra, 2013). On average, land degradation resulted in losses in agriculture productivity amounting to ₹ 3654 per hectare annually (at 2011-12 market prices). In absolute terms, the annual production losses are 13.4 Mt, valued at ₹ 205.32 billion, considering the minimum support price of 2011-12 (Sharda and Dogra, 2013). It is estimated that reducing land degradation by 10% can help to reduce direct economic losses from land degradation to ₹ 3145 per hectare, which is a significant improvement (Gorain *et al.,* 2023). Similarly, land degradation is a major cause of depletion and contamination of water resources due to siltation. Activities such as soil erosion and deforestation disrupt hydrological cycles, leading to decreased base flow, groundwater recharge, and river flow patterns. Additionally, degraded lands produce runoff that carries sediments, pollutants, and agrochemicals into water bodies, degrading water quality and posing health risks to both humans and aquatic life. Fertile soil eroded annually gets deposited in the reservoirs, reducing their storage capacity by 1-2 % (UNEP, 2001). Biodiversity is impacted by land use transformation primarily through habitat loss or modification, changes in species diversity and abundance, and soil quality degradation. Loss of vegetation cover and habitat destruction result in the decline of indigenous plant and animal species, disrupting ecological balance and reducing ecosystem services. Deforestation and degradation of forests reduce carbon sequestration capacity, leading to increased atmospheric carbon dioxide levels and exacerbating global warming. Furthermore, degraded lands are more susceptible to extreme weather events such as floods, droughts, and wildfires, which are becoming increasingly frequent and severe due to climate change. The economic costs of land degradation in India are substantial, affecting various sectors such as agriculture, water resources, tourism, and infrastructure. According to a report by TERI (2018), the cost of land degradation and land use change accounted for up to 2.54% of India's gross domestic product (GDP) in 2014-15. This is a serious concern because India aims to achieve land degradation neutrality by 2030, wherein equivalent gains in land reclamation offset any increment in land degradation.

Addressing land degradation in the country has encompassed strategies such as sustainable land management practices, afforestation and reforestation programs, watershed management initiatives, and regulatory measures to control land use change and soil erosion. This included various programs undertaken over the years to address the issue, *viz.,* Drought Prone Area Programme, Desert Development Programme, Integrated Watershed Management Programme, National Afforestation Programme, etc. The impact, however, has been meagre (Bhan, 2013). Furthermore, the Government of India has already put in place several acts and policies such as the Indian Forest Act 1927, Forest Conservation Act 1980, Environment Protection Act 1986, National Forest Policy 1988, Biological Diversity Act 2002, National Environment Policy 2006, National Action Plan on Climate Change 2008, The National Green Tribunal Act 2010, National Agroforestry Policy 2014, and the National Working Plan Code 2014 (MoEFCC, 2018) towards addressing the land degradation problem in the country. However, restoring degraded lands at regional and national levels creates a paradox due to competing demands as envisaged in these policies (Edrisi *et al.,* 2023). Further, among several factors that caused the failure of the strategies undertaken in the past was a lack of communication between the involved stakeholders, such as remediation or restoration experts, landowners, and auditors (Edrisi and Abhilash, 2016). This emphasizes proper synchronization of local and scientific knowledge involving relevant stakeholders.

The land degradation-climate change-biodiversity nexus further exacerbates the problem and, therefore, needs a comprehensive policy framework to add value to nature's contribution to people as per the focus of the UN-based Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). The present paper advocates an application of the conceptual policy framework given by IPBES towards resetting the programs and actions to address the ecosystem services and sustainability issues. The IPBES, also known as the 'IPCC for biodiversity', plays a crucial role in understanding and addressing the impacts of climate change. Collaborating with the line departments dedicated to conserving and managing natural resources is essential in formulating effective policies that tackle concerns like land degradation and restoration, following the path set by IPBES.

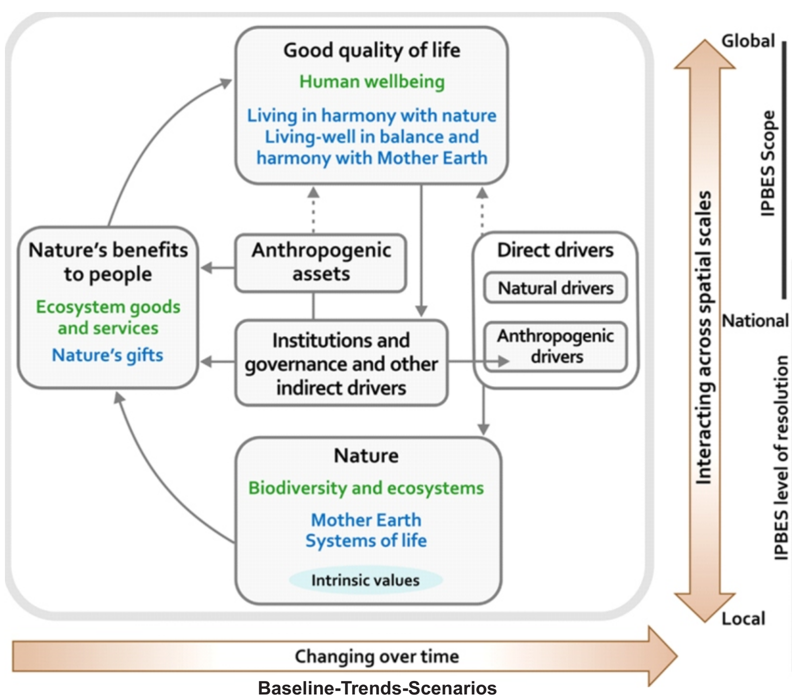
2 | THE IPBES FRAMEWORK

The IPBES, an independent inter-governmental agency supported by the United Nations Environment Programme (UNEP), was formed to strengthen the science and policy interface for ecosystem and biodiversity services to conserve and sustainably use biodiversity, achieve enduring well-being of humans, including sustainable development in the backdrop of climate change scenarios. Established in Panama City in 2012, it is open to all the UN member countries and currently has 142 member states.

IPBES aims to provide credible assessments and evidence-based knowledge to aid informed decision-making at all levels. IPBES has three distinctive features in framing enabling and action-oriented policies respecting the social and cultural framework to benefit people and nature (Diaz *et al.,* 2015a). First, the engagement with all stakeholders, including policymakers, practitioners, civil society organizations, and the private sector, in defining questions to be addressed, assessing trends, and identifying evidence-based solutions for action. Second, it aims to incorporate knowledge from diverse sources, including natural, social, and engineering sciences, as well as indigenous local and technical knowledge (ILK/ITK). The inclusion of ILK is a matter of equity; it also is an available source of knowledge that can no longer be ignored (Tengö *et al.,* 2014). Third, IPBES, besides producing assessments, includes capacity-building, policy tools development, and the generation of critical new knowledge.

The conceptual framework of IPBES explicitly includes multiple knowledge systems interlinked around the central theme, *i.e.,* nature, nature's benefit to people, and good quality of life (Fig. 1). As depicted in the figure, six interlinked elements capture the relationships between the natural world and humankind operating at various temporal and spatial. This includes i) nature, ii) nature's benefits to people, iii) anthropogenic assets, iv) institutions and governance systems and other indirect drivers of change (such as institutions and governance systems), v) direct drivers of change, and finally vi) good quality of life, *i.e.,* general wellbeing of individual and group relating to nature.

The framework's components, particularly the 'institutions and governance systems and other indirect drivers of change,' hold significance at different policy interface scales in India, from panchayat to municipalities and higher echelons. The governance challenges related to biodiversity



The platform's primary focus is on nature and society, as shown by boxes and arrows in the middle panel bounded in grey. The black headlines in each box represent inclusive categories that should be comprehensible and pertinent to all parties interested in IPBES. These headlines embrace the categories of western science (in green) and comparable or analogous categories according to other knowledge systems (in blue). The green and blue categories are described in more detail in the main text and are merely illustrative. In the main panel, solid arrows show how different parts influence one another, while dotted arrows show links acknowledged as significant but not the Platform's primary focus. The thick-color arrows to the right and below the central panel show that the interactions between the elements occur at different scales in space (vertical arrow) and vary over time (horizontal bottom arrow). Cross-scale interactions are common, and they might include mismatches between scales. The vertical lines that appear to the right of the spatial scale arrow show that, while the scope of IPBES assessments will be at supranational, sub-regional, and global geographical scales, they will also draw in part from properties and relationships operating at finer, national and subnational, scales (resolution, in the sense of minimum discernible unit).

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FIGURE 1 IPBES Conceptual Framework

and ecosystem services are substantial (Chandrasekharan, 2018). The awareness about biodiversity and the ecosystem is crucial for understanding the process of land degradation and, therefore, its restoration through relevant policy actions by the institutions to recommend appropriate anthropogenic assets to harness the ecosystem services flow sustainably. These challenges were observed in the case study by Chandrasekharan (2018).

The objectives of IPBES encompass four areas *viz.,* i) focus on particular topics and addressing methodological concerns at both the regional and global scales., ii) providing policy support for identifying, facilitating the use of, and catalysing the development of policy-relevant tools and methodologies, iii) member states, experts, and stakeholders have their priority capacity, knowledge, and data needs identified and met through capacity building and knowledge development and iv) communications and outreach, to ensure that the outcome has the broadest possible reach and impact.

By following the framework, the emerging policy will strengthen the member countries' existing policies on natural resource management. The policy focuses on assessment, capacity building, and widescale outreach programs. What sets this new IPBES initiative apart is the central role played by institutions, governance, and decision-making through the links among these framework elements. The conceptual framework is expected to contribute to the analysis of the trend towards interdisciplinarity in understanding and managing the environment. Instead of replacing disciplinary science, the framework will provide new contexts of discovery and policy applications (Diaz *et al.,* 2015a).

2.1 | The IPBES as a robust policy framing tool

With the involvement of member countries and contributions from more than 1000 scientists worldwide, IPBES produced evidence-based reports for the benefit of policymakers to act upon the land-based ecosystem for human well-being and the environment. The mission is to enhance policy and decision-making processes by critically assessing past, present, and future scenarios using scientific and indigenous knowledge, models, tools, and techniques. The ultimate goal is to promote biodiversity conservation and sustainable use, ensure long-term human well-being, and support sustainable development. IPBES is often referred to as the "IPCC for Biodiversity". It is a global science-policy forum that aims to provide the most reliable evidence to all decision-makers for creating a connection between humans and nature. In 2017, IPBES released the Regional Assessments and the thematic Assessment of Land Degradation and Restoration, which were featured in 37 different languages across more than 124 countries by over 2,500 media outlets (http://www.ipbes.net).

Establishing IPBES ensures that all the elements of the policy process, assessment and monitoring, and policy development (Chan *et al.*, 2012) are in place and function effectively to strengthen the policy framework (Chan *et al.*, 2012). So, the IPBES conceptual framework can now serve as a good example to arrive at policy options to evaluate the relative merits of mitigation, adaptation, and stabilization strategies for land degradation control to make the right decisions in the face of climate change scenarios of IPCC. This requires a much higher level of commitment to capacity-building and engagement with the community. Establishing IPBES offers a unique opportunity to build on what has already been done (Perring *et al.*, 2011).

2.2 | Embedding local knowledge

Collaboration between knowledge systems is crucial in providing policymakers, science practitioners and implementors with the best available scientific, indigenous and local knowledge (ILK). This will help them make informed decisions on the urgent actions that need to be taken to stop the rapid degradation and loss of biodiversity and ecosystem services essential for sustainability and resilience in the face of global change. One of the key principles of IPBES is to recognize and respect the importance of indigenous and local knowledge in all aspects of its operation.

A recent assessment report on land degradation and restoration suggests integrating Indigenous and local knowledge (ILK) by including people and communities with such indigenous knowledge and expertise. Interactions with Indigenous knowledge bearers, indigenous people, local communities, and indigenous organizations can help achieve this (Scholes *et al.,* 2018, IPBES, 2018). This is a novel, inclusive approach to strengthening the policy by integrating other evidence-based knowledge systems. The formal documentation of ILK/Indigenous and technical knowledge (ITK) on soil and water conservation in India was initiated for scientific validation to formally include in natural resource management programs (Mishra, 2002) with scientific validations by addressing the researchable issues. Traditionally, the strength of ILKs in the context of nature-based development is well-knit in the socio-cultural fabrics of the indigenous people. The evidence-based inclusion of these user-friendly and tested technologies over the years will have wider acceptance by the local people while implementing the restoration policy in real field situations. This process of inclusion of ILK formally in the IPBES assessment is evolving and is under progress. In resolution IPBES-5/1, the IPBES Plenary endorsed a strategy for IPBES to acknowledge and utilize indigenous and local knowledge, providing IPBES with a bold and innovative method for integrating indigenous and local knowledge into large-scale evaluations (https://files.ipbes.net/ipbes-web-prod-public-files/inline/files/ipbes_ilkapproach_ipbes-5-15.pdf).

3 | LAND RESTORATION INITIATIVES IN INDIA

India's commitment to land restoration and sustainable development is evident through its numerous programs and initiatives. Numerous national policies relevant to land degradation issues have been implemented over the past 40 years. These policies have been revised and updated over time and include the National Water Policy 2012, the National Forest Policy 1988, the National Agricultural Policy 2000, the Forest (Conservation) Act 1980, the Environment (Protection) Act 1986, the National Environmental Policy 2006, the National Policy for Farmers 2007, and the National Agroforestry Policy 2014. The land degradation restoration policies that evolved lacked a comprehensive framework to simultaneously account for drivers of change and the evolving institutions in place to address them at different scales, *viz.,* local, regional, and national (WRI, 2023). Subsequently, a mechanism was envisaged. A National Rainfed Area Authority was created for central and state-level policy harmonization, encompassing different ministries such as agriculture and farmers' welfare, rural development, water resources, environment and forests, and *Panchayati Raj*. The Integrated Watershed Management Program (IWMP), a holistic approach to addressing land degradation, was suggested to address it in all its forms comprehensively. The watershed approach, in fact, directly contributes to achieving 10 Sustainable Development Goals, including poverty reduction, climate action, food security, gender equity, employment, and sustainable forest management, the co-benefits of restoring the degraded lands. This approach focused on interventions to strengthen natural resources supporting production and livelihood. The program evolved over the years with best practices adopted on the ground, and various studies on the impact and effectiveness of the programs reported positive impacts on the ground.

However, there are lessons to be learned from different regions of the country on participatory watershed development programmes. The major concerns expressed are lack of equity and post-project sustenance, inadequate community participation and scaling-up methods, and lack of holistic approaches in the technical support to most NGO development projects (Joshi *et al.,* 2008). Further, an extensive discussion is available in the literature about the issues of mainstreaming participatory principles, reorienting the concept of sustainability in Watershed Development Programs, reemphasizing equity aspects of watershed programs, reconsidering scales of operationalisation of watershed programs, cost-sharing, evaluation and mid-term correction of watershed development programs amongst others (Sen, 2008). Despite growing awareness about the program limitations and countermeasures taken, the land restoration programs in India suffer from several overarching policy gaps. Inadequate scientific support in planning and monitoring, fragmented policies, ineffective stakeholder engagement, insufficient economic incentives, lack of adaptive management, and insufficient focus on ecosystem services can be listed as common limitations restricting the realisation of potential benefits of land restoration programs on a sustainable basis (Table 1).

TABLE 1 The relevance of the IPBES approach to the major land restoration programs of India

	Strategies	Policy Gaps	IPBES Contributions scope
1. National Afforestation Programme (NAP)	Increase forest and tree cover through community-based afforestation through Joint Forest Management Committees (JFMCs)	Limited use of up-to-date scientific data for afforestation site selection and species choice. Inconsistent monitoring and evaluation frameworks across different regions.	Use IPBES assessments to guide site selection and species choice based on ecological suitability. Develop standardized monitoring and evaluation frameworks based on IPBES guidelines to ensure consistency and effectiveness.
2. Green India Mission (GIM)	Enhance carbon sinks, biodiversity conservation, and livelihood improvement through Afforestation, eco-restoration, and agroforestry on degraded ecosystems.	Insufficient engagement with local communities and indigenous knowledge systems. Limited mechanisms for adaptive management based on new scientific findings.	Facilitate more inclusive stakeholder engagement by integrating indigenous and local knowledge as recommended by IPBES. Implement adaptive management strategies informed by IPBES scientific assessments to respond to changing environmental conditions.
3. Integrated Watershed Management Programme (IWMP)	Restore ecological balance by harnessing, conserving, and developing degraded natural resources with a watershed-based approach involving community participation with soil and water conservation, afforestation, pasture development, and promotion of sustainable agriculture.	There is a lack of comprehensive assessment of ecosystem services in watershed management and limited integration of interdisciplinary approaches combining hydrology, ecology, and social sciences.	Utilize IPBES frameworks to assess and value ecosystem services comprehensively within watersheds. Promote interdisciplinary approaches by incorporating IPBES guidelines on combining hydrological, ecological, and social sciences.
4. National Mission for Sustainable Agriculture (NMSA)	Promote adoption of climate-resilient and sustainable farming techniques with improved soil health management, water use efficiency, agroforestry, and conservation agriculture	Insufficient focus on biodiversity's role in enhancing agricultural resilience to climate change. Limited mechanisms for transferring scientific knowledge to farmers.	Use IPBES assessments to emphasize the role of biodiversity in climate-resilient agricultural practices. Strengthen knowledge transfer mechanisms from scientists to farmers, guided by IPBES best practices.

TABLE 1 Continued.....

	Strategies	Policy Gaps	IPBES Contributions scope
5. Soil Health Card Scheme	Promote judicious use of fertilizers and soil amendments by regular soil testing and issuance of soil health cards with recommendations.	Focus on chemical properties without sufficient attention to biological and ecological aspects of soil health. Limited farmer engagement in the development and use of soil health cards.	Integrate IPBES insights on the ecological and biological aspects of soil health into the soil health card recommendations. Incorporate local knowledge and feedback mechanisms, as advocated by IPBES, to increase farmer participation.
6. National Agroforestry Policy	Provide policy support, incentives, and technical guidance to farmers to encourage agroforestry practices that enhance farm productivity, soil health, and biodiversity.	Inadequate integration of agroforestry practices with broader biodiversity conservation goals. Insufficient economic incentives for farmers to adopt agroforestry.	Align agroforestry practices with biodiversity conservation goals using IPBES policy support tools. Develop better economic incentive mechanisms based on IPBES valuation of ecosystem services provided by agroforestry.
7. National Action Programme to Combat Desertification (NAPCD)	National and state-level projects focused on Land restoration, soil conservation, water management, and livelihood improvement to address land degradation and desertification in alignment with the UNCCD	Lack of detailed baseline data and clear targets for land degradation neutrality. Fragmented approaches to combating desertification across different regions.	Provide detailed baseline data and clear targets for LDN using IPBES assessments. Promote integrated approaches combining scientific, socio-economic, and policy dimensions as per IPBES guidelines.
8. Sustainable Land and Ecosystem Management (SLEM) Programme	Integrated approach combining policy, investment, and community participation for promoting sustainable land management practices, including soil conservation, water management, afforestation, and biodiversity conservation.	Fragmented land management practices without a holistic view. Limited dissemination of best practices and scientific knowledge.	Promote holistic land management practices using IPBES integrated ecosystem management frameworks. Facilitate better dissemination of best practices and scientific knowledge as recommended by IPBES.
9. Compensatory Afforestation Fund Management and Planning Authority (CAMPA)	Promote afforestation and regeneration activities as a compensatory measure for forest land diverted for non-forest purposes by utilization of funds collected from user agencies for afforestation and regeneration projects.	Lack of long-term monitoring and evaluation of afforestation projects. Limited focus on the ecological suitability of species planted.	Establish long-term monitoring and evaluation frameworks based on IPBES guidelines. Through IPBES-informed assessments, the ecological suitability of species planted is ensured.
10. Tree Outside Forest (TOF)	Encourages farmers, landowners, and communities to plant trees on their lands with adequate technical & financial support using incentive schemes and subsidies in collaboration with local governments, NGOs, and private sector stakeholders.	Insufficient scientific data on the impact of TOF on biodiversity and ecosystem services, lack of standardized monitoring and evaluation frameworks, limited engagement with local communities, lack of incorporation of Indigenous knowledge in planning and implementation, weak economic incentives for farmers, inadequate market linkages for non-timber forest products and agroforestry produce, and fragmented implementation across different states and regions.	Utilize IPBES global and regional assessments to enhance the scientific data collection and impact analysis. Implement standardized monitoring and evaluation frameworks based on IPBES guidelines to assess TOF's ecological, social, and economic impacts. Foster inclusive stakeholder engagement by integrating indigenous and local knowledge systems as recommended by IPBES to connect TOF initiatives with local needs and conditions. Develop improved economic incentive mechanisms based on IPBES valuation of ecosystem services provided by TOF, which can include payment for ecosystem services (PES) schemes and subsidies. Promote the integration of TOF initiatives with broader land management, biodiversity conservation, and climate resilience policies using IPBES policy support tools. Encourage interdisciplinary approaches that combine TOF's ecological, social, and economic dimensions.

3.1 | THE IPBES RELEVANCE WITH LAND RESTORATION PROGRAMS

The Integrated Watershed management approach has a scope of refinement as envisaged in the conceptual framework (CF) of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). The New Generation Watershed Development Projects (WDC-PMKSY 2.0) (DoLR, 2021) guidelines, though, suggested a modified path for improvement in the backdrop of India's commitment towards Sustainable Development Goals (SDGs), 2030; Nationally Determined Commitments (NDCs) and Land Degradation Neutrality (LDN). The goal of sustainable development, including sustainable forest management, sustainable agriculture and sustainable land management (such as ILUP and ILM), implicitly attempts to address land degradation (Singh *et al.,* 2023). The landscape approach to achieving LDN envisages a collaborative, multifaceted, and multistakeholder process to provide solutions at different levels and scales (*ibid*). Yet, an explicit framework encompassing the issues of institutional governance at different scales and times is lacking. The IPBES framework can address some of these issues (Table 2).

TABLE 2 NRM approach and IPBES conceptual framework in addressing land degradation

Description	NRM policy-Integrated Watershed management	IPBES conceptual framework	New proposed framework
Purpose / goal / objective	Managing natural resources to address poverty/ improvement of lives and sustainable resource development	Connecting nature and people for conservation and sustainable use of biodiversity, human well-being, and sustainable development	Managing natural resources to address poverty, improve lives, and promote sustainable resource development while also fostering the connection between nature and people for the conservation, sustainable use of biodiversity, human well-being, and sustainable development
Focus	Focuses on natural resource base for livelihood support, income generating activities	Focuses on nature, nature's benefits to people, and good quality of life	Focussing on complete array of natural diversity elements within an ecosystem corridor situated in a continuous landscape
Management mechanism by stakeholders	Integrated community-based resource management, institution building, decentralized decision making	Central role of institutions, governance and decision making, indirect and direct drivers, anthropogenic assets, multiple knowledge systems (western science with ILK)	Emphasising local community, bolstered by local civil society organizations, working in collaboration with scientists and policymakers for sustainable management of anthropogenic assets
Approach to problem-solving: components of Conceptual Framework			
i) Nature	IWM approach considers watershed as a basic unit comprising all types of land that provide benefits to people	Nature is comprised of all cropland, forestland, rangeland, surface water bodies etc	A holistic approach that fosters the coexistence of natural diversity alongside all human activities.
ii) Anthropogenic assets	The watershed benefits draw upon production technologies, dominated by grey structures, and livelihood enterprises to improve people's lives	These are all infrastructure, knowledge (both western and ILK), human, social, and financial resources that contribute towards people's good life quality	Encompasses all green infrastructures or assets; Emphasis should be given to all-encompassing approach that nurtures the harmonious coexistence of biodiversity in tandem with every facet of human activities. This involves recognizing and promoting the intricate interplay between nature's diversity and the entirety of human endeavours
iii) Nature's benefit to people	This approach strives to improve provisioning, regulating, cultural as well as supporting ecosystem services that provide a good life	Strengthening all four ecosystem services is inherent in this conceptual framework	The framework should inherently focus on fortifying and maximizing the benefits derived from these essential services, ultimately enhancing the overall well-being and sustainability of ecosystems and human societies.
iv) Institutions and governance and other indirect drivers	a) This confines to institutions and governance issues within watershed boundaries b) There is no mechanism to address / control biotic and abiotic pressures from outside c) There is a poor synchronization with other multiple laws and regulations leading to conflict of interests, which adversely affects either nature's benefit to people or good quality of life	a) All national and international regulations and policies are given due cognizance. b) There is flexibility in the creation and modification of institutional mechanisms to account for the balance between nature and anthropogenic assets c) There is sufficient scope for accommodating different property regimes, policies, and incentives to ensure good quality of life through nature's benefits	A) Establishing a community-based initiative known as a "Local Living Wisdom Club," which brings together individuals who hold the invaluable knowledge legacy of Indigenous and Local Knowledge (ILKs). This club should aim to foster a collaborative environment where these knowledge holders can share, preserve, and pass on their traditional wisdom to present and future generations. b) Local NGOs and civil society should play a crucial role in facilitating the mobilization of local communities. c) Interdisciplinary team specializing in regenerative farming, with a dedicated emphasis on revitalizing local agro-biodiversity should be an integral part. d) Policymakers must embrace green financing with thoughtful integration into the realm of science administration. e) All the hierarchy of the system actors should co-innovate to co-produce a system of diversity
v) Direct drivers	a) This has provisions to address natural drivers, such as drought, land use changes, etc., within a watershed boundary. b) There is a limited scope to account for externalities arising from direct drivers beyond the geohydrologic boundary. This sometimes leads to the weakening of linkages between nature and nature's benefits to people.	a) This approach recognizes the role of drivers, both natural and anthropogenic, in ensuring nature's benefit to people. b) By recognizing the linkage between direct drivers and anthropogenic assets, this approach ensures people's good quality of life from nature's benefits, which is a missing link in NRM approaches such as IWM.	a) The approach should take cognizance of the primary factors or activities that directly impact agro-biodiversity. The drivers can include land use changes, agricultural practices, introduction of new species, and other human-induced activities. b) Each driver is associated with specific attributes or parameters that help in understanding its impact on agro-biodiversity. These attributes might include factors like intensity, frequency, duration, and spatial extent of the driver's influence. c) Identifying how different drivers interact with each other and how their combined effects can lead to changes in agro-biodiversity. This could involve considering synergistic or cumulative effects of multiple drivers, 1) agro-biodiversity might be vulnerable or resilient to different drivers, considering factors such as ecosystem health, genetic diversity, and adaptation capacity. 2) might consider the policy implications and management strategies that can help mitigate negative impacts of certain drivers and promote sustainable agro-biodiversity. 3) might consider feedback loops and dynamic processes. For instance, how changes in agro-biodiversity due to certain drivers might lead to modifications in other drivers, creating a cyclic pattern.

TABLE 2 Continued.....

Description	NRM policy-Integrated Watershed management	IPBES conceptual framework	New proposed framework
vi) Good quality of life	This approach focuses on alleviating poverty and has no exclusive consideration for good life quality	Good quality of life, encompassing all ecosystem benefits, is a major focus of this approach. Aligning institutions, rules, and regulations to obtain this is inherent in it.	Enhancing the quality of life should extend beyond just benefits to primary stakeholders, but encompass all interconnected flora and fauna within the ecosystem chain.

The equity in benefits to the different segments of stakeholders in the watershed program can be addressed following the IPBES conceptual framework (Chaplin-Kramer *et al*., 2019; Schröter *et al*., 2020), as it inherently focuses on fortifying and maximizing the benefits derived from these essential services, ultimately enhancing the overall well-being and sustainability of ecosystems and human societies. Further, there is flexibility in the creation and modification of institutional mechanisms to account for the balance between nature and anthropogenic assets (Diaz *et al.,* 2015b). Also, there is sufficient scope for accommodating different property regimes, policies, and incentives to ensure a good quality of life through nature's benefits, ensuring the program's sustainability. By taking cognizance of both direct and indirect drivers that influence the execution and outcome, the IPBES conceptual framework would further ensure sustainability in the management of the program.

The program-specific gaps and IPBES relevance are listed in Table 1. In general, the IPBES provides a practical framework to deal with the program deficiencies listed below.

3.1.1 | Inadequate Scientific Data and Monitoring: Many land restoration programs lack comprehensive, reliable, and up-to-date scientific data, making it challenging to assess the true impact of restoration efforts and adaptively manage them (Hoffmann, 2021). The IPBES provides robust scientific assessments and methodologies for data collection, enabling more accurate monitoring and evaluation of ecosystem services and biodiversity. The IPBES can enhance the scientific rigour of land restoration programs by employing standard assessment methods to establish baselines, monitor progress, and evaluate the impact of land restoration projects, which is required for a reliable assessment of ecosystem health and better-informed decision-making processes.

3.1.2 | Fragmented Policy and Implementation: Policies and programs often operate in silos without sufficient coordination (Malhotra *et al*., 2023), leading to fragmented efforts and suboptimal outcomes. Additionally, policy coherence encompassing economic, environmental and social goals is basic to achieving SDGs (Coscieme *et al*, 2021). This has been attempted through integrated approaches advocated by IPBES that consider ecological, social, and economic dimensions, fostering better coordination and coherence across policies and programs. In fact, IPBES CF is regarded as a boundary object that aligns diverse actors (Dunkley *et al.,* 2018) with scope for improvement to provide space for dissension and ways of dealing with contrasting rationalists, diverging ontologies and different criteria for knowledge validation (Löfmarck and Lidskog, 2017). Adopting the IPBES conceptual framework, redesigned to accommodate diverse opinions, in order to integrate land restoration efforts with broader national and international biodiversity and sustainability goals can enhance policy coherence and allow the efficient use of resources.

3.1.3 | Limited Stakeholder Engagement: There is often insufficient involvement of local communities, Indigenous groups, and other stakeholders in the planning and implementation of land restoration projects (Chazdon *et al.,* 2020). The IPBES emphasizes the importance of inclusive stakeholder participation and incorporating indigenous and local knowledge, ensuring that restoration efforts are culturally appropriate and broadly supported. Implementing IPBES recommendations for inclusive participation, ensuring that local communities, indigenous peoples, and other stakeholders are actively involved, which would ensure greater community ownership, more culturally appropriate practices, and increased sustainability of restoration efforts.

3.1.4 | Insufficient Economic Incentives and Market Linkages: Degradation of land and forest has been attributed to the failure of the agricultural commodity market to internalize the externalities, particularly environmental. Market-based policy incentives have been suggested to be effective instruments for this (Farley and Costanza, 2010). Economic incentives for land restoration are often weak (Lant *et al.,* 2008), and there is a lack of strong market linkages for non-timber forest products and agroforestry produce. The IPBES can guide the development of better economic incentives and market mechanisms based on the valuation of ecosystem services, encouraging sustainable land use practices. Utilising IPBES methodologies to value ecosystem services and develop economic incentives such as payment for ecosystem services (PES) schemes can contribute to more robust economic motivations for sustainable land management and better market linkages for ecosystem service-based products.

3.1.5 | Lack of Adaptive Management Practices: Many programs fail to incorporate adaptive management practices, limiting their ability to respond to changing environmental conditions and new scientific insights. The IPBES supports using adaptive management frameworks that allow for flexibility and continuous improvement based on ongoing monitoring and evaluation. It is essential to apply adaptive management practices to facilitate programs' evolution in response to new data and changing conditions, increasing the resilience and effectiveness of land restoration programs.

3.1.6 | Insufficient Focus on Ecosystem Services: The land use and management practices typically govern the types of ecosystem services and their magnitude (Goldstein *et al.,* 2012). Traditional land restoration efforts, particularly forest restoration, ignored crucial ecosystem services like water regulation, carbon sequestration, and biodiversity conservation (Roy and Fleischman, 2022). A holistic view of ecosystem services recognizes not only basic biophysical knowledge but also temporal and spatial scale (Menzie *et al.,* 2012), as promoted by IPBES, it is needed to encourage the integration of multiple ecosystem benefits into land restoration planning and implementation. The IPBES ecosystem services framework into land restoration planning will likely yield more comprehensive benefits from land restoration efforts, including enhanced biodiversity, improved water regulation, and increased carbon sequestration.

Integrating the IPBES approach into India's land restoration programs addresses critical policy gaps by enhancing scientific rigour, promoting policy integration, strengthening stakeholder participation, developing economic incentives, fostering adaptive management, and adopting a holistic ecosystem services approach. As awareness of these gaps grows in India, leveraging IPBES can significantly enhance the effectiveness and sustainability of land restoration efforts, contributing to national and global biodiversity and sustainability goals.

4 | WAY FORWARD

4.1 | Setting policy target elements

The worsening degradation pace and environmental impact have fastened the thrust of ground actions and the commitment to land degradation neutrality. Restoration policies have helped address the issue; however, the effect of degradation on biodiversity value, ecosystem services, and, ultimately, human well-being has been considered in the arena of policies and programmes only lately. The policies and programmes need redesign to synchronize the commitments at scales from local to international.

Meanwhile, the degradation has outpaced restoration, leading to adverse effects on the environment. In the present scenario, complacency in putting degraded land restoration policy to the desired action is unaffordable. Drastic coordinated measures should be taken in a fast-track mode to address the SDGs sustainably and to achieve national and international commitments and negotiations in different formal forums and platforms. In the context of land degradation, the new policy initiatives will facilitate the issues relating to LDN target achievements by 2030, GHG emission targets to restrict temperature rise by 1.5 ^{o}C. The enabling policy for restoration of degraded lands should address i) protecting the productive land from further degradation, ii) slowing or reversing degradation while boosting biodiversity, soil health, and food production by implementing sustainable land management, and iii) enhancing efforts to restore the degraded lands to a natural or more productive state.

Based on the Summary for Policy Makers (SPM), while framing policy on the restoration of degraded lands, the relevant points (Table 2) need to be considered by the policymakers as target elements of policy formation to achieve the sustainability goals while addressing the UN commitments / negotiations / protocols / agreements / conferences on climate emergency and protecting the nature and earth, including SDGs, net zero emission, LDN, nationally determined contributions (NDCs), etc. are as under.

A comprehensive policy for land degradation restoration includes, among others,

I. Studying land degradation, following the IPBES pathway, with climate change, biodiversity, and ecosystem services.

II. Rigorous assessment (with available information, data, models, etc.) of the cause and effect of different types of degradation problems at the national, subnational, and local levels for developing a robust policy framework. Besides, Indigenous and local knowledge (ILK) needs special focus.

III. Wide-scale consultations (including civil societies and the public) on various degradation issues over temporal and spatial scales to improve the assessment process.

IV. Comprehensive studies on all available policies (with different departments) having bearings on land degradation control are essential (with scope for improvements) to address the present and emerging land degradation issues.

V. Defining roles and responsibilities for participating institutions to enact the policies with proper legal framework.

VI. Addressing the multinational conventions, commitments, agreements, etc., appropriately as deliverables.

VII. Simple to understand and empowering policy (with short and long-term goals) to implement massive restoration programs in real field situations.

VIII. Integrity in database creation and management, funding mechanism and smooth flow of financial resources for project implementation and developing effective monitoring and evaluation system for appraisal and reporting.

Further, the desired outcome at different hierarchy levels can be ensured by creating appropriate awareness across time and space (Table 2).

4.2 | National restoration policy from a global perspective - revisiting the approach

Lately, the comprehension of land degradation has expanded beyond traditional concerns like soil erosion, wind erosion, desertification, acid soils, soil salinity, waterlogging, loss of forests, and biodiversity. These issues impact agriculture, forest resources, and livelihoods. Additionally, our understanding now includes greenhouse gas emissions, carbon flux, temperature rise, and climate change scenarios. These scenarios involve rainfall, temperature, humidity, solar radiation, and the increasing frequency and reach of extreme weather events like droughts, cloudbursts, heavy rains, floods, landslides, and forest fires. Coastal erosion, water and soil pollution, cyclones, heat waves, cold waves, heavy snowfalls, thunderstorms, and dust storms at various scales and regions contribute to land degradation's intensity. Human activities, particularly improper and unsustainable soil and land management practices, significantly accelerate land degradation. Moreover, as data on spatial loss and damage estimates become more available (encompassing landscapes, crops, human and animal lives, and infrastructure), it becomes feasible to craft effective national policies for controlling land degradation and moving towards land degradation neutrality (LDN). Adaptations of these policies can be tailored to different administrative levels, even down to block level, based on data availability, to translate policy into action in real-world scenarios. A study conducted in 2018, sponsored by the Ministry of Environment, Forest and Climate Change, focused on the Economics of Desertification, Land Degradation, and Drought in India. The findings revealed that India's GDP experiences a 2.5% loss due to land degradation, and the consequences of not taking action would exceed the cost of restoration. This is particularly crucial as land degradation and climate change are closely interconnected. The estimated impact on India's GDP for 2014-15 is 2.5%, and it corresponds to around 15.9% of the Gross Value Added (GVA) from the agriculture, forestry, and fishing sectors. Notably, approximately 82% of the overall estimated cost is attributed to land degradation, with the remaining 18% arising from land use changes (www.teriin.org).

The land degradation restoration policy encompasses various concerns such as the environment, water, land use, land tenure, forests, livestock, agriculture, farmers, biodiversity, watershed management, rural employment guarantees, insurance, disaster management, and the respective national action plans on climate change. To facilitate this process, a wealth of scientific databases, models, and information, including indigenous and local knowledge (ILK) embraced by IPBES, should be employed. This amalgamation aims to construct an all-encompassing policy that not only advances ecosystem functions but also positively contributes to nature and human well-being. Clarity and transparency in data sources, overarching guidelines, and the delineation of roles and responsibilities for all stakeholders are crucial. This empowers implementers to execute restoration initiatives promptly without encountering administrative or financial obstacles. Visualized in Fig. 2, the policy development framework demonstrates how inputs from multinational commitments and agreements, including the IPBES synthesis report, can enhance prevailing and evolving national policies, action plans, and guidelines. Ultimately, this iterative process leads to the creation of an inclusive national restoration policy and action plan. This plan sets the course for implementation by 2030, 2040, or 2050, adhering closely to established commitments and respectfully acknowledging alternative knowledge bases like indigenous and local knowledge.

5 | CONCLUSIONS

Attaining land degradation neutrality (LDN) necessitates a conducive backdrop, encompassing policies, sustainable institutions, financial accessibility, and a productive science-policy nexus. With inclusive and conscientious governance, equilibrium in land management is upheld as fundamental for food security, climate mitigation, adaptation, and biodiversity preservation. The IPBES framework adeptly amalgamates scientific insight and indigenous knowledge, paving a route to formulate resilient policies for the well-being of both nature and humanity. All ministries and departments must collaborate to develop a comprehensive national policy on land degradation and restoration. This includes agriculture, water resources, environment, climate change, and more. They should define and review their roles, address challenges through policy documents, and assess ecosystem services. Collaboration with stakeholders is crucial for effective policy implementation. An awareness campaign aligned with the IPBES framework should be initiated for informed participation. The commitments established in the 2021-2030 UN Decade on Ecosystem Restoration reinforce short-term (by 2030) and long-term (by 2050) goals aligned with various global objectives. However, many countries are falling short of their targets, requiring swift and decisive actions, including robust policy

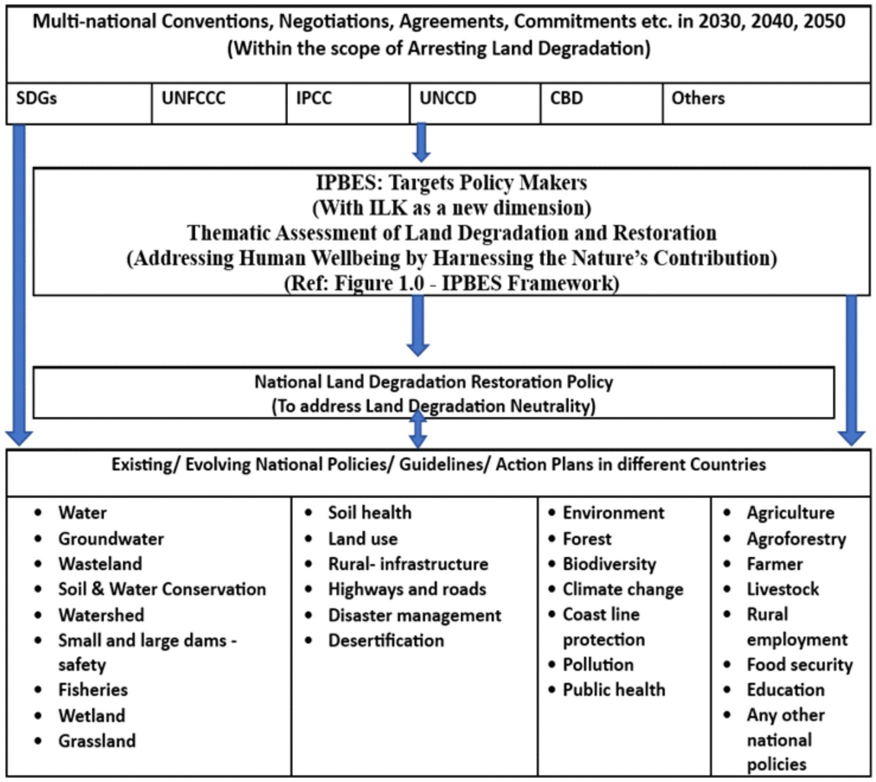

FIGURE 2 National policy framework for restoration of degraded lands - an approach

implementation and enforcement, for the well-being of humanity. Unprecedented climate challenges are complicating the timetable for sustainable objectives. Overcoming these hurdles requires united efforts and comprehensive strategies at all levels.

To protect and restore degraded lands while safeguarding biodiversity and nature's contributions, we need stronger domestic and international laws, improved implementation processes, and enforcement of these rules using feasible technologies, as per the IPBES conceptual framework.

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DATA AVAILABILITY STATEMENT

The data presented in this study are available in the public domain and published literature.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR'S CONTRIBUTION

P.K. Mishra: Conceptualization, analysis, writing; D.R. Sena: Review of literature, data analysis; V.C. Pande: Analysis of policy framework, writing and editing; R.K. Singh: Reviewing national degradation policies and editing.

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ORIGINAL ARTICLE

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Valuation of ecosystem services benefits from a ravine watershed in south-eastern Rajasthan

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ABSTRACT

Evaluating ecosystem services has become an essential area of study, highlighting the vital benefits that natural environments provide to human societies. This research focuses on the economic benefits of ecosystem services generated through watershed development interventions in the Badakhera Ravine Watershed in Bundi district, Rajasthan. Spanning 682.5 ha, the watershed underwent treatment between 1997 and 2003, employing various soil and water conservation measures such as land leveling, bunding, and water resource development. The economic valuation of ecosystem services utilized primary and secondary data, applying the market price method. The impact of watershed interventions was measured by comparing the enhanced ecosystem services against baseline ecosystem service values. The results indicate that, based on the soybean grain equivalent prices for 2019-20, these interventions significantly increased agricultural productivity, yielding additional returns of ₹ 60,000 per hectare per year from crop production. Furthermore, the interventions contributed ₹ 917 $ha^{-1}yr^{-1}$ from fodder production and ₹3,989 $ha^{-1}yr^{-1}$ from livestock production. Fuelwood generated from community and agroforestry trees added approximately ₹ 6,864 $ha^{-1}yr^{-1}$, while employment opportunities increased by 62 man-days $ha^{-1}yr^{-1}$, valued at ₹ 12,404. Regulating and cultural services from the watershed were also quantified, including an additional harvest of 24.93 cubic m ha^{-1} of surface water, valued at ₹ 374, and improvements in groundwater recharge, estimated at ₹ 9,007 $ha^{-1}yr^{-1}$. Nutrient loss due to erosion was valued at ₹ 117 $ha^{-1}yr^{-1}$. Average carbon sequestration across various land uses was estimated at ₹ 36,392 $ha^{-1}yr^{-1}$, and the demonstration value for education and training was calculated at ₹ 70.80 $ha^{-1}yr^{-1}$. This comprehensive valuation underscores the critical role of ecosystem services in sustainable watershed management and development policy.

HIGHLIGHTS

- The enhanced ecosystem services to baseline values were quantified due to the impact of watershed interventions.
- Watershed interventions increased agricultural productivity by an additional ₹ 60,000 $ha^{-1}yr^{-1}$ from crops, contributed ₹ 917 ha^{-1} from fodder, ₹ 3,989 from livestock, and ₹ 6,864 from fuelwood.
- Employment opportunities rose by 62 man-days ha^{-1} annually, valued at ₹12,404.
- An additional 24.93 cubic meters of surface water per hectare (valued at ₹ 374) and improvements in groundwater recharge are estimated at ₹ 9,007 $ha^{-1}yr^{-1}$.
- Soil and nutrient loss reduction due to watershed interventions was valued at ₹117 ha^{-1}, while carbon sequestration averaged ₹ 36,392 ha^{-1}.
- The skill development facilitation was valued at ₹ 70.80 ha^{-1}.

1 | INTRODUCTION

Ecologists and economists have long explained how human societies depend on natural environments. In recent years, more explicit language and data have enhanced understanding of how natural and economic processes benefit society. These ideas, called "ecosystem services" or something else, are crucial to future environmental policy. The concepts have been globally accepted by organizations such as the World Bank, World Resources Institute, UN Millennium Ecosystem Assessment (2005), Goldman Sachs, and the Heinz Foundation.

These organizations have chosen ecosystem-based management because other frameworks fail to effectively integrate economics and ecology while communicating their benefits to broader audiences. The concept emphasizes the connection between environmental management and human well-being. However, increasing human activity and rapid urbanization have led to the over-exploitation of natural resources, affecting achieving sustainable development goals (SDGs). In recent decades, policymakers and academics have had considerable interest in estimating the monetary value of ecosystem services (ES). This valuation can highlight their impact on human welfare and support their integration into public decision-making processes (Constanza *et al.,* 1997). Sharda *et al.* (2019) assessed the economic cost of soil erosion in India using the replacement cost principle, which calculates the cost of replacing nutrients lost due to erosion. The energy expended in producing fertilizers to replenish these nutrients was also estimated. Economic valuation of ecosystem services assists in decision-making regarding trade-offs between production and environmental conservation. It quantifies the benefits ecosystems offer and the impact of changes on human comfort. Therefore, monetary values should be considered when making economic decisions. Proponents argue that ecosystem service valuations can (i) enhance understanding of challenges and solutions, (ii) provide a basis for precise decision-making, (iii) illustrate profit allocation and support cost-sharing, and (iv) promote innovative organizational and market mechanisms for sustainable ecosystem management.

The primary aim of valuation studies is to inform decision-makers of the importance of ES for human well-being. These estimates may encourage policymakers to consider ES data when making land-use decisions prioritizing environmental sustainability (Kieslich and Salles, 2021). Several studies have focused on the challenges of valuing ES (Costanza *et al.,* 1997) and the complexity of understanding interactions between ecological functions and human use (Polasky *et al.,* 2011). These challenges stem from the indirect and spatially displaced effects of environmental change on human health, making them difficult to grasp (Bogardi *et al.,* 2020). Though ES valuation methods have improved, a lack of understanding of ecosystem dynamics, human needs, and technical issues in the valuation process still leads to uncertainty, particularly in stated preference methods. Market imperfections and policy failures can distort expected monetary values when using such methods. High-quality transaction data, large datasets, and sophisticated statistical analysis are essential for accurate valuations. However, stated preference approaches can be both expensive and time-consuming.

Market valuation methods, which primarily rely on production or cost data, are easier to apply but are limited in assessing ES due to the lack of or distorted markets. Consequently, these methods can produce skewed values, offering unreliable data for policy decisions (Muthee *et al.,* 2017). Various efforts have been made to value natural resources, especially forest-based resources and recreational / ecotourism (Chopra, 1998), water supply, and wetlands (Bhatta *et al.,* 2016). Scholars have valued soil conservation functions in a watershed context, but many other supporting, regulating, and cultural services affected by natural resource interventions remain under studied. This calls for a complex biophysical and socio-economic data set to value watershed interventions properly.

Since the 1970s, Watershed Development (WSD) has been integral to India's efforts to improve agricultural productivity and alleviate poverty in rainfed regions. These programs aim to rehabilitate degraded watersheds to enhance rainwater harvesting, prevent soil erosion, and increase soil nutrient and carbon content, improving crop productivity and rural livelihoods. Most of India's rural poor live in these areas, relying on natural resources for subsistence. Improved agricultural yields enhance both human welfare and national food security. However, despite significant attention and funding from the government, the success of WSD programs in achieving food security and reducing hunger remains unclear. This is partly due to inconsistent data collection and evaluation efforts across implementing agencies. Most reviews focus on changes in key indicators and anecdotal project outcomes, lacking a comprehensive understanding of the economic, social, and environmental benefits for beneficiaries. Studies like Verma's (2007) research on Uttarakhand's forest ecosystems demonstrate the need for more rigorous data to evaluate the benefits of watershed services, especially regarding water flow monitoring. A recent meta-analysis by Meena *et al.* (2022) on 221 watersheds across five agro-climatic zones in India revealed watershed ecosystem services worth ₹ 34,113 ha^{-1}. Due to the scarcity of studies on watershed-based ecosystem services, none have attempted to value these services in the degraded ravine areas of the region. This research seeks to comprehensively examine the ecosystem services of a particular ravine watershed, evaluating its ecological, economic, and social significance. This study aims to quantify the advantages of the rehabilitated degraded ravine watershed by utilizing an interdisciplinary method that combines ecological, economic, and social sciences while underscoring the necessity for ravine area development and sustainable management through a watershed framework. Comprehending the significance of ecosystem services in ravine watersheds can enhance policy formulation, direct conservation initiatives, and elevate public consciousness regarding safeguarding these habitats. This research enhances the existing knowledge on ecosystem service valuation and provides practical insights for stakeholders engaged in watershed management, environmental planning, and sustainable development.

2 | MATERIALS AND METHODS

2.1 | Study Area

The Badakhera Watershed, located in Rajasthan's Bundi district (Fig. 1), was selected for this study due to the availability of extensive data. Badakhera is a rain-fed ravine watershed at a latitude of 25°36' N and a longitude of 76° 15'E. The watershed spans 682.5 ha and drains into the Mej river near its confluence with the Chambal river. The elevation varies from 150 to 172.5 meters above sea level. The Mukundara range of the Vindhyan Hills flanks the watershed to the north and south. Approximately 20% of the watershed comprises tablelands that gradually transition into slopes ranging from 2% to 10% as they approach the extensive network of gullies, which cover about 80% of the downstream area. The ravenous slopes range from 20% to 30%. The highest stream order within the watershed is 4, and the drainage density was calculated at 14.86 km km^{-2}. The multidirectional slopes of adjacent cultivated fields and subsistence farming with low productivity provide a significant opportunity to demonstrate and evaluate recommended agricultural practices.

The Badakhera watershed covers a total area of 682.5 ha, of which 378.9 ha are privately owned agricultural land and 303.6 ha are community-owned. Work on the watershed began in 1997-98 and concluded in March 2003, with a total project cost of ₹ 27.3 lakhs. Several conservation measures were implemented on arable lands as part of the development activities. These included land leveling between bunds, constructing masonry, gabion, or loose boulder spillways for safely disposing of excess runoff, and building graded and peripheral bunds reinforced with grasses. Drainage lines were treated with stabilization methods such as straight-drop masonry or gabion spillways at gully heads, check dams, gully plugs, and live hedge barriers to flatten and stabilize the gully beds. Depending on the runoff-generating area, either masonry (>5 ha), gabion (1-5 ha), or loose boulders (<1 ha) were constructed. Rectangular waste weirs were provided at the lowest portion of the graded

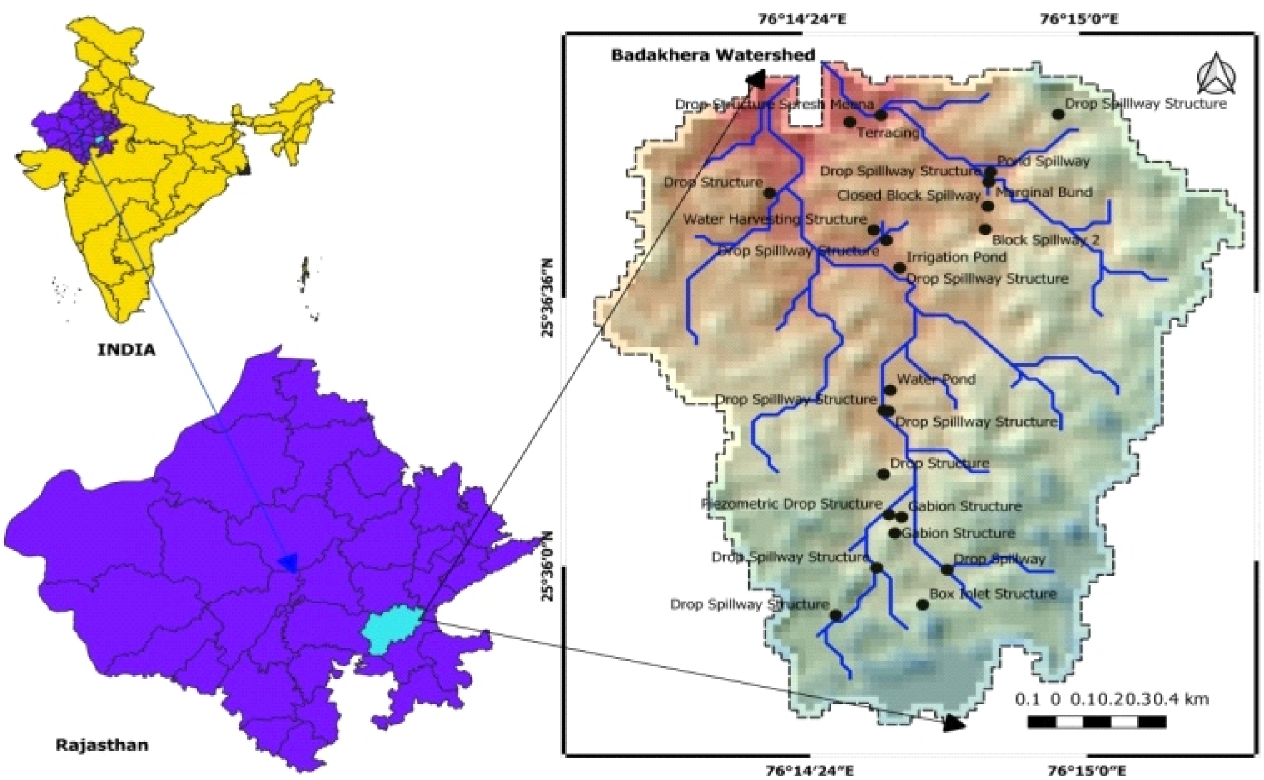

FIGURE 1 Location and interventions map of selected watershed

bund. The crest of the waste weir was kept 15 cm above ground level. In some places, a shoulder bund perpendicular to the graded bund was provided to trap the silt in continuation of the waste weir. These measures were employed either individually or in combination, depending on the problem to be addressed. Additionally, two agricultural ponds with capacities of 1.6 and 0.6 ha-m were constructed, and crop demonstrations of improved practices were introduced.

2.2 | Data and Valuation Methods

The study adopts a "before and after" project approach, comparing benchmark data from 1997-98, when the project was initiated, with data collected in 2013-14, 10 years after the project was completed. The considerable duration of 10 years was necessitated by the understanding that soil and water conservation methods require extended periods to realize their full potential and necessitate adequate time for the complete stabilization of the watershed ecoregion. Data on specific ecosystem services such as soil organic carbon (SOC) and carbon sequestration related to cultural ecosystem services were collected from field observations and secondary sources such as reports and official records for 2019-20. The impact of integrated watershed management (IWM) and soil and water conservation interventions on ecosystem services (ES) was measured using the Pande *et al.* (2023) approach.

$$ESWM = IWMES_1 - IWMES_0$$

Where, ESWM = Ecosystem Service change due to IWM; $IWMES_0$ = ES before IWM intervention (baseline); $IWMES_1$ = ES after IWM intervention.

This protocol was applied as a matrix for each ecosystem service supported by integrated watershed management. The yields of different crops are converted into crop equivalent yields (CEY) of any one crop (in the present case, Soybean) based on the price of the produce.

$$CEY = Cy + C1y * \frac{P_{c1}}{P_c} + C2y * \frac{P_{c2}}{P_c} + \text{-------}-$$

CEY is the crop equivalent yield; Cy is the yield of the main crop, the yield of other crops converted to its equivalent, and Pc is its respective price; C1y, C2y .... are yields of intercrops / other crops which are to be converted to the equivalent of main crop yield and Pc1 and Pc2 are their respective prices. (Rana and Kumar, 2014).

2.3 | Ecosystem Services Categorization

Based on the Millennium Ecosystem Assessment, over 20 ecosystem services (ES) have been classified into four main categories: provisioning, regulating, supporting, and cultural services. Based on available data, a comprehensive list of ecosystem services resulting from watershed management interventions was identified and valued at 2019-20 prices, as detailed in Table 1.

3 | RESULT AND DISCUSSION

3.1 | Provisioning Services

Watershed development provisioning of ecosystem services refers to the provision of commodities and resources by ecosystems, especially those located within watersheds, directly to the activities of humans. Services of this nature are crucial for the welfare of communities and may encompass the following

3.1.1 | Crop Production: For annual crop production, yields were analyzed based on the area under cultivation before and after watershed interventions. Depending on availability, these yields were converted into major crop equivalents using either the Minimum Support Price or the market price. The by-products and pure fodder crop output were also converted into grain equivalent terms using farm harvest prices and local prices of by-products and green fodder (Table 2). This provided a comprehensive view of total productivity, comparing pre- and post-NRM (Natural Resource Management) interventions. It was found that the watershed interventions generated an additional return of approximately ₹ 41,491,159 from crop production when expressed in major crop grain equivalents (soybean). This corresponds to an additional return of approximately ₹ 60,000 $ha^{-1}yr^{-1}$. The significant rise in the value of provisioning ecosystem services was mainly due to changes in farming practices and the increased land usage after the interventions. Enhanced productivity was further supported by improved irrigation systems made possible through groundwater recharge and soil and water conservation measures that helped retain moisture in the soil. A study by Kumar *et al.* (2024) conducted in the Kokriguda watershed, Odisha, found that provisioning ecosystem services increased to $ 392.9 ha^{-1} in crop production at 2020-2021 prices. The analysis by Dhayani *et al.* (2020) of 38 years of data in the Bhaintan participatory integrated watershed management project, located in the Indian North Western Himalayas (INWH), also demonstrated a steady improvement in all provisioning ecosystem services (ES) indicators compared to the pre-project period.

3.1.2 | Livestock Production: Livestock is vital in providing ecosystem services and is a fundamental component of many agroecosystems. It contributes by converting non-edible feed into nutritious food and valuable products (e.g., converting grass into milk or meat), interacting with ecosystems through grazing and trampling, and producing dung and urine.

Additionally, livestock mobility allows them to respond to resource and climate fluctuations. The impact of watershed interventions was assessed by evaluating additional income

TABLE 1 Ecosystem services and methods used for valuation

Ecosystem services	Indicator	Methodology	Data use
Provisioning services			
- Food	Crop production	Change in crop production due to integrated Watershed Management (IWM) before and after intervention.	Crop-wise area, yield, the market price of the crop (MSP/Farm harvest price)
- Fodder	Fodder production	Change in fodder production due to IWM intervention	Area under fodder crop, yield, local market price
- Forest	Timber / fuel wood / grass production	Change in tree / grass biomass production due to IWM intervention	Area under tree/ grass species, number, height, DBH of tree, grass yield, local market price of fuelwood, grass, stumpage price of timber
- Livestock	Livestock production	Change in milk and dung production due to IWM intervention	Number of cattle in lactation, milk production, dung production, local market price of milk and dung
- Water	Fresh water for household use	Change in surface water storage due to IWM intervention	Surface water harvest from different water bodies, watershed area, cost of municipal water supply
- Livelihood support	Employment generation	Change in employment generated in the watershed due to IWM intervention	Number of days employed (casual and regular) in different activities, local wage (MGNREGA) rate
Regulating services			
- Water flow regulation	Groundwater recharge	Change in annual groundwater recharge due to IWM intervention	Watershed area, average annual water level fluctuation, watersheds specific yield, cost of municipal water supply
- Atmosphere temperature regulation	Carbon sequestration	Change in carbon stock in soil and vegetation due to IWM intervention	Carbon stock in soil and vegetation in different land uses, area under land uses, Certified Emission Reduction (CER) price
Cultural services	Awareness creation / education service (demonstration)	Value of acquiring knowledge about natural resource management due to IWM intervention	Number of people acquiring knowledge, the average expenditure on the watershed visit by the trainees or visitors

TABLE 2 Changes in provisioning ecosystem Value of crop production with watershed interventions in Badakhera watershed

Agricultural crop products on arable land	Total Production (q) in Soybean grain* equivalent	Value in (₹ Lakh)
Pre-project		
i) Crop -main (grain)	2844.84	105.54
Crop by-products -cob	0.444	0.02
Stalk	26.61	0.99
ii) Fodder production	103.70	3.85
Post project		
i) Crop main (grain)	13859.5	514.19
Crop by-products-cob	0.528	0.02
Stalk	290.29	10.77
ii) Fodder production	272.300	10.10
Change as a result of IWM [(b) - (a)]		
I) Crop main (Grain)	11014.66	408.64
Crop by-products-cob	0.084	0.00
Stalk	263.6	0.01
ii) Fodder production	168.59	6.25
Additional return total return from watershed	--------	414.91
Return $ha^{-1}yr^{-1}$		0.61

**Soybean price 3710 q^{-1}*

from milk and dung production (Table 3). Results indicate that additional income post-intervention was estimated at ₹ 3,552 $ha^{-1}yr^{-1}$ from milk and ₹ 436 $ha^{-1}yr^{-1}$ from dung.

3.1.3 | Fuel wood Availability: Firewood and timber yield were considered based on the area under tree plantations within the watershed. Forest productivity was calculated by summing the total biomass (yield multiplied by area) of all forest trees in the watershed and dividing this by the total plantation area. The Badakhera watershed covers 682.5 ha, with 378.9 ha of arable land and 303 ha of degraded land. The community land, covering 432 ha, is mainly used for grazing and is dominated by *P. juliflora* and mixed vegetation, including medicinal and non-timber forest products (NTFP) species. Fuelwood sourced from *P. juliflora* is the village's major household fuel for cooking. Hence, the value of fuel wood provided by the watershed was assessed accordingly, and it was found that an additional return of ₹ 6864 ha^{-1} was generated by fuel wood in the watershed.

3.1.4 | Employment Generation: The watershed development program positively impacted employment opportunities. During 2013-14, the program generated 56,333 man-days of crop and livestock production employment, compared to 23,957 man-days before the project (Table 4). Additionally, 10,167 man-days were created during the project's implementation phase. In monetary terms, this translated to an additional ₹ 12,404 $ha^{-1}yr^{-1}$ in employment. Increased cropping intensity due to improved irrigation facilities was a major factor in this employment growth.

3.2 | Regulatory Ecosystem Services

The regulation of ecosystem services from watershed growth focuses on the advantages that ecosystems offer by controlling environmental processes. These services contribute to preserving ecological equilibrium and assure the long-term viability of natural resources. The listed regulatory services have been examined:

3.2.1 | Water Storage and Groundwater Recharge: Soil and water conservation measures were instrumental in enhancing groundwater recharge and water storage through reduced surface runoff, increased infiltration, and improved soil moisture retention. Techniques such as contour farming, terracing, and planting cover crops slowed water flow, mitigated soil erosion, and improved water absorption. These practices helped maintain groundwater levels and ensured a steady water supply during droughts. The study estimated that watershed interventions resulted in an additional harvest of 24.93 m^3 ha^{-1} of surface water by reducing runoff (Table 5). Groundwater storage increased by 409,500 m^3, valued at ₹ 374 for surface water and ₹ 9,007 for groundwater using a replacement cost approach. A similar study by Esen *et al.* (2023) in Turkey's Southern Aegean Region estimated the value of groundwater recharge at approximately € 40.4 million yr^{-1}, or around € 35 $ha^{-1}yr^{-1}$.

TABLE 3 Valuation of ecosystem services of animal husbandry in watershed

Particulars	Pre-project	Post project	Net Change
Total nos of milch animals (SAU*)	104	187.2	83.2
Milk production(lit) / yr^{-1}	71740	149791	78051
Dung production (t) yr^{-1}	743.4	872.07	128.67
Milk Productivity (lit) $animal^{-1}yr^{-1}$	689.8	744.25	54.45
Milk productivity (lit) $ha^{-1}yr^{-1}$	105.11	217.6	112.49
Dung production(t) $ha^{-1}yr^{-1}$	1..08	1.27	0.19
Gross value (₹) of Milk yr^{-1}	2331010.5	4755455	2424445
The gross value of dung (₹) yr^{-1}	728500.5	1026344	297843
Value of milk (₹) ha^{-1}	3415.4	6967.7	3552.3
Value of dung (₹) ha^{-1}	1067.4	1503.8	436.4

**1 SAU = 1 buffalo, 0.7 cow, 0.08 goat,0.09 sheep*

TABLE 4 Valuation of Employment created by the watershed interventions

Activity	Pre-project			Post project			Net change value ₹ lakh ha^{-1}
	Employment generated (man days)	Gross value (₹ in lakh)	Value ₹ lakh ha^{-1}	Employment generated (man days)	Gross value (₹)	Value ₹ lakh ha^{-1}	
Crop production	9837.3	19.58	0.03	30778	61.25	0.09	0.06
Livestock production	14120	28.10	0.04	25555	50.85	0.07	0.03
Casual employment (Project activities)	----	-----	-----	10167	20.23	0.03	0.03
Total	23957.3	47.67	0.07	66500	132.34	0.19	0.12

Valuation of employment generation was done using the MGNERGA rate in Rajasthan state @199 Rs during 2019-20

3.2.2 | Carbon Sequestration: Carbon sequestration is a critical ecological process that regulates atmospheric carbon dioxide levels, helping mitigate climate change. Watershed interventions, such as soil and water conservation measures, enhance this process by improving soil and vegetation quality. Carbon inventories were assessed using soil and vegetation sampling, and carbon was converted into CO_2 equivalents, which were then valued based on the market price of certified emission reductions (carbon credits) (Table 6). The carbon sequestration value for the Badakhera watershed was calculated at ₹ 36,392 $ha^{-1}yr^{-1}$, mainly due to the extensive coverage of *Prosopis juliflora* and other mixed vegetation in the area. Pande *et al.* (2012) also found an incremental soil carbon buildup of ₹ 41,000 ha^{-1} in bamboo plantations with recommended harvest practices.

3.2.3 | Erosion Control: Soil conservation structures, such as check dams, contour bunds, and vegetative barriers, play a key role in storing silt and minimizing nutrient loss. These structures help reduce soil erosion, capture sediment, and prevent nutrient-rich topsoil from being washed away. Nutrients retained in the soil were valued using the market price of nitrogen, phosphorus, and potash, applying the replacement cost technique. Data about silt retention and nutrient loss collected from different reach of the watershed are given in Table 7. The study found that the annual value of nutrients lost through erosion was ₹ 79,931 annually (₹ 117 $ha^{-1}yr^{-1}$). A study by Lemma *et al.* (2017) estimated that soil nutrient loss due to rill erosion in a 768.8 ha watershed amounted to $ 1,341 annually.

TABLE 5 Valuation of Groundwater recharge and water harvesting

Particulars	Pre-project	Post-project
A. *Groundwater storage*		
Average water level fluctuation (m)	1.25	2.25
Specific yield	0.06	0.06
Storage volume (m^3)	511875	921375
Change in groundwater storage due to watershed intervention (m^3)		409500
Value in ₹ ha^{-1}		9007
B. *Surface water harvested*		
Surface (water storage m^3)	5000	22000
Surface water storage per unit area (m^3ha^{-1})	7.2	32.25
Addition in surface water harvested due to watershed intervention (m^3ha^{-1})		24.93
Value in ₹ ha^{-1}		374

3.3 | Cultural Ecosystem Services

Cultural ecosystem services resulting from watershed development pertain to the intangible advantages individu-

TABLE 7 Nutrient value from silt retention as a result of soil and water conservation measures in Badakhera Watershed

Location	Silt retention (tones)	Nutrient retained (kg)		
		N	P	K
		Upper reach		
WUR 1	1500.2	112.7	4.2	274.9
WUR 2	1243.2	92.3	3.1	251.7
WUR 3	1981.2	148.0	4.8	3698.0
WUR 4	673.3	50.6	1.9	123.3
WUR 5	611.9	38.2	1.6	115.3
WUR 6	2668.9	197.8	6.6	514.4
WUR 7	668.4	45.9	1.9	140.8
		Middle reach		
WMR 1	583.7	43.9	1.4	112.4
WMR 2	1200.5	85.5	2.7	171.6
WMR 3	807.5	55.3	1.7	155.6
		Lower reach		
WLR 1	739.5	49.0	1.8	147.9
WLR 2	855.1	54.1	1.9	161.8
Total		973.6	31.7	2376.5
Annual value of nutrients lost using replacement cost (₹)*				79931.4
Cost per ha^{-1} yr^{-1}				117

**Prices of UREA = ₹ 5.36 kg^{-1}, SSP ₹ 7.24 kg and MOP = ₹ 15.7 kg^{-1} https://agritech.tnau.ac.in/*

TABLE 6 Impact of Watershed interventions on Carbon sequestration values

Particulars	Arable lands		Non arable lands	
	Pre-project	Post- project	Pre-project	Post-project
Above ground biomass Carbon stock (t ha^{-1})	14.15	31.7	29.45	52.55
Below ground biomass carbon stock (t ha^{-1})	3.16	6.34	5.21	7.65
Soil carbon stock (t ha^{-1})	2.76	3.34	3.74	6.2
Total Carbon stock (t ha^{-1})	20.07	41.38	38.4	66.4
CO_2 eqv in Mg m t^{-1}	73.68	153.89	140.93	243.69
Area covered in watershed (ha)	36	36	303	303
Total carbon seq. potential Mg (matric tonne) year	2652.48	5540.04	42701.8	73838
Total value of carbon sequestration for treated area @ US $ 10 t^{-1}	26524.8	55400.4	427017.8	738380.8
Change in value due to watershed interventions in US $	-	28875.6	-	311363
Average carbon sequestration value in INR* $ha^{-1}yr^{-1}$ (1 US$ = INR 73)	-	-	-	36392

The carbon credit price in the agricultural sector was US$10.38 in 2020 and US$8.81 in 2021; hence, US$10 was used for computations. Source: www.forest Trends.com als derive from the ecosystems within the watershed. These services foster human well-being by providing education or skill development facilitation, offering recreational activities, and facilitating aesthetic experiences.

3.3.1 | Skill Development: One of the cultural services ecosystems provide to societies is the valuation of training the IISWC provides to watershed implementing agency personnel, watershed committee members, farmers, and engineering students through field exercises and exposure visits. While we have developed valuation methods for several ecosystem services, we have not given much attention to training / education as an ecosystem service. The classification of ecosystem services classifies education as a cultural service. The critical criterion for including the activity as an education service is the direct association of the educational activity with the natural ecosystem. The scope includes institutionally organized watershed education through capacity building and training. One can assess the monetary value of a watershed training ecosystem service, which does not produce a market product, through expenditures or stated preferences associated with the service. Unlike other ecosystem services, the distinctive feature of training services is that the financial costs of providing a training service are relatively well-defined and can be expressed as a specific amount of money. In our case, the sponsor agency or training institution finances the trips for trainees who visit watersheds for educational purposes, eliminating individual expenditures. The valuation of training services was based on the total expenditure for training trips to the watershed, valued at ₹ 483,200 or ₹ 70.8 $ha^{-1}yr^{-1}$ over the past decade (Table 8). Muniyandi Balasubramanian (2021) also estimated the economic value of recreational ecosystem services at sites like Nandi Hills and Nagarhole National Park using a similar approach.

4 | CONCLUSIONS

The study of the Badakhera Ravine Watershed indicates that watershed development initiatives significantly enhance agricultural productivity, livestock production, water storage, groundwater recharge, carbon sequestration, and soil conservation. These initiatives create socio-economic benefits, such as employment opportunities and improved livelihoods for rural communities. The research highlights the crucial role of watershed management in promoting environmental sustainability, economic development, and climate resilience. However, data limitations often hinder the accurate valuation of ecosystem services, underscoring the need for further research to understand their importance fully. The study stresses prioritizing watershed improvement initiatives in ravine ecosystems nationwide. Policymakers can enhance ecosystem services - such as increased agricultural output, groundwater recharge, and carbon sequestration - by implementing soil and water conservation measures, including bunding, land leveling, mechanical structures, and water resource development. This strategy bolsters environmental sustainability and provides socio-economic benefits, such as higher farmer incomes and job creation, ultimately improving rural livelihoods and enhancing national food security. Furthermore, integrating watershed management with agroforestry and livestock rearing can increase the resilience and multifunctionality of these ecosystems, highlighting the essential role of policy in promoting comprehensive and sustainable resource management.

TABLE 8 Watershed training ecosystem service value (₹)

Parameter	Value
a. average travel costs for one trainee (₹). Calculated based on average bus rental price (₹ 667 hr^{-1}), average rental duration (12 hrs), typical trainee group size (25)	667*12/25 = 320.16
b. Total numbers of trainees visited the watershed	1510
c. Watershed training ecosystem service value (₹)	4,83,200
d. Watershed training ecosystem service value ₹ $ha^{-1}yr^{-1}$	70.80

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DATA AVAILABILITY STATEMENT

The data supporting this study's findings are available with the corresponding author.

CONFLICT OF INTEREST

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

AUTHOR'S CONTRIBUTION

AK: Conceptualization, data compilation, methodology, writing original draft, review and editing of manuscript, RKS: Conceptualization, Supervision and editing, IR: Data collection, analysis, review, and editing; SK: Data collection, analysis, review, and editing. KK: Review and editing. GLM: Data collection and Map preparation. AKS: Data compilation. SA: Supervision and editing.

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ORIGINAL ARTICLE

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Modelling of water regulating agro-ecosystem services in India

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ABSTRACT

Agroecosystem models are recognized as effective and potential tools for understanding the interactions between different agro-ecosystem components for identifying the suitable management measures and sustainable management agro-ecosystem. The study illustrates the use of models in agroecosystems for simulating water-regulating services in India and emphasizes the vital role of the audience in advancing this research. Developed agro-ecosystem simulation models in India are effectively employed for simulating the water-regulating agroecosystem services, including infiltration, potential groundwater recharge, water storage, surface runoff yield, and soil erosion. Applications of developed infiltration models for constant as well as varying depths of ponding are successfully applied for a range of soils. Simulated potential groundwater recharge from WHSs (Water Harvesting Structures) by the developed potential groundwater recharge simulation model varied between 83 and 90% of stored water in the WHSs. Simulation of soil erosion by a derived model ranged from 0.09-3.83 t ha^{-1} yr^{-1} for different crops and cropping systems. Modeled surface runoff by the NAPI-based rainfall-runoff model for an agro-ecosystem's degraded land use system ranged from 10-20% of the rainfall. Simulation studies on a few water-regulating agro-ecosystem services employing the derived models showed varied hydrologic responses of varying land use systems in India's agro-ecosystem. In conclusion, these agro-ecosystem modelling applications could be extended to similar agro-ecological regions of the world, with the audience playing a crucial role in this extension and in improved understanding and calculating water-regulating agro-ecosystem services.

HIGHLIGHTS

- Study illustrated the use of agro-ecosystem models to simulate water regulating services.
- Application of developed infiltration models is demonstrated for a variety of soils.
- Simulated groundwater recharge by IPGRS model ranged from 83.0 to 90.2% of runoff.
- Simulation of soil erosion by a derived model ranged from 0.09-3.83 t ha^{-1} yr^{-1}

1 | INTRODUCTION

Globally, an agroecosystem is a dominant ecosystem covering about 40% of the earth's surface. It plays a crucial role in the overall development of the socio-economical conditions of a nation for the well-being of humans. An agroecosystem is the stronghold of a developing countries' economies. About 58% of India's population depends on agro-ecosystem services for their livelihoods. Globally, an agroecosystem demonstrates significant structural and functional disparities due to varied climatic, socioeconomic and cultural conditions that represent them. The functioning of the agro-ecosystem is an omnibus of a variety of components, including crops and cropping systems, tree-grass association, agri-horti and agri-silvi systems, pasture systems, and home gardening.

Agroecosystem service is defined as benefits, including tangibles and intangibles, provided by an agroecosystem for the human and society's well-being and country. Traditionally, the agroecosystem is primarily considered a provisioning services source for using products and by-products from the agricultural system. In addition to provisioning services, a variety of ecosystem services from agro-ecosystem services are documented, including regulating, cultural and supportive services (Fig.1). Agro-ecosystem provisioning services are the most visibly recognizable of all types of ecosystem services as they provide direct products to the people that can be used and monetized. Agro-ecosystem provisioning service offers products that include 4-Fs (food, fodder, fiber, and fuel) and supplementary harvestable produce. The regulation service regulates important components of ago-ecosystem processes, including hydrologic and climatic regulation. Hydrologic regulation agroecosystem services are associated with the movement and storage of water in terms of quantity. It impacts hydrological processes like runoff, infiltration, groundwater recharge, evaporation, evapotranspiration, and hydrologically linked natural vulnerabilities/ hazards (i.e. droughts and floods), irrigation and drainage as agricultural water management practices, water decontamination, and treatment of wastewater. It also affects land degrading processes, including soil erosion, loss of soil organic matter, carbon and nutrients from water, acidification salinization, and biodiversity. Supporting service refers to the fundamentals of soil and plant production processes, which include soil formation and structures, nutrient supply and cycling, natural pest and disease control, photosynthesis, and pollination. These are vital for providing provisioning ecosystem services. Cultural ecosystem services refer to non-material benefits gained from ecosystems, such as aesthetics, scenic beauty, inspiration, education, recreation, tourism, and traditional uses. The interactions between / amongst the agro-ecosystem services are highly multifaceted and complex and depend on interconnected and multiple ecosystem services. Simultaneously, it is accountable for altering or changing several ecosystems and their associated services and habitats.

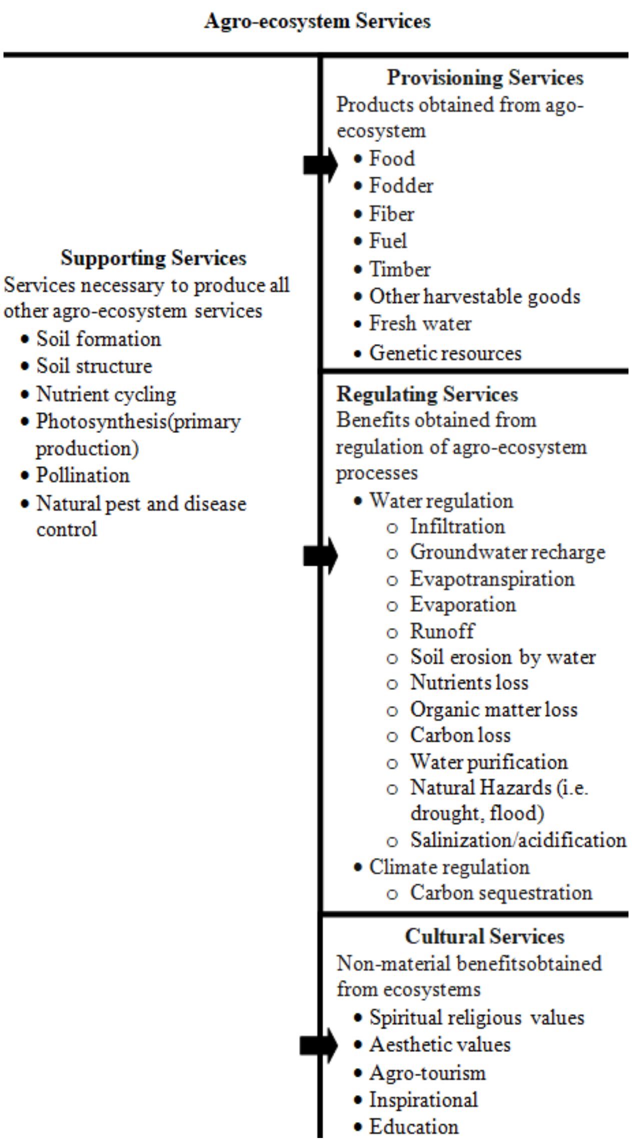


FIGURE 1 Eco-system services made available by an agro-ecosystem

Water is one of the most indispensable components for the functioning of an agro-ecosystem. Assessment and a better understanding of water-regulating agro-ecosystem services enhance the 4Fs and energy security through water management and help tackle water security problems. The objective of this paper is not to present the minutiae of the water-related agroecosystem services models but to demonstrate the applicability of different models developed in India for quantifying and predicting the water-regulating agroecosystem services under Indian conditions. Water is central to sustaining and supporting human and society's well-being. The paper focuses on the water-regulating services of the agroecosystems, mainly water movement and storage.

2 | AGRO-ECOSYSTEM SERVICES MODELING

An agroecosystem is a more complex and composite ecosystem due to several driving forces. These include the growing population and their demand for agroecosystem services, dwindling per capita agricultural lands of agro-ecosystems for intensifying the provisioning of agro-ecosystem services, changes in land use production system, and mounting pressures on natural resources for their sustainable uses. To overcome these varying and numerous problems of agro-ecosystem, there is growing interest in applying agro-ecosystem models in recent years. The agroecosystem models are necessary for increasing basic scientific understanding of agroecosystem components and interactions of the components, which assesses the production potentiality of the agroecosystem. Agro-ecosystem models also help to the decision and policymakers and ecosystem managers for screening the potential risk or vulnerable areas and identify the best management practices (BMPs) to maximize the profitability and sustainability of the agro-ecosystem for maintaining food water and energy security and better quality of environment.

2.1 | Agro-Ecosystem Models

Agro-ecosystem model is a simplified description of a complex agro-ecosystem that simulates/reproduces the temporal and/or spatial response of the agro-ecosystem. Agro-ecosystem models are either explanatory or descriptive. A descriptive model uses one or more mathematical equations based on experimental data to simulate the behaviour of a system. Explanatory models are used to model the system's process(s) and mechanics. These models include different combinations of mechanistic and functional model components. Explanatory models help to amplify the basic and better scientific understanding of the ecosystem. Mechanistic models are used to model basic mechanisms of plant and soil processes to simulate specific outcome (s). These are usually based on the agroecosystem's hypothesized and / or known physical, chemical, and biological processes. They are often used to understand specific processes and interactions better. Richards and Green-Ampt model for water movement in the soils are examples of mechanistic models in agro-ecosystem. Functional models use simplified approaches to simulate complex processes. Penman-Monteith or Priestley-Taylor models for simulation of potential evapotranspiration and radiation use efficiency models are some examples of functional models. The models use much less input data than mechanistic models, making them more simple and useful for those unfamiliar with the biophysical processes involved in the simulations**.** Functional-type models are now normally used in the DSSs (decision support systems). Dynamic system (DS) models have a mathematical function(s) with time-based on physical law governing the system that describes the future and change in response of the system with time by external forces such as management practices, climate, etc. The DS models may have mechanistic and functional components. Good examples of the DS Models for cropping systems are APSIM, CROPSYST, and EPIC. The agro-ecosystem models have been developed at field, farm, regional, national, and global scales. The users of the agro-ecosystem model ranged from farmers to policymakers interested in improving decisions and policies from the field to national and global levels.

3 | MODELING OF WATER-REGULATING AGRO-ECOSYSTEM SERVICES

Water movement processes in an agro-ecosystem involve surface runoff, infiltration [i.e. movement of water into the soil and its subsequent release to the atmosphere as evaporation from soil and transpiration from the plants (i.e. evapotranspiration)], groundwater recharge, and evaporation from the water surface. Water movement as surface runoff with a velocity greater than erosive velocity causes soil erosion and soil organic matter, nutrients, and carbon stock losses. To characterize and simulate water-regulating agroecosystem services, modelling these water movement regulating services is paramount. The paper herein discusses the principal applications of a few water-regulating agro-ecosystem models developed in India for some essential water-regulating service processes such as infiltration, potential groundwater recharge, surface runoff, water storage and soil erosion in agro-ecosystem under Indian conditions.

3.1 | Infiltration

Infiltration is one of the essential components of the agro-ecosystem that involves the entrance of the water from the soil surface into the soil profile and subsequent movement of this water through the unsaturated zone below the plant root zone as potential recharge/deep percolation and finally joins the groundwater table as groundwater recharge. The infiltration process in an agro-ecosystem is controlled by rainfall characteristics (i.e. intensity and duration), land slope (uniform and non-uniform), land use systems (agriculture, fallow, vegetation, pasture and forest), soil properties (i.e. moisture content, texture, layers, and surface sealing and crusting), movement and entrapment of soil air, plant density/architecture (i.e. broad or close spaced), and amount of litter at the soil surface and below the surface. The management practices of agroecosystems (i.e. tillage practices, mulch, manure, etc) and carbon stocks / pools also drastically alter the infiltration process. The agroecosystem has a higher rate of infiltration and cumulative infiltration than that of the fallow land ecosystems, and it tends to increase soil moisture status in the soil profile and groundwater recharge in the aquifers and reduce the peak flow and, consequently, floods.

Numerous infiltration models have been developed in the past and used to assess the infiltration behaviour of the upper soil layer in agro-ecosystems at a point scale. These models are classified as empirical, semi-empirical and physically based infiltration models. The empirical and semi-empirical infiltration models include Kostiakove, Holtan, Horton, and Philip models, that were developed based on laboratory or field experiment data and utilized simple mathematical expressions/equations. These models are not capable to explain the infiltration process fully. On the other hand, the physically based infiltration models explain the infiltration process substantially. The Green-Ampt (GA) and Richards models are the most widely and commonly used process-based infiltration or water flow models. Richards' model mingles the Darcy equation with the continuity equation and includes a sink term for soil water extraction by the root systems. Richards' model is solved by means of an iterative implicit numerical technique with fine discretization in both the space and time. Richards' and Richards' based modelling codes are still inappropriate for all soil types (principally soils with high clay or organic matter). However, the implicit GA model and its several modifications in explicit GA (Ali *et al*., 2016) are extensively employed to simulate 1-D infiltration into various soils due to their simplicity and excellent field performance.

Ali and Islam (2018) have recently derived a simple and accurate explicit GA model for the implicit GA equation employing a two-step curve-fitting approach. The developed implicit model matched well with the implicit GA model (Fig. 2) with a MPRE (maximum percent relative error) of 0.012 and 0.146% for the dimensionless rate of infiltration and cumulative infiltration, respectively, and respective, PB (percent bias) of 0.0005 and 0.070. Field applications of the developed model over various soils showed its potential for application with MPRE ≤ 0.110% and PB ≤ 0.080 for infiltration rate and MPRE ≤ 0.130% and PB ≤ 0.050 for cumulative infiltration. Unlike following an iterative or trial and error method, as in the case of the implicit GA model, the developed model offers an explicit expression/equation without restriction to infiltration period and water depth in an agro-ecosystem. The derived explicit models for infiltration rate and cumulative infiltration are defined as:

$$F(t)=\frac{s^2}{2K_s}\left\{ t^* + 2.5009\ \ln\left[1+0.5833\sqrt{t^*}\right] \left[\begin{array}{l} 0.9723+0.0117\left[1-\mathrm{Exp}\left(-27.36\, t^*\right)\right] \\ +0.0162\left[1-\exp\left(-2.5168\, t^*\right)\right]\end{array}\right]\right\} \quad ...(1)$$

and $$f(t)=K_s\left[1+\frac{\eta_f\left(H+\psi_f\right)}{F\left(t^*\right)}\right] \quad ...(2)$$

In which, $$t^* = \frac{K_s t}{\eta_f\left(H+\psi_f\right)} = \frac{2K_s^2\, t}{s^2} \quad ...(3)$$

Where F(t) = cumulative infiltration at time, t [L]; f(t) = rate of infiltration at t [LT^{-1}]; t is the time [T]; t^* = dimensionless time [-]; K_s = saturated hydraulic conductivity of transmission zone [LT^{-1}]; H = depth of water over soil surface [L]; ψ_f = suction head / negative pressure head at wetting front [L]; η_f = fillable porosity [-] and equal to θ_s- θ_i; in which θ_i = initial volumetric moisture content [dimensionless]; and θ_s = total porosity (i.e. volumetric water content at near or fully saturation) [dimensionless], and s = sorptivity parameter [L $T^{-1/2}$].

Ali *et al.* (2013) also derived a generalized model for simulating the length of advancement of the wetting front (L_f); consequently, cumulative infiltration (=$\eta_f L_f$) and infiltration rate {= K_s [1+η_f (H+ψ_f)/L_f]} For the constant depth of water depth by replacing the logarithmic term of the implicit GA model with sequential segmental second-order polynomials. The developed model is simple in nature and has no

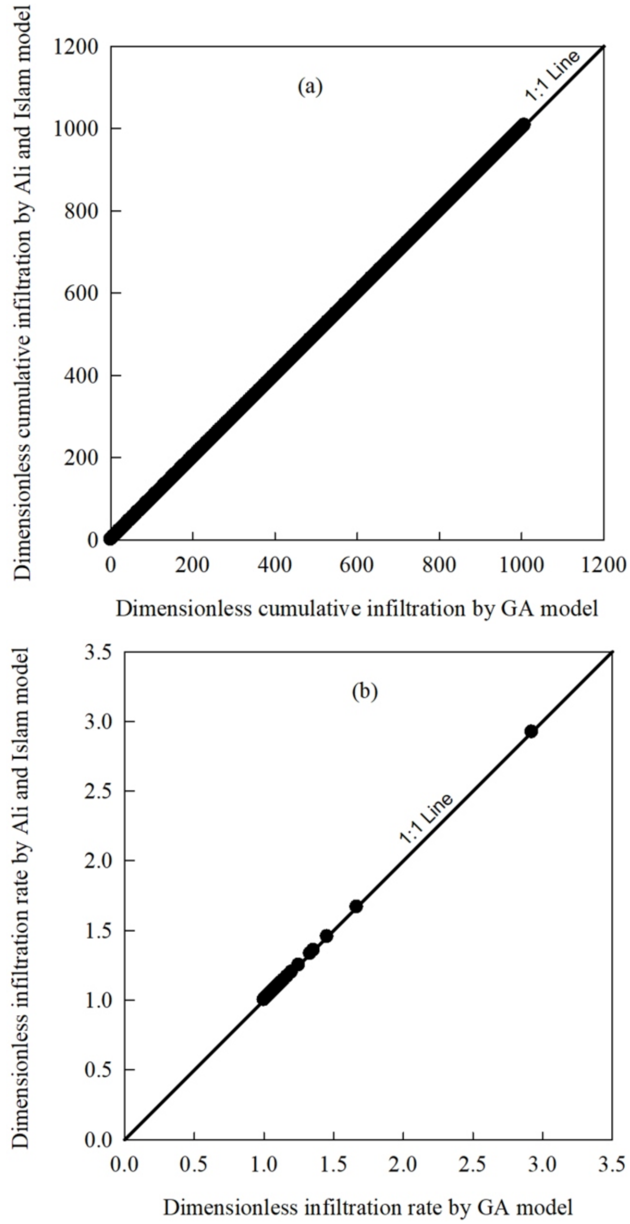


FIGURE 2 Visual performance of dimensionless: (a) cumulative infiltration, I*(t*), and (b) infiltration rate, I*(t*) simulated by the derived explicit model and implicit GA model

restriction to infiltration time and water depth, alike the explicit GA model of Ali and Islam (2018). However, the model has higher errors than the Ali and Islam (2018) model, with MPRE of 3.21 and 11.43% for the dimensionless infiltration and cumulative infiltration rate, respectively, and the respective PB of 0.0005 and 0.070%. The model's validity has also been tested with the field experiment data, which compare well with field data. The model for the L_f is defined as:

$$L_f(t) = \left(H+\psi_f\right)\left[\sqrt{\frac{F_1 K_s}{\eta\left(H+\psi_f\right)}\, t + F_2} + F_3\right] \quad ...(4)$$

Where, $L_f(t)$ = length of advancement of the wetting front at t [T]; F_1, F_2 and F_3 = model coefficients for different ranges of dimensionless length of advancement of wetting front.

Application of the model of Ali *et al.* (2013) also suggested that the time delays for wetting front to reach shallow depth to water table (1-5 m) for a constant water depth of 2 m ranged between 1 hr and 13 days in most of the soils except medium and fine texture soils and from 1 to 135 days in all textural soils except fine texture soils for medium depth to water table (10-25 m). For larger depths to water table (≥ 50 m), time delays were from 1 month to several months in most soils except for very coarse textures such as loamy sand and sand.

Ali and Ghosh (2016) developed an infiltration model and used it to estimate the cumulative infiltration rate under variable water depths by modifying the GA equation. The derived models for cumulative infiltration and infiltration rate are:

$$F(t)=\eta\left\{L_f(t-\Delta t)+[H(t-\Delta t)+\psi]\left\{\sqrt{\frac{F_1 K_s}{\eta[H(t-\Delta t)+\psi]}\,t+F_2}-\sqrt{\frac{F_1 K_s}{\eta[H(t-\Delta t)+\psi]}(t-\Delta t)+F_2}\right\}\right\} \quad ...(5)$$

and

$$f(t)=K_s\left[1+\frac{H(t)+\psi_f}{L_f(t-\Delta t)+[H(t-\Delta t)+\psi]\left\{\sqrt{\frac{F_1 K_s}{\eta[H(t-\Delta t)+\psi]}\,t+F_2}-\sqrt{\frac{F_1 K_s}{\eta[H(t-\Delta t)+\psi]}(t-\Delta t)+F_2}\right\}}\right] \quad ...(6)$$

Where, H(t) = depth of water at t [L]; Δt = change in time from t to t-Δt [T]; and other terms are defined earlier.

The models provide a solution for estimating infiltration with no restrictions on the infiltration time, water depth, and soil types, unlike the rigorous solution of the Richards model. Performance of the derived model compared well with Richards's (Richards, 1931) and Warrick *et al*. (2005) models with published field experiment and laboratory data (Fig. 3). Comparative studies of the model for variable water depth over variety of soils demonstrated its capability for their field application to estimate potential infiltration or groundwater recharge, evaluate the performances and Design of the WHSs (water harvesting structures), AGR (artificial groundwater recharging) facilities, irrigation systems, and resolving solute transport problems.

3.2 | Potential Groundwater Recharge

Groundwater recharge (GR) is the process of replenishing groundwater storage. The GR process has two distinguished mechanisms: one is regarded as the wetting front advance-

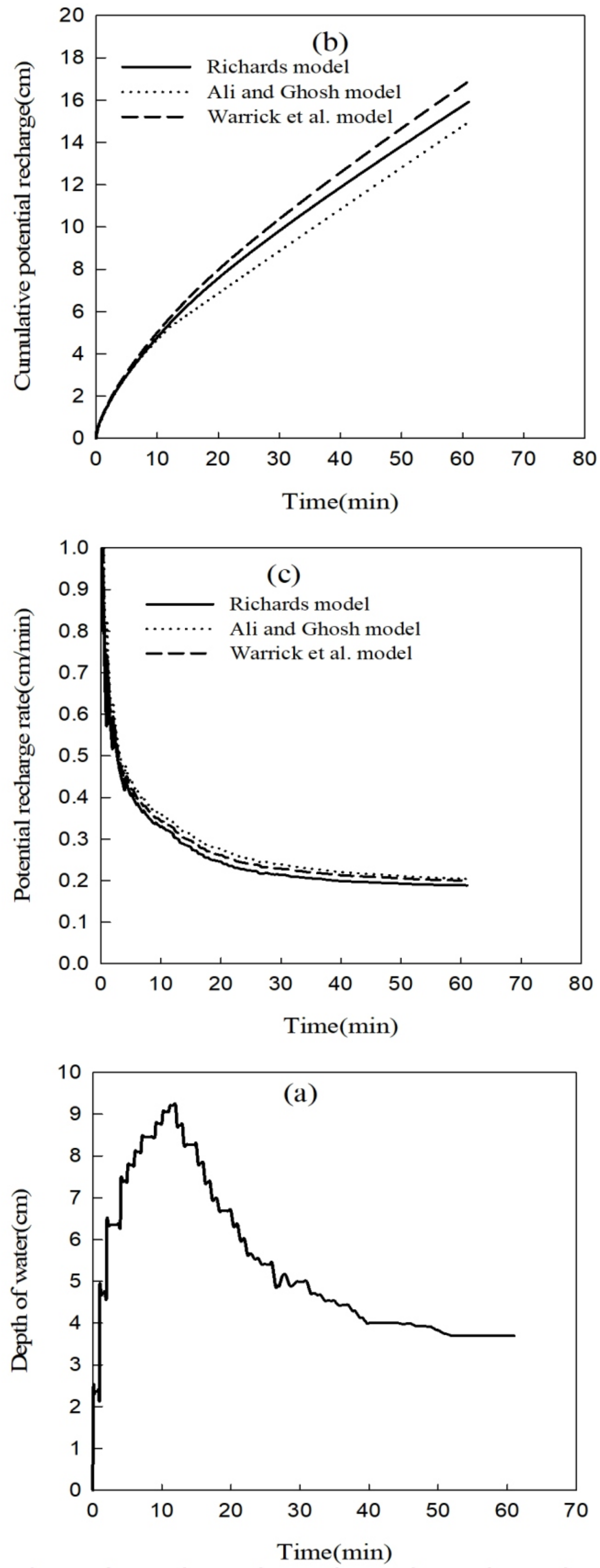


FIGURE 3 Response of time-variant: (b) cumulative potential recharge, (c) potential recharge rate from irrigation basin over superstition sand under varying depths of ponding, and (a) depths of ponding

ment by downward movement of water through the unsaturated zone and continues till the wetting front touches the water table, known as potential infiltration/groundwater recharge; and the other one is subsequent recharge after the wetting front touches the groundwater table, known as actual groundwater recharge or groundwater recharge (Ali *et al.,* 2013). The groundwater table progresses after the actual groundwater recharge process starts. Hydrogeological and climatic conditions control groundwater recharge amount and timing. The key factors affecting the GR are rainfall characteristics (amount and duration), ponding depth over soil surface, soil type, vegetation characteristics, etc. The influx of the potential groundwater recharge to the groundwater table depends on unsaturated zone processes and depth and the capability of the zone of saturated to allow it.

Several empirical and physical-based models of varying complexity are exited to quantify potential and actual groundwater recharge. The process-based potential groundwater recharge models are implicit and explicit GA, and Richards' and Richards' based numerical modelling codes such as HYDRUS, UNSAT-H, and TOUGH2. The models for estimation of actual groundwater recharge are MODFLOW and its variants, i.e. Visual MODFLOW, PMWIN-Processing Modflow for Windows, HYDRUS-MODFLOW, FEFLOW-Finite Element subsurface FLOW System, SWAP (Soil-Water-Atmosphere-Plant) and GMS-Groundwater Modelling System.

Ali and Ghosh (2019) developed the IPGRS (Integrated Potential Groundwater Recharge Simulation) model using the modified GA equation for variable water depth in the water balance equation. The IPGRS model estimates time-varying potential groundwater recharge rates under variable water depths from AGR facilities and WHSs in an agro-ecosystem. The parameters of the IPGRS model are time-variant rainfall, runoff, water evaporation, surplus/outflow, and length of advancement of the wetting front into the soil. The model also considered soil-related physical parameters, namely, saturated hydraulic conductivity, fillable porosity of the soil material, and suction head/negative pressure head at the wetting front. The IPGRS model is process-based and holistic in nature, easy to use and capable of simulating potential groundwater recharge rates with reasonable accuracy. The IPGRS model has broad field applications and can successfully be extended to estimate potential groundwater recharge rates from AGR facilities and WHSs of any size and shape situated at any location or geographical region of India and elsewhere. The IPGRS model is defined (Ali *et al*., 2015; Ali and Ghosh, 2019):

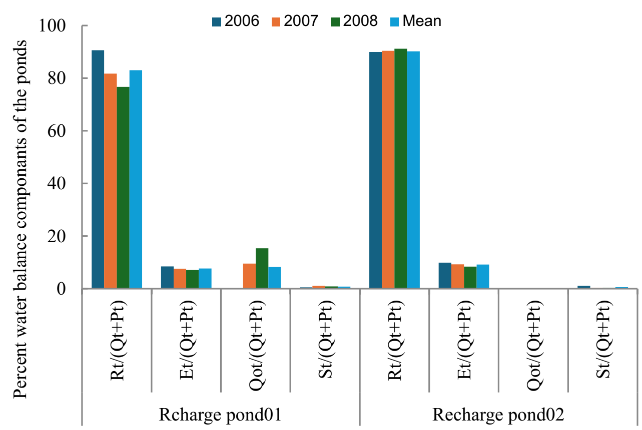
$$R_p(t) = \frac{K_s}{\left[L_f(t)A_{ws}(t) + K_s \bar{A}_{rs}(t)\Delta t\right]} \left\{ \begin{array}{l} H(t-\Delta t)A_{ws}(t-\Delta t) + \left[Q(t)A_w + P(t)A_s - E(t)\bar{A}_{ws}(t) - Q_0(t)\right]\Delta t \\ + \left[L_f(t) + \psi_f\right]A_{ws}(t) \end{array} \right\} \quad ...(7)$$

In which the $l_f(t)$ is:

$$L_f(t) = L_f(t-\Delta t) + \left[H(t-\Delta t)+\psi\right] \left\{ \begin{array}{l} \sqrt{\dfrac{F_1 K_s}{\eta\left[H(t-\Delta t)+\psi\right]} t + F_2} \\ - \sqrt{\dfrac{F_1 K_s}{\eta\left[H(t-\Delta t)+\psi\right]}(t-\Delta t) + F_2} \end{array} \right\} \quad ...(8)$$

Where, $R_p(t)$ = potential recharge rate AGR/WH structure at time, t [LT^{-1}]; $Q_i(t)$ = runoff into structure at t [LT^{-1}]; $P_i(t)$ = rainfall over the structure at t [LT^{-1}]; $E_p(t)$ = evaporation from the structure at t [LT^{-1}]; $Q_o(t)$ = outflow rate of surplus runoff from the structure at t [L^{3T-1}]; H(t) = water depth at t [L]; H(t-Δt) = water depth at t-Δt [L]; Δt = time interval [T]; L_f length of advancement of wetting front at t [L]; L_f(t-Δt) = length of advancement of wetting front at t-Δt [L]; K_s and ψ_f = defined earlier; A_w = AGR/WH structure's catchment [L^2]; A_t = surface area of the structure at top [L^2]; $\bar{A}_{ws}(t)$ = average water storage surface area between time t-Δt and t [L^2]; $\bar{A}_{rs}(t)$ = average wetted planner area for recharge at time t [L^2].

Application of derived IPGRS model in BK watershed, Rajasthan, India showed that on average, 83 to 90% of stored runoff in the recharge ponds added as potential groundwater recharge into aquifer underneath recharge ponds. Evaporation losses from recharge pond varied between 8% and 9% of stored runoff. Surplus flows from the ponds and stored runoffs in recharge ponds at the end of simulation periods ranged from 0 to 8% and 0.6 to 0.8%, respectively (Fig. 4).



This is the ratio of the total volume of water recharged into the aquifer, R_t, to the total volume of inflows, which is the sum of the volume of runoff into the pond and the volume of rainfall directly over the pond, (Q_t+P_t); $E_t/(Q_t+P_t)$ the ratio of the total volume of water loss by evaporation, Et to the total volume of inflows; $Q_{ot}/(Q_t+P_t)$ is the ratio of the total volume of outflows from the pond, Q_{ot}, to the total volume of inflows, and is the ratio of the total volume of water remaining as pond storage at the end of the simulation period, S_t, to the total volume of inflows.

FIGURE 4 Partition factors of the water balance components (percent) for the recharge ponds during the simulation period (2006-08)

3.3 | Surface Runoff

Runoff yield from an agro-ecosystem provides water security to the water resources such as surface and groundwater through infiltration, interflow and base flow, and groundwater recharge. Assessment/estimation of surface runoff yield in an agroecosystem is a highly complex problem. It is influenced by several characteristics of the agro-ecosystem, including topography, morphology, antecedent soil moisture condition, land use land covers, and cover conditions, rainfall characteristics (i.e. amount, intensity and duration) and conservation measures density (Ali and Singh, 2001; Ali *et al*., 2010; Ali *et al*., 2017). The need to better understand the runoff process and its quantification is further aggravated due to climatic variability and change and the desire to develop climate-resilient agro-ecosystem technologies / practices. Several runoff simulation models based on statistical, conceptual, physical, and combination approaches have been derived and used in the past according to the need and availability of data for better understanding and predicting the highly non-linear, dynamic and complex runoff process worldwide. The commonly used methods include SCS-CN (Soil Conservation Service - Curve Number), HEC-HMS (Hydrologic Engineering Center-Hydrologic Modeling System), CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems), KINEROS (Kinematic Runoff and Erosion Model), SVAT (Soil-Vegetation-Atmosphere Transfer), SWAT (Soil Water Assessment Tool), and PRMS (Precipitation Runoff Modeling Systems).

Ali *et al.* (2010) derived a rainfall-runoff model analogous to the SCS-CN model based on the NAPI (Normalized Antecedent Precipitation Index) using the water balance concept in an agroecosystem. The model is mathematically defined as:

$$Q = \frac{P\left(-bP + c\,NAPI + a\right)}{\left[\left(-bP + c\,NAPI + a\right) - 1\right]} \quad \text{valid for } P > 0 \qquad ...(9)$$

Where, Q = runoff for corresponding rainfall, P [L]; NAPI = normalized antecedent precipitation index [-]; *a* [-], b [L^{-1}], and c[-] are model parameters related to a specific agro-ecosystem / watershed.

The developed rainfall-runoff model is simple in mathematical nature, user-friendly, and minimum data driven. Only rainfall and rainfall-derived NAPI is required if model parameters (i.e. a, b, and c) are known previously for the given agroecosystem. The derived rainfall-runoff model is a handy runoff tool for simulating runoff yields in the agro-ecosystems, and has broad applicability. The developed model could also be employed for runoff assessment / estimation from gauged and un-gauged agroecosystem / watersheds with the least data, i.e. rainfall only. The surface runoff predicting the potentiality of the developed rainfall-runoff model has also been compared with the SCS-CN model. Results revealed that the developed rainfall-runoff model matched well with the SCS-CN model (Fig. 5), which is a comparatively large data-driven model (i.e. AMC (antecedent moisture condition), and information on land use cover, conservation / treatment practice, hydrological oil group and hydrologic condition). The developed runoff model was also applied in a small agricultural watershed, and two ravine watersheds located in a semi-arid agro-ecosystem of Rajasthan, India (Fig. 6). The assessed runoff yield for the ravine and cropped areas of the agro-ecosystems varied

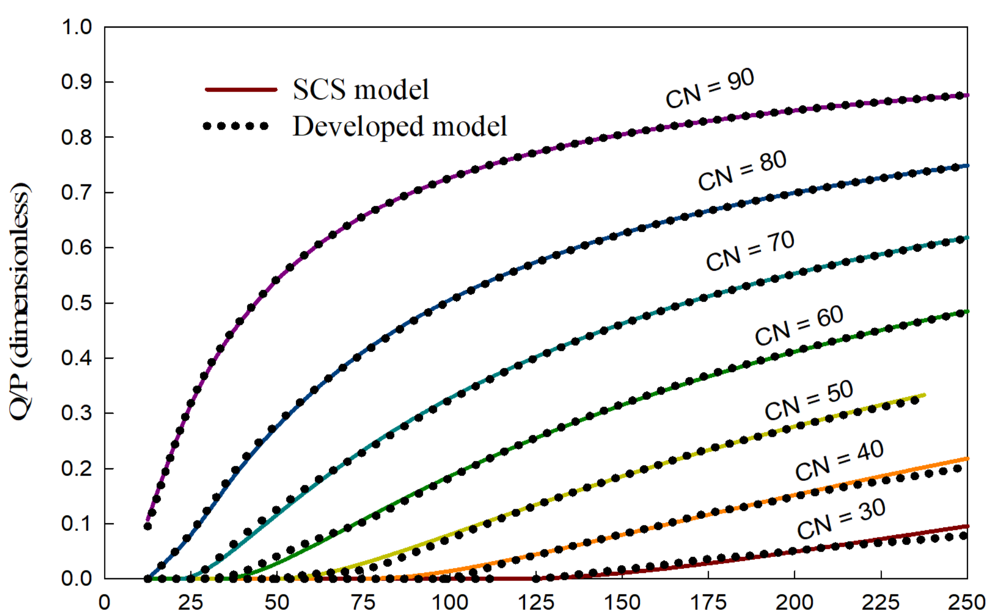


FIGURE 5 Visual evaluation of the derived Q/P profiles by the SCS-CN model for the P and different CN-values with the corresponding profiles of the derived rainfall-runoff model

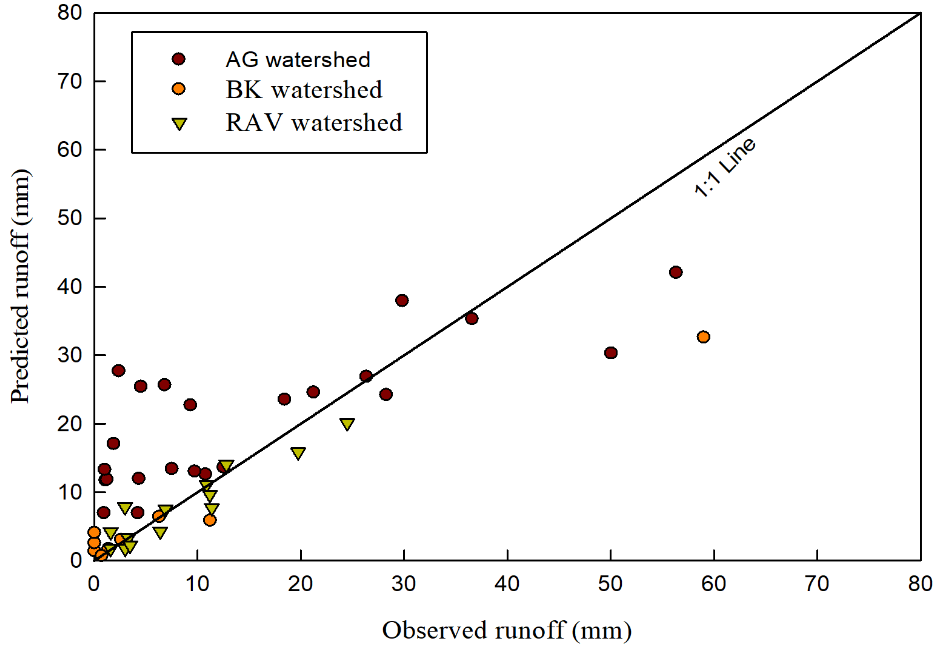


FIGURE 6 Visual judgment of the simulated and observed runoffs by the derived rainfall-runoff model in three small watersheds in the agro-ecosystems of a semi-arid region of India

between 10 and 20% of the rainfall over the agro-ecosystems.

A rainfall-runoff model for un-gauged watersheds for the agro-ecosystem has also been developed correlating the model parameters of the un-gauged and gauged watersheds of the agro-ecosystems and mathematically defined (Ghosh *et al.*, 2021) as:

$$Q^* = \frac{P\left(-b^* P + c^* NAPI + a^*\right)}{\left[\left(-b^* P + c^* NAPI + a^*\right) - 1\right]} \quad \text{valid for } P>0 \qquad ...(10)$$

Where *a**, b*, and c* are the un-gauged watershed model parameters; others are defined previously.

The un-gauged watershed model parameters are defined as:

$$a^* = a \times CGI \times CLI;\ b^* = b \times CGI \times CLI;\ \text{and}\ c^* = c \times CGI \times CLI \qquad ...(11)$$

In which CGI and CLI are the cumulative geo-morphologic indexes and cumulative land use and land cover index, respectively, and these are defined as:

$$CGI = \sum_{i=1}^{n} IOP_i^G = \sum_{i=1}^{n} RW_i^G \left(\frac{GP_i}{GP_i^*}\right) \qquad ...(12)$$

$$CLI = \sum_{i=1}^{j} IOP_i^L = \sum_{i=1}^{j} RW_i^L \left(\frac{AL_i/AL}{AL_I^*/AL^*}\right) \qquad ...(13)$$

Where, IOP_i^G = index of the i[th] geomorphologic parameter [-]; RW_i^G (= w_i^G/W^G) = relative weightage of the i[th] geomorphologic parameter [-]; w_i^G = weightage of the i[th] geomorphologic parameter [%]; W^G = sum of the all selected geomorphologic parameter [%]; GP_i = value of the i[th] geomorphologic parameter of the gauged watershed[unit of parameter]; GP_i^* = value of the i[th] geomorphologic parameter for the un-gauged watershed[unit of parameter]; IOP_i^L = index of the i[th] land use and land cover (LULC) class[-]; RW_i^L (= w_i^L/W^L) = relative weightage of the i[th] LULC class [-]; w_i^L = weightage of the i[th] LULC class [%]; W^L = sum of the all LULC classes [%]; AL_i = area of the i[th] LULC class of the gauged watershed [ha]; AL = total area of the LULC classes of the gauged watershed[ha]; AL_i^* = area of the i[th] LULC class of the un-gauged watershed [ha]; AL^* = total area of the LULC classes of the un-gauged watershed [ha]; and i = integer, i = 1, 2, 3, …………n/j.

The values of the w_i^G or w_i^L are arbitrarily chosen based on the importance of selected geomorphologic parameters or LULC class, and $0 < w_i^G < 100$, $0 < RW_i^G < 1$, $0 < w_i^L < 100$, and $0 < RW_i^L < 1$. The values of the W^G, W^L, RW^G and RW^L are:

$$W^G = \sum_{i=1}^{n} w_i^G = 100; \qquad RW^G = \sum_{i=1}^{n} RW_i^G = 1 \qquad ...(14)$$

$$W^L = \sum_{i=1}^{j} w_i^L = 100; \qquad RW^L = \sum_{i=1}^{j} RW_i^L = 1 \qquad ...(15)$$

The derived model was tested and validated for un-gauged (Rahatgarh, 1180 km^2) and gauged (Korwal, 2806 km^2) watersheds by utilizing the 339 rainfall-runoff events that occurred in 18-year periods (1990-2007). The field application exhibited a close match between the observed and computed values of runoffs from an un-guaged watershed. The derived model parameters *a**, *b** and *c** for the un-gauged watershed were - 0.2136, 0.00202, 0.02313, respectively, and -0.21038, 0.00199, and 0.02279, respectively, for the *a*, band *c* model parameters for the gauged watershed.

3.4 | Water Storage

Natural and anthropogenic surface water bodies in the agro-ecosystem play a fundamental role in maintaining an ago-ecosystem's hydrological, environmental and ecological balance, primarily by increasing or improving water availability for longer periods. The time-varying availability of water in surface water bodies also plays a crucial role in coordinated and comprehensive planning for the utilization of surface water resources in the agro-ecosystems. Numerous models have been derived and employed in the past for simulating water depth or volume of water in surface water bodies. These include dynamic linear predictor models, non-linear intelligence models, and modelling codes, i.e. SPAW (Soil-Plant-Air-Water), etc.

The HWDS (Holistic Water Depth Simulation) model was developed by Ali et al. (2015) by integrating the derived models for the rainfall-runoff, length of advancement of the wetting front and evaporation in the water balance equation of the surface water body. Alike IPGRS model for assessing the potential groundwater recharge, the developed HWDS model also take account of the time-variant rainfall, runoff, surface water evaporation, outflow and length of advancement of wetting front; saturated hydraulic conductivity, fillable porosity of the surface water body's bed material and suction head as model parameters. The derived HWDS has been defined mathematically (Ali *et al*., 2015; Ali, 2016):

$$H(t) = H(t-\Delta t)\frac{A_{ws}(t-\Delta t)}{A_{ws}(t)} + \frac{\Delta t}{A_{ws}(t_i)}\left[Q(t)A_w + P(t)A_s - E(t)\bar{A}_{ws}(t) - Q_0(t)\right]$$

$$-\frac{K_s\,\bar{A}_{rs}(t)\,\Delta t}{A_{ws}(t)}\left[1 + \frac{H(t)+\psi_f}{L_f(t-\Delta t) + \{H[t-\Delta t] + \psi_f\}\left\{\sqrt{\frac{F_1 K_s}{\eta\,[H(t-\Delta t)+\psi_f]}t_i + F_2} - \sqrt{\frac{F_1 K_s}{\eta\,[H(t-\Delta t)+\psi_f]}(t-\Delta t) + F_2}\right\}}\right] \quad ...(16)$$

$$\text{and } V(t) = H(t)\,\bar{A}_{ws}(t) \quad ...(17)$$

Where V(t) = volumetric water availability in a surface water body at time t_i [L^3]; $\bar{A}_{wa}$ = average water storage area at t_i [L^2] = 0.5[$A_{ws}(t\ )+ A_b$]; and A_b = water body's bottom surface area [L^2]; and rest of the terms = defined prior.

The derived HWDS model is process-based and holistic in nature, user-friendly, and capable of predicting the time-varying depth of water and consequent volumetric water availability in the surface water bodies in the agro-ecosystem with reasonable accuracy. The HWDS model has broad field applicability and could successfully be extended to assess water availability in a water body of any size and shape in any location or geographical region in India and elsewhere. The simulated time-varying water availability employing the derived HWDS model matched well with the ponds data of the BK watershed in an agro-ecosystem in Rajasthan, India (Fig.7). The predicted time-varying water availability in the pond#1 and Pond #2 is observed higher in July, August and September, and almost empty in the November and December during the study period.

3.5 | Soil Erosion

Soil erosion by water in agroecosystems is a significant threat and impacts society and the economy to a greater extent in the agroecosystems of the world. Soil erosion in the agro-ecosystems causes on-site problems with the removal of the significant top productive soil layer, losses of agro-ecosystem land, soil organic matter and nutrients, deterioration of soil properties (i.e. physical, chemical and biological) and diminution of agro-ecosystem productivity and production as soil erosion diminishes or reduces soil nutrients, soil water storage capacity and impacting crop growths. Soil erosion also fetches off-site damages, including sediment deposition or silting of the water bodies (i.e. pond, reservoir, channel / stream, river, etc.) and surface water quality by agrochemicals and colloid-facilitated transport. The rate of soil erosion is affected by various factors, such as anthropogenic factors (i.e. intensification of the agroecosystem, land use changes and human activities) and climatic factors, mainly rainfall characteristics (amount, intensity and duration). Changes in rainfall characteristics and spatio-temporal distribution patterns of rainfall mainly cause the impacts of change in the rate of soil erosion. Several investigators assessed the soil erosion problems and their effect on the crop and cropping systems in the different agroecosystems of India (Ali and Sharda, 2005; Sharda and Ali, 2008).

Ali *et al.* (2002) derive a very simple soil erosion model for predicting potential soil erosion from an agro-ecosystem. The developed soil erosion model is:

$$Y = a\,(RKC)^b \quad ...(18)$$

Where Y = annual soil loss [t ha^{-1}]; R = annual rainfall erosivity factor; K = soil erodibility factor [t ha^{-1} unit of IE_{30}]; C = crop and cover management factor[-], and *a* and n = model parameters specific to the agro-ecosystem.

The developed soil erosion model has reasonable accuracy, is simple, user-friendly, and minimally data-driven. The soil erosion model has also been tested for different crops and cropping systems in the agro-ecosystem in the semi-arid region of India and recorded that the model

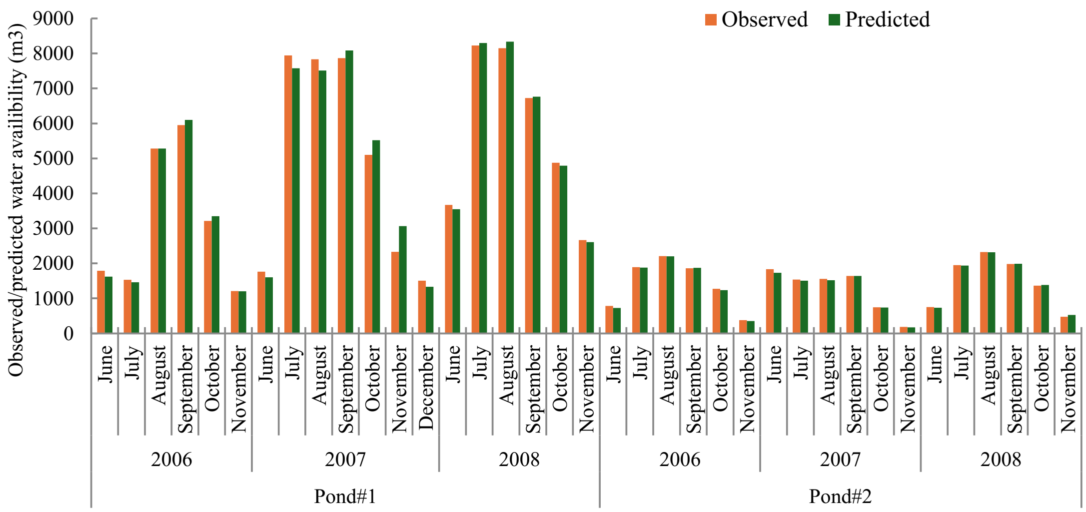


FIGURE 7 **Visual comparison of the time-variant predicted and observed water availability by the derived HWDS model in pond#1 and pond#2 in an agro-ecosystem in the semi-arid region of India**

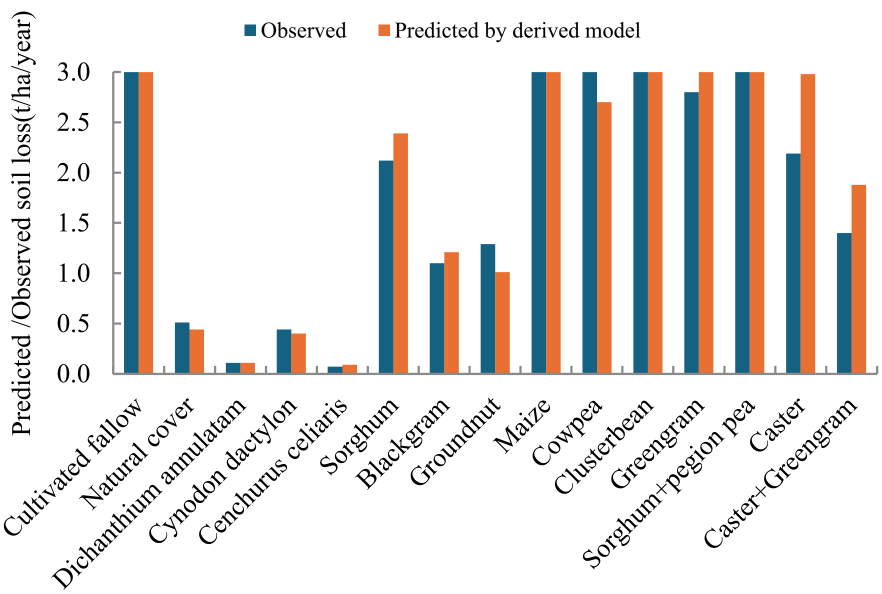


FIGURE 8 **Visual comparison of the time-variant predicted and observed water availability by the derived HWDS model in pond#1 and pond#2 in an agro-ecosystem in the semi-arid region of India**

performed well in the agro-ecosystem of India (Fig. 8). The simulated soil erosion employing the developed erosion model for the grasses (i.e. *Dichanthium annulatam*, *Cenchurus celiaris and Cynodon dactylon*), close growing crops (i.e. green gram, black gram, cowpea and groundnut), broad spacing crops (i.e. sorghum, maize, cluster bean and caster) and mixed crops (caster + green gram and sorghum + pigeon pea) system varied from 0.09 to 0.11, 1.01 to 3.05, 2.39 to 4.22, 1.88 to 3.83 t ha^{-1} yr^{-1}, respectively.

5 | CONCLUSIONS

Globally, the agroecosystem is a principal ecosystem, and it offers 4Fs (food-fodder-fibre-fuel) termed as provisioning ecosystem service for more than 7.7 billion human population in the world, which are indispensable to human well-being. Agroecosystems also provide an array of water-regulating and cultural agroecosystem services. These services depend on supporting ecosystem services offered by the agroecosystems. To better understand and quantify the unpredictability of agroecosystem services, agroecosystem prediction models have the potential to do it better. The study demonstrates the promising capability and applicability of some agroecosystem models in India for predicting the water-regulating agroecosystem services such as surface runoff, soil erosion, infiltration, potential recharge and water storage. Developed water-related agro-ecosystem simulation models have been successfully applied to the different agroecosystem services in India's agroecosystems.

The application of the derived infiltration model accurately predicted the time delays for the wetting front to reach depth to the water table in various soil textural classes. The simulated potential groundwater recharge from WHSs by the developed IPGRS model varied between 83 to 90% of stored runoff in the WHSs. Modelled agroecosystem surface runoff ranged from 10-20% of the rainfall. The derived model for soil erosion is effectively applied to different crops and cropping systems in the agroecosystems of India, and the mean annual soil loss is assessed as 0.09 to 3.83 t ha^{-1} yr^{-1}. These modelling studies for water-regulating agro-ecosystem services indicated that modelled values vary across the models and the land-use system within the agroecosystem. The developed models for water-regulating agroecosystem services offer valuable and important information for policy decisions on preparedness, adaptive planning, and preventive and conservation measures to mitigate the effects of climate variability and change on water-regulating ago-ecosystem services. In future, there is a need to develop evaporation and evapotranspiration water regulating and provisioning ecosystem service models for their better understanding of Indian conditions.

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DATA AVAILABILITY STATEMENT

Data used in the manuscript is with the author and may be supplied on demand.

CONFLICT OF INTEREST

There is no conflict of interest among the authors.

AUTHOR'S CONTRIBUTION

The author solely contributed to the manuscript.

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ORIGINAL ARTICLE
Indian Journal of Soil Conservation

Are the soil properties and organic carbon stocks influenced by different land use systems in tropical semi-arid region, India?

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ABSTRACT

Different land uses significantly affect soil properties due to variations in organic matter addition, decomposition, and stabilization. A study assessed organic carbon stock in soils from various landforms and its use in granite-gneiss and schist geological settings in the semi-arid Chitradurga district, Karnataka. Nine soil profiles (pedons) from upland areas and four from lowland areas were analyzed. Soil characteristics such as pH, electrical conductivity (EC), organic carbon (OC), clay content, bulk density (BD), cation exchange capacity (CEC), base saturation, and calcium carbonate equivalent (CCE) were measured. The results showed a pH range from 6.09 (slightly acidic) to 9.74 (very alkaline) with non-saline soils (EC < 2 dS m^{-1}). Organic carbon levels varied from 1.40 to 7.30 g kg^{-1} in the surface layer and 1.10 to 8.50 g kg^{-1} in the subsurface layer. Clay content ranged from 6.92% to 53.52% (surface) and from 9.83% to 64.81% (subsurface). Bulk density ranged from 1.31 to 1.98 Mg m^{-3} (surface) and 0.78 to 1.89 Mg m^{-3} (subsurface). Cation exchange capacity spanned from 3.44 to 53.14 cmol (p+) kg^{-1} (surface) and from 4.92 to 57.93 cmol (p+) kg^{-1} (subsurface). Base saturation was between 37% and over 100%. Organic carbon stock ranged from 0.33 to 1.95 kg m^{-2} (surface) and from 0.23 to 5.46 kg m^{-2} (subsurface). Fallow land and sapota plantations had higher organic carbon stocks than agricultural lands, with coconut and banana plantations following. Most pedons had low organic carbon content, were alkaline, calcareous, and experienced moderate to severe erosion. To address these issues, implementing management practices like reclamation, irrigation, organic manure application, and soil conservation measures is critical for improving crop yield, controlling erosion, and maintaining soil health and sustainability.

Key words:
Landform
Land use
Semi-arid region
Soil organic carbon stock
Soil properties

HIGHLIGHTS

- Soil organic carbon stocks (SOCS) influenced by soils of different land use systems.
- Bulk density of soils ranged from 1.31-1.98 on the surface to 0.78-1.89 Mg m^{-3} in subsurface.
- SOCS ranged from 0.33-1.95 on surface to 0.23 to 5.46 kg m^{-2} in subsurface soils.
- Fallow land and plantations recorded higher SOCS compared to agricultural lands.

1 | INTRODUCTION

The stock and stability of soil organic carbon (SOC) are critical to soil functions and the global carbon cycle. However, little quantitative information is available on the precise location across various climatic gradients. SOC storage is regulated by climatic conditions at the regional scale. The soils semi-arid climate regions in Chitradurga district, Karnataka, are prone to erosion, and high temperature influences higher oxidation of organic matter, making the soil maintain soil organic carbon levels, resulting in land / soil degradation due to its changes in climate from humid to semiarid and arid which dominantly influences soil organic carbon stocks and fluxes. Different land use has more significant implications on soil properties due to its differential organic matter addition, decomposition and stabilization rate. Soil fertility is one of the critical factors controlling crop yields in hot, moist, semi-arid eco sub-regions like Chitradurga district; it receives low to moderate rainfall and is one of the drought-prone districts in the state. Intensive agriculture without adequate and balanced use of chemical fertilizers and with little or no use of organic manure caused low C inputs, thereby causing severe fertility deterioration of agricultural soils, resulting in stagnating or even declining crop productivity and soil health and resulting in barren and unproductive lands over long-term cultivation in drought-prone coupled with erosion prone areas like Chitradurga district. Chemical land degradation due to low C levels and nutrient status in soil highly affects rural livelihoods, land productivity, and sustainability, and it then reduces the soil's productive capacity, exacerbating poverty and food and nutritional insecurity. In the context of global warming, understanding the SOC stabilization mechanisms across different climatic and edaphic conditions is of prime importance to improve the prediction of SOC dynamic and global C cycle (Lal, 2004). Soil is the largest carbon sink, leading to atmospheric CO_2 concentrations. Hence, Soil Organic Carbon Stock (SOCS) significantly influences the global carbon cycle. The geology, landform, and land use have impacted soil fertility, agricultural productivity, food security, terrestrial and global carbon cycle and climate change. Climatic conditions such as temperature and precipitation influenced the association of SOC with minerals by governing soil chemical weathering. The slope gradient, topography, biomass production / vegetation, land use, land cover change, erosion-induced topsoil loss, altitude and climate, and fire affect SOCS. Different type of land use influences the quantity of carbon stock due to its differential rate of production, addition and accumulation of biomass and vegetation; various researchers reported significant variation in SOCS due to changes in land use land cover. Long-term cultivation and monoculture without proper nutrients and manure input reduces SOCS and carbon content in soil due to nutrient imbalance. Reducing SOCS and carbon content reduces soil and land productivity and fertility by influencing soil nutrient retention, physical structure, and water-holding capacity. Thus, changes in land use type support soil property and maintain soil health and sustainability by controlling land degradation / deterioration and soil erosion. Similarly to land use, landform positively or negatively influences soil properties by varying vegetation cover and availability of soil moisture content for biomass production. Generally, lowlands will have better AWC than uplands, which influences biomass production and distribution, thereby SOCS. Also, climatic conditions such as rainfall and temperature influence land use cover and SOCS; when precipitation rises, and temperature becomes colder, it changes vegetation distribution, and a rise in temperature leads to oxidation of organic matter and stabilization, thus affecting SOC stock. However, geology such as granite-gneiss and schist are developed under different rates of metamorphism under different heat and pressures, resulted different mineral compositions (gneiss developed under high heat and temperature under high-grade metamorphism resulted in mineral composition of quarts and sodium and potassium feldspar whereas schist developed under medium grade heat and pressure and medium metamorphism resulted in mineral composition of mica, chlorite and talc) which influences differential rate of mineral weathering degree thus influences nutrient composition in soil particularly organic carbon thereby SOCS. With these above views, the present investigation has been undertaken in the semiarid region of Chitradurga district, Karnataka, with the objectives i) to know the soil physicochemical properties in soils of different landforms and land use systems, ii) to determine the bulk density in soils, of different landform and land use systems and iii) to estimate organic carbon stock in soils of different landform and land use systems.

2 | MATERIALS AND METHODS

2.1 | Study Area

Chitradurga owes its name to “Chitrakaladurga,” or “Picturesque castle”. This massive fortress on top of granite hills rises dramatically from the ground. The present study has taken up in the southern part of the Chitradurga district i.e., Hiriyur and Hosadurga taluks with a total geographical area (TGA) of 1.72 lakh ha and 1.45 lakh ha, respectively lying between the north latitude of 13º 32' 20.721" to 15º 3' 27.178" N latitude to east longitude of 75º 58' 55.046" to 77º 55' 57" E with an elevation ranging from 569 m (main valley) to 760 m (Pediment) above mean sea level (amsl) (Fig.1). These taluks fall under Agroclimatic Region (Planning Commission) Southern Plateau and Hills Region-10 and Agroclimatic Zone-4 i.e. Central Dry Zone and Agroecological sub-region: 8.2. i.e. Central Karnataka Plateau, hot moist semi-arid eco sub-region. Hiriyuru taluk has 32 gram panchayats covering 159 villages in 4 hoblies and Hosadurga taluk has 33 gram panchayats covering 225 villages in 4 hoblies. The soil temperature regime is isohyperthermic. These taluks receive scanty and unevenly distributed rainfall from the southwestern monsoon (June-September) and NE Monsoon (October-December). The average rainfall of the district is 592.5 mm, with 32 rainy days. However, Hiriyuru taluk receives 549.9 mm on 29 rainy days, and Hosadurga taluk receives 626.4 mm on 32.1 rainy days. The district's average minimum temperature is 21.0 °C, and the maximum is 31.8 °C. The minimum and maximum temperatures of Hiriyur are 21.0 °C and 32.0 °C, respectively, whereas that of Hosadurga is 22 °C and 32.0 °C. In Hiriyur and Hosadurga taluks, granitic-gneisses and schists are the main ground water bearing formations. The highest cropping intensity is in Hiriyuru taluk (122%),

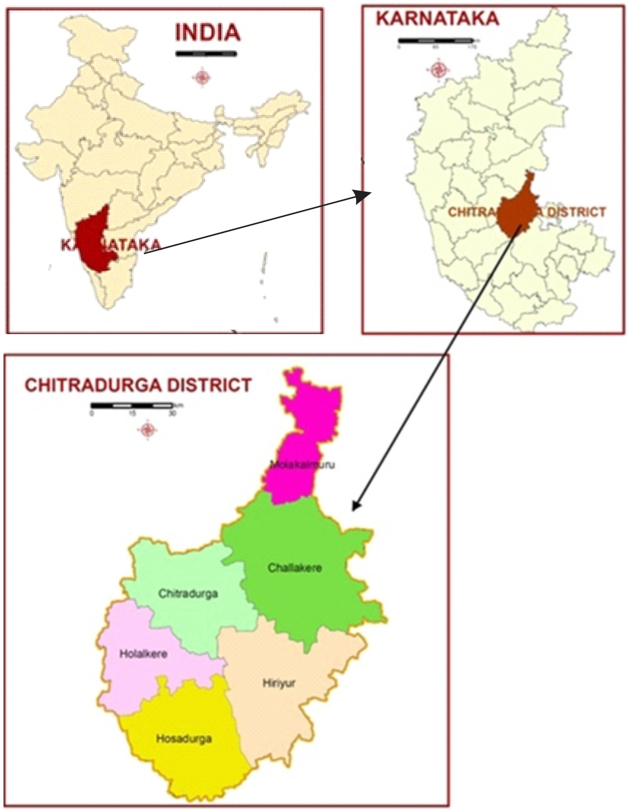

FIGURE 1 Location map of Chitradurga district, Karnataka

mainly because of the area under irrigation. The Chitradurga district has minimal irrigation resources, and the agriculture of the district is mainly rainfed. These taluks have granite-gneiss and schist geology (Fig. 2). Slope of the area is nearly level to (0-1%) and very gently sloping (1-3%), and little area is gently sloping (3-5%) uplands. Agriculture is the major economic activity. Major land use is maize, finger millet, jowar, paddy, red gram, ground nut, sunflower, banana, mango, pomegranate, sapota, onion, chilly, tomato, brinjal, coconut, areca nut, beetle vine, crosandra, jasmine, and chrysanthemum are being cultivated (Fig. 3). Natural vegetation is Prosopis sp., Lantana, Tamarind, Acacia sp., Neem, Cactus etc. (Fig. 4).

2.2 | Detailed soil characterisation and laboratory soil analysis

Detailed soil survey carried out on 1:10000 scale using landform map; land uses land cover map prepared by sentinel-2 satellite imagery and survey of India toposheets (1:50,000 scale) in Hiriyur and Hosadurga taluks during February to March 2023 followed by depth-wise soil samples collected from nine pedons from uplands from different land uses viz., ground nut, sorghum, maize, bengal gram, sunflower, coconut plantation, sapota plantation and fallow land and also four pedons from lowlands of different land uses viz., ground nut, bengal gram, banana plantation

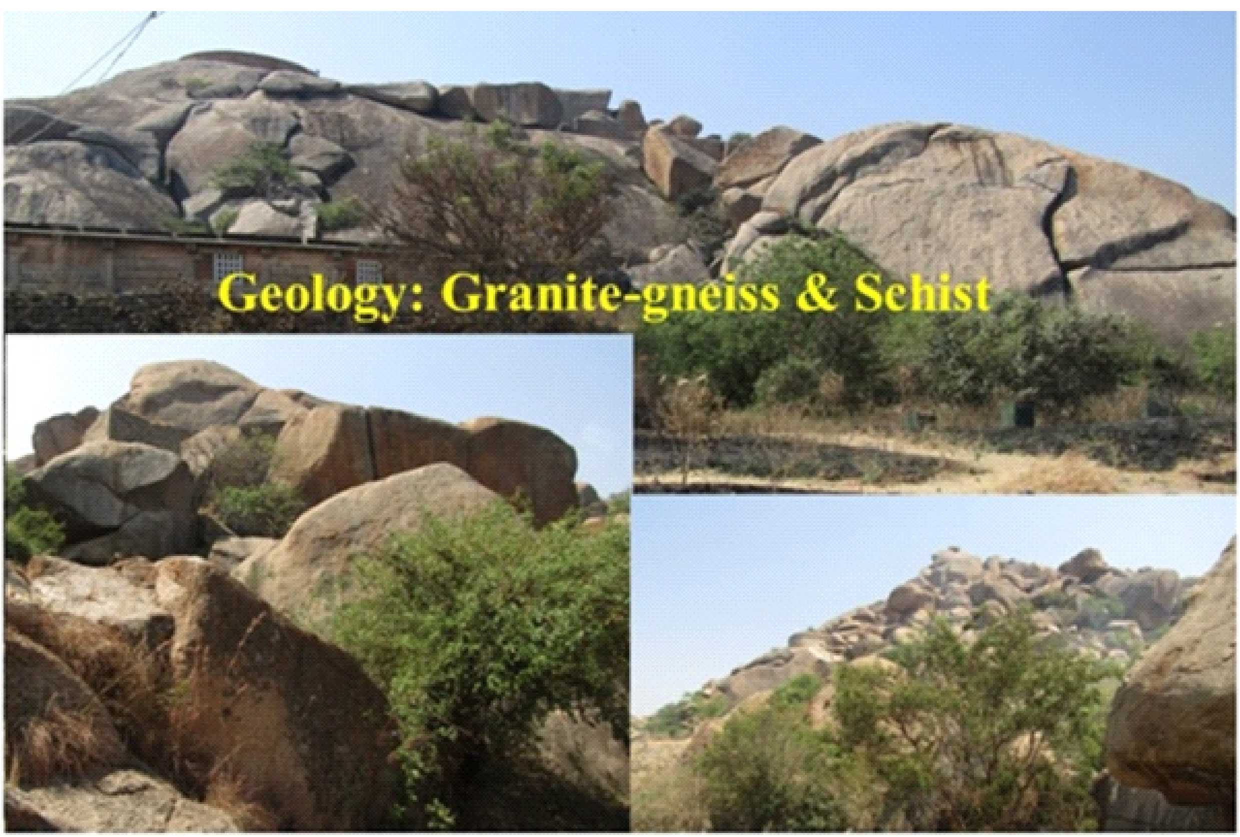

FIGURE 2 Geology of the tropical semi-arid region, Chitradurga district, Karnataka

FIGURE 3 **Land use pattern of the tropical semi-arid region, Chitradurga district, Karnataka**

FIGURE 4 **Natural vegetation in the tropical semi-arid region, Chitradurga district, Karnataka**

and coconut plantation of from both the two geology (Granite-gneiss and Schist). Bulk density samples were collected using a standard core from all 13 pedons from all the depths. Horizon-wise soil profile samples were brought to the laboratory, air-dried, ground and sieved through a 2-mm sieve. The samples were analysed for their particle size class, soil reaction, electrical conductivity, organic carbon, cation exchange capacity, exchangeable bases, and calcium carbonate equivalent following standard procedures as outlined in Table 1. Bulk density was estimated using the oven-dry weight of core soil samples divided by core volume, and base saturations were estimated by taking the summation of all the bases divided by CEC for all the pedons. Soil organic carbon stocks were estimated using the equation below.

$$SOCS\ (kg\ m^{-2}) = OC\ (g\ kg^{-1}) \times BD\ (Mg\ m^{-3}) \times Depth\ (m)$$

Where, SOCS - representative C stock for the soil of interest in kg m^{-2}. OC - concentration of soil organic carbon in a given soil mass in g C kg^{-1}. BD - Bulk Density - soil mass per sample volume in Mg m^{-3}. Depth - horizon depth or thickness of soil layer in m.

3 | RESULT AND DISCUSSION

3.1 | Morphological properties of soils under different landforms and land use

Morphological properties of soils of different landforms and land use are presented in Table 2, which shows that soils are shallow (25-50 cm) to deep (100-150 cm). Different soil depths are due to differences in landform, physiography and slope gradient of the land; however, this indicates that soils are under development and climatic conditions are not congenial for weathering; hence, very deep soils have not been identified. Soil colour varied from dark red (2.5YR 3/6), dark reddish brown (5 YR 3/3), dark brown & brown (7.5YR 3/4; 4/3; 4/4), very dark grey, very dark greyish brown, dark yellowish brown (10YR 3/1, 10YR 3/2, 10YR 4/3) in surface to dark reddish brown, red (2.5YR3/4; 4/6), dark reddish brown, reddish brown, (5YR 3/3, 4/3), dark brown, (7.5YR3/4, 3/3), very dark grey, very dark greyish brown, dark brown, dark yellowish brown (10YR 3/1; 3/2; 3/3, 3/4) in subsurface. Different colour due to different parent materials and mineral composition (quartz, potassium and sodium feldspar, mica, talc, chlorite) and iron is oxidised more readily due to the higher oxygen content as the semi-arid climatic conditions with low rainfall imparted red and red associated colour and coatings of organic compounds on soils by organic matter addition, accumulation and decomposition with the parent materials during weathering process imparted brown and grey associated colour (Chandrakala *et al*., 2023) Texture of the soil varied from loamy sand, sandy loam, sandy clay loam, clay loam and clay in surface to loamy sand, sandy loam, sandy clay loam, silty loam, silty clay loam, clay loam and clay in subsurface. Different textures are due to differential rates of weathering degree of minerals and soils. Generally, the texture will not change in a short-term period; changes occur over a very long period under intense weathering and soil-forming processes. The soil structure varied from weak to moderate, with medium sub-angular blocky. Consistency varied from friable to firm and very firm, non-sticky to moderately sticky, slightly sticky, sticky and very sticky and non-plastic to moderately plastic, plastic and very plastic. The rate of organic matter addition and soil aggregate formation influenced soil structure and consistency. Coarse fragments/ gravels varied from 0 to 60 %. Erosion was slight to moderate in the lowlands to moderate to severe in the uplands. In the drought prone areas of the Karnataka state, moisture stress during crop growth period is a major challenge to crop production, emphasizing needs of conserving soil moisture. For conserving soil moisture, adoption of soil and water conservation (SWC) technologies is critical because of their various synergetic and positive impact on sustaining natural resources and rendering resilience to crop production in drought prone areas like Chitradurga district (Kumar *et al.,* 2021). Erosion was slight under soil / land covered with soil conservation measures like graded bunding and contour bunding with lower slope (0-1%) areas. Severe erosion was noticed in uplands with higher slopes (2-5%) without proper soil conservation measures. Hence, suitable soil conservation measures like residue recycling, mulching, cover cropping in conjunction with contour farming, terracing and simple engineering structures and also reliable and proven soil conservation technologies include ridge-planting, no-till cultivation, crop rotation, strip cropping and contour planting, and cover crops can be adopted to control soil erosion in uplands (Sharda *et al.,* 2019).

TABLE 1 Methods employed for soil analysis in the present study

S.No.	Analytical Parameter	Method	Reference (s)
1.	Particle size analysis	International pipette method	Piper (1966)
2.	Bulk density	Core sampler method	Blake and Hartge (1986)
3.	Soil reaction (pH)	pH meter with a glass electrode (soil water ratio 1:2.5)	Jackson (1973)
4.	Electrical Conductivity (EC)	Conductometry (soil water ratio 1:2.5)	Jackson (1973)
5.	Organic carbon	Chromic acid wet digestion	Walkley and Black (1934)
6.	Free calcium carbonate	Rapid titration method	Piper (1966)
7.	Cation Exchange Capacity (CEC)	Neutral Normal Ammonium acetate method	Schollenberger and Dreibelbis (1930)

TABLE 2 Morphological properties, bulk density and soil organic carbon stock (SOCS) in soils of different landforms and land use, tropical semi-arid region, Karnataka

Depth (cm)	Horizon	Colour	Texture	Structure	Consistence	Coarse fragments	Erosion	BD ($mg\ m^{-3}$)	SOCS ($kg\ m^{-2}$)
				Granite -gneiss : Uplands					
Pedon 1: P71: Ground nut									
0-14	Ap	2.5YR3/6	scl	2msbk	fr, ms, mp	-	severe	1.68	0.33
14-35	Bt	2.5YR3/4	sc	1msbk	fr, s, p	40-50		1.48	1.80
Pedon 2: P46: Sorghum									
0-12	Ap	7.5YR3/4	scl	2msbk	fr, ss, sp	25-30	severe	1.31	0.80
12-38	Bw1k	10YR3/4	scl	2msbk	fi, s, p	-		1.45	0.68
38-57	Bw2k	2.5Y5/4	cl	2msbk	fi, s, p	-		1.70	0.45
57-85	Bw3k	2.5Y5/4	scl	2msbk	fi, s, p	-		1.17	0.46
Pedon 3: P63: Maize intercrop with sunflower									
0-16	Ap	10YR3/1	c	3msbk	fi, vs, vp	-	moderate	1.35	0.87
16-38	Bw1k	10YR3/1	c	3msbk	fi, vs, vp	-		1.54	1.36
38-57	Bw2k	10YR3/1	c	3msbk	fi, vs, vp	-		1.54	1.17
57-82	Bw3k	10YR3/1	c	3msbk	fi, vs, vp	-		1.23	1.02
82-100	Bw4k	10YR3/1	c	3msbk	fi, vs, vp	-		1.16	0.23
Pedon 4: P37: Fallow land									
0-13	Ap	5YR3/3	sl	2msbk	fr, ms, mp	-	moderate	1.54	1.93
13-32	Bt	5YR3/3	scl	2msbk	fr, ms, mp	35-50		1.48	0.31
32-70	BC	5YR4/3	sl	1msbk	fr, ss, sp	>50		1.61	5.46
Pedon 5: P119: Fallow land									
0-13	Ap	2.5YR3/4	sl	1msbk	fr, ss, sp	20-30	severe	1.57	1.12
13-32	Bt	2.5YR4/6	sl	1msbk	fr, ss, sp	20-25		1.26	0.79
32-50	BC	2.5YR4/6	sl	1msbk	fr, ns, np	5-10		1.41	0.56
Pedon 6: P22: Coconut plantation									
0-17	Ap	7.5YR4/3	ls	1msbk	fr, ns, np	-	moderate	1.98	1.11
17-33	AB	5YR4/3	ls	1msbk	fr, ns, np	-		1.89	1.00
33-60	Bt1	2.5YR3/4	c	1msbk	fr, s, p	>60		1.34	1.59
				Lowlands					
Pedon 7: P21: Ground nut									
0-13	Ap	2.5YR3/4	scl	1msbk	fr, ss, sp	10-15	moderate	1.50	0.51
13-28	Bt	2.5YR3/4	sl	2msbk	fr, ss, sp	10-15		1.48	0.58
28-55	BC	7.5YR3/4	scl	2msbk	fr, ms, mp	-		1.23	0.96
Pedon 8: P72: Bengal gram									
0-15	Ap	10YR3/2	scl	3msbk	fi, s, p	-	slight	1.65	0.54
15-35	Bw1k	10YR3/3	scl	2msbk	fi, s, p	-		1.50	0.42
35-64	Bw2k	10YR3/2	sl	2msbk	fi, s, p	-		1.53	0.98
64-95	Bw3k	10YR3/2	scl	2msbk	fi, s, p	-		1.44	1.16
95-120	Bw4k	10YR3/2	cl	2msbk	fi, s, p	-		1.55	2.44
Pedon 9: P4: Banana plantation									
0-20	Ap	5YR4/3	scl	1msbk	fr, s, p	35-60	moderate	1.92	1.69
20-30	Bt	2.5YR3/4	cl	1msbk	fr, vs, vp	35-60		1.30	0.89
				Schist : Uplands					
Pedon 10: P20: Sunflower									
0-15	Ap	10YR3/2	c	2msbk	fi, s, p	-	severe	1.33	0.80
15-40	Bwk	10YR3/2	c	3msbk	fi, vs, vp	-		1.54	2.00
Pedon 11: P11: Bengal gram									
0-12	Ap	10YR3/2	c	2msbk	fr, vs, vp	-	moderate	1.04	0.50
12-22	Bw1k	10YR3/2	c	2msbk	fi, vs, vp	-		0.94	0.41
22-33	Bw2k	10YR3/2	c	2msbk	fi, vs, vp	-		0.78	0.38
33-50	Bck	2.5Y3/2	sl	1msbk	fr, ms, mp	-		1.53	0.68
Pedon 12: P52: Sapota plantation									
0-17	Ap	10YR4/3	scl	1msbk	fr, ss, sp	15-35	slight	1.57	1.95
17-38	Bw1	10YR3/2	c	2msbk	fr, s, p	-		1.49	2.65
38-58	Bw2	10YR3/2	c	2msbk	fr, s, p	-		1.28	1.97
58-84	CB1k	2.5Y6/3	sil	1msbk	vfr, ms, mp	5-10		1.26	1.25
84-100	CB2k	2.5Y6/3	sil	1msbk	vfr, ms, mp	5-10		1.33	0.32
100-130	CB3k	2.5Y6/3	sl	1msbk	vfr, ms, mp	5-10		1.21	0.40
				Schist: Lowlands					
Pedon 13: P2: Coconut plantation									
0-13	Ap	7.5YR4/4	cl	3msbk	fi, s, p	-	moderate	1.46	0.64
13-41	Bt1	7.5YR3/4	sicl	2msbk	fi, s, p	-		1.47	1.24
41-73	Bt2	7.5YR3/3	cl	2msbk	fi, s, p	-		1.63	1.77
73-110	Bt3	7.5YR3/3	cl	2msbk	fi, s, p	-		1.69	1.69

TABLE 3 Physico-chemical properties in soils of different landforms and land use in a tropical semi-arid region, Karnataka

Depth (cm)	Particle size distribution (% of <2 mm)			pH	EC (dS m^{-1})	OC (g kg^{-1})	Exchangeable bases (cmol (p+) kg^{-1})				CEC (cmol (p+) kg^{-1})	B.S (%)	CCE (%)
	Sand	Silt	Clay				Ca	Mg	K	Na			
							Granite-gneiss: Uplands						
Pedon 1: P71: Ground nut													
0-14	56.71	22.84	20.45	7.58	0.052	1.4	5.01	2.24	0.16	0.02	10.33	72	0.00
14-35	46.27	7.18	46.56	7.07	0.048	5.8	11.33	3.82	0.10	0.06	18.70	82	0.00
Pedon 2: P46: Sorghum													
0-12	62.14	10.65	27.21	7.28	0.066	5.1	32.53	5.04	0.13	0.03	29.89	126	2.62
12-38	56.49	16.45	27.07	7.89	0.157	1.8	54.95	6.52	0.06	0.19	41.33	149	4.88
38-57	43.98	28.11	27.91	8.69	0.135	1.4	80.78	8.21	0.03	0.08	36.04	247	21.84
57-85	56.46	22.05	21.49	8.89	0.166	1.4	82.20	7.43	0.02	0.11	29.64	303	23.07
Pedon 3: P63: Maize intercrop with sunflower													
0-16	32.14	14.34	53.52	9.05	0.144	4.0	64.50	8.46	0.29	0.70	52.15	142	12.27
16-38	27.94	14.80	57.25	9.13	0.170	4.0	75.80	7.51	0.17	1.12	54.74	155	11.99
38-57	24.42	10.77	64.81	9.14	0.193	4.0	75.08	9.20	0.13	1.71	57.20	151	11.52
57-82	25.52	12.85	61.63	9.25	0.233	3.3	81.68	9.44	0.18	2.19	57.93	161	13.84
82-100	25.63	12.65	61.72	9.12	0.251	1.1	76.23	9.65	0.14	2.70	57.07	155	16.26
Pedon 4: P37: Fallow land													
0-13	65.43	20.92	13.65	7.78	0.062	9.6	13.37	3.84	0.10	0.48	18.08	98	8.97
13-32	62.10	8.05	29.85	8.41	0.092	1.1	15.76	3.88	0.05	0.07	21.53	92	3.02
32-70	79.21	1.55	19.24	8.51	0.071	8.9	7.20	1.93	0.03	0.10	9.47	98	2.78
Pedon 5: P119: Fallow land													
0-13	73.79	9.92	16.30	6.09	0.038	5.5	2.99	1.74	0.16	0.03	7.38	66	0.00
13-32	80.06	6.62	13.32	6.25	0.041	3.3	2.69	1.49	0.05	0.19	6.40	69	0.00
32-50	77.82	9.43	12.75	6.54	0.041	2.2	2.85	1.73	0.03	0.07	4.92	95	0.00
Pedon 6: P22: Coconut plantation													
0-17	84.95	8.12	6.92	7.34	0.126	3.3	2.33	0.98	0.07	0.14	3.44	102	0.00
17-33	82.90	7.27	9.83	7.88	0.078	3.3	1.49	0.92	0.06	0.10	4.92	52	0.00
33-60	42.98	4.75	52.27	7.56	0.093	4.4	10.74	6.52	0.37	0.34	21.03	85	0.00
							Granite-gneiss: Lowlands						
Pedon 7: P21: Ground nut													
0-13	54.79	18.56	26.65	8.71	0.131	2.6	64.55	8.09	0.06	0.07	25.46	286	14.79
13-28	68.64	13.80	17.57	8.74	0.181	2.6	36.33	4.26	0.05	0.12	19.56	208	3.64
28-55	64.94	14.08	20.97	8.35	0.123	2.9	14.98	4.03	0.13	0.02	21.40	89	3.10
Pedon 8: P72: Bengal gram													
0-15	52.41	22.82	24.77	9.21	0.413	2.2	26.30	4.22	0.18	1.38	26.32	122	9.78
15-35	51.86	21.41	26.73	9.73	0.398	1.4	55.35	5.45	0.14	2.74	26.69	239	8.80
35-64	72.44	9.89	17.67	9.64	0.411	2.2	54.88	4.55	0.06	3.60	16.48	383	9.59
64-95	48.39	16.98	34.63	9.74	0.620	2.6	40.45	4.79	0.12	4.34	32.96	151	10.36
95-120	44.75	18.76	36.50	8.28	0.462	6.3	34.08	4.71	0.14	4.99	34.69	127	8.33
Pedon 9: P4: Banana plantation													
0-20	64.92	12.60	22.48	7.51	0.137	4.4	6.87	2.87	0.14	0.85	12.67	85	1.03
20-30	43.51	18.87	37.62	7.03	0.244	6.9	9.94	3.35	0.39	0.34	17.96	78	0.00
							Schist: Uplands						
Pedon 10: P20: Sunflower													
0-15	26.09	24.90	49.01	8.19	0.159	4.0	75.03	7.06	0.21	0.05	45.88	179	14.52
15-40	18.60	27.32	54.08	8.69	0.182	5.2	96.13	8.37	0.09	0.07	47.60	220	21.78
Pedon 11: P11: Bengal gram													
0-12	23.46	26.77	49.77	6.09	0.038	5.5	52.10	4.92	0.20	0.06	53.14	108	0.00
12-22	22.20	27.23	50.58	6.25	0.041	3.3	57.18	6.23	0.13	0.11	52.64	121	0.00
22-33	27.27	24.66	48.07	6.54	0.041	2.2	65.05	5.53	0.10	0.28	45.88	155	0.00
33-50	62.95	24.35	12.70	6.09	0.038	5.5	44.45	3.07	0.03	0.18	11.19	426	0.00
Pedon 12: P52: Sapota plantation													
0-17	51.60	18.80	29.61	7.90	0.082	7.3	13.20	7.55	0.29	0.06	26.20	81	0.52
17-38	34.03	24.09	41.88	8.71	0.221	8.5	26.70	4.96	0.12	0.86	35.67	92	3.01
38-58	30.71	22.27	47.01	8.97	0.172	7.7	54.13	5.95	0.15	1.47	36.41	169	4.37
58-84	41.52	42.13	16.35	9.42	0.153	3.8	56.80	5.99	0.06	1.25	21.65	296	3.37
84-100	51.70	31.76	16.55	9.29	0.163	1.5	37.90	4.75	0.04	1.44	25.46	173	5.00
100-130	64.35	28.60	7.05	9.49	0.130	1.1	40.88	5.08	0.03	1.37	23.00	206	0.77
							Schist: Lowlands						
Pedon 13: P2: Coconut plantation													
0-13	22.67	32.44	44.90	8.98	0.249	3.4	2.51	3.85	0.19	1.23	21.03	37	1.44
13-41	14.94	34.60	50.47	9.49	0.331	3.0	2.32	4.18	0.24	5.68	25.58	49	1.29
41-73	26.03	38.45	35.52	9.42	0.491	3.4	10.12	4.92	0.28	10.25	24.48	104	1.44
73-110	31.98	35.23	32.79	9.51	0.680	2.7	8.38	8.74	0.29	10.55	22.63	124	2.06

3.2 | Physico-chemical properties in soils of different landform and land use

Physico-chemical properties of soils of different landforms and land use in Table 3 show that soil properties did not differ among landforms and land use except for organic carbon content. The sand was the dominant size fraction identified in the semi-arid region (22.67-84.95% in the surface to 14.94-82.90 % in subsurface), followed by clay (6.92-53.52% on the surface to 9.83-64.81% in sub-surface) and silt content (8.12-32.44% in surface to 1.55-42.13% in subsurface). Differential soil textural classes / size fractions are expected due to the differential rate of weathering of parent materials by different soil-forming processes. Due to moderate to severe erosion in the study area (Table 1), upward movement of coarser particles occurred due to selective surface erosion of clay and biological activity and swelling and shrinking, and a combination of two or more soil-forming processes resulted in sand as a dominant size fraction (Chandrakala *et al.,* 2021). Generally, the subsurface recorded higher clay content than the surface due to clay illuviation, and the vertical distribution of clay in the subsurface resulted in the formation of Bt and Bw sub-surface horizons (Table 1). The sand content was recorded lower in subsurface because more silt and clay percentage shows sufficient vertical migration of clay and silt. Soils are slightly acidic (pH: 6.09) to very strongly alkaline (pH: 9.21) on the surface and slightly acidic (pH: 6.09) to very strongly alkaline (pH: 9.74) in the subsurface. Higher soil reaction was recorded due to the presence of higher content of base saturation and also calcium carbonate both in the surface and subsurface (CCE ranged from 0-14.79 % in the surface to 0-23.07 % in the subsurface) resulting in formation of calcic horizon (Bwk) in subsurface (CCE > 5%) however, there was a positive correlation existed between pH and calcium carbonate equivalent (r = 0.436). Since the optimum pH for crop production is up to neutral soil reaction (pH: 6.50-7.30) the study area is not suitable for most of the crops due to alkalinity; thus, it needs suitable management practices like soil reclamation by application of organic manures and amendments (application of gypsum) along with irrigation with good quality water is necessary and also in the case of calcareous soil flooding and draining out calcium salts is recommended (Chandrakala *et al*., 2021). Soils are non-saline (EC was <2.0 dS m^{-1}). Organic carbon content was low to high, ranging from 1.4-9.6 on the surface to 1.1-8.9 g kg^{-1} in the subsurface. Fallow land and plantations recorded higher organic carbon content than agricultural lands. Lower organic carbon content recorded in agricultural land was due to intensive cultivation, lower biomass production, and the addition and application of lower external organic inputs to soils during crop production. Among bases, exchangeable calcium content was highest (2.33-75.03 cmol (p+) kg^{-1} in surface to 1.49- 96.13 cmol (p+) kg^{-1} in subsurface) followed by exch. magnesium and exch. sodium. Exch. potassium was recorded lowest among all the bases (0.03-1.38 cmol (p+) kg^{-1} in surface to 0.02-10.55 cmol (p+) kg^{-1} in subsurface). Exchangeable bases are recorded in the order of Exch.Ca > Exch.Mg > Exch. Na > Exch. K. Cation exchange capacity was generally good and it ranged from 3.44-52.15 cmol (p+) kg^{-1} in surface to 4.92-57.93 cmol (p+) kg^{-1} in subsurface.

Clay content and CEC are directly related, and lower CEC was recorded wherever lower clay content was recorded, as the correlation between CEC and clay was highly positive (R = 0.840) (Table 4). Base saturation was high in all the soils, and it recorded 37 to >100 % on the surface and 49 to >100 % in the subsurface, irrespective of geology, landform and land use, which was highly and positively correlated with calcium carbonate equivalent (r= 0.674). All the soils have Iso-hyperthermic temperature and Ustic soil moisture regime. Based on morphological and physicochemical properties, soils are classified as alfisols, inceptisols, and vertisols.

3.3 | Soil organic carbon stock (SOCS) in soils of different landform and land use

The bulk density in Table 2 ranges from 1.33-1.92 Mg m^{-3} on the surface to 0.78-1.89 Mg m-3 on the subsurface. It was reported that bulk density higher than 1.6 Mg m^{-3} is unfavourable for plant growth as it can restrict the penetration of plant roots in clay loam soil. The soil bulk density in most of the areas was found to be below the critical value, denoting that there was no extreme soil compaction.

TABLE 4 Correlation coefficient (r) among soil properties of different landforms and land use, tropical semi-arid region, Karnataka

	SOCS	pH	Clay	CEC	BS	CCE	BD	OC
SOCS	1							
pH	-0.058	1.00						
Clay	0.054	0.272	1.00					
CEC	-0.142	0.476	0.840	1.00				
BS	-0.222	0.478	-0.122	0.129	1.00			
CCE	-0.188	0.436	0.320	0.542	0.674	1.00		
BD	0.313	-0.163	-0.372	-0.497	-0.126	-0.180	1.00	
OC	0.739	-0.298	0.174	-0.009	-0.332	-0.213	0.033	1

Organic carbon stock did not differ much among geology and landforms (Table 2). However, it recorded higher in fallow lands (1.12-1.93 kg m^{-2} in the surface to 0.31-5.46 kg m^{-2} in the subsurface) followed by plantations like sapota plantations, coconut plantations and banana plantations (0.64-1.95 kg m^{-2} in surface to 0.32-2.65 kg m^{-2} in the sub-surface) and agricultural land recorded lower SOCS and it ranged from 0.33-0.80 kg m^{-2} in surface to 0.23-2.44 kg m^{-2} in the subsurface which expresses the lowest SOC, and confirm that the most intensively cultivated plots are the most exhausted and tillage practices, which exposes SOC through layer inversion to microbial attack leading to higher rate of decomposition. Frequent cultivation could have increased soil aggregate disturbance and microbial activities, thus lowering SOCS concentration. Soils with lower SOCS generally have a higher potential to sequester further carbon, and more clay and silt fractions influence higher carbon sequestration potential. Land use systems and cultivation practices such as tillage, manuring, etc., also influence SOCS to a greater extent. The carbon sequestration potential was inversely related to SOCS, i.e., soils with higher SOCS generally have a lower potential to sequester further carbon in them and vice versa. Soil texture is a predictor of SOC storage, and clay content influences SOC stabilization by protecting it against microbial activities. Therefore, different rates of clay and silt fractions play key roles in carbon storage in different land use systems and depths, particularly in sub-surfaces. Root exudates and faunal bioturbation could have significantly increased SOC stock accumulation in plantations. Different vegetation has different quantities of nutrient composition (particularly N levels), which creates different soil microclimates and thus influences SOCS. Land use change causes changes in soil quality and land productivity over time and space by altering the structure and functioning of ecosystems and biogeochemical cycles. It influences soil organic carbon content, stock and C stabilization. The quantity of SOC / SOCS that can be stored in a specific soil / land is estimated by the difference between the rate of carbon input (vegetation and roots biomass) and output (CO_2 emission to the atmosphere). There are many factors*, viz. topography, climate, soil type, soil sampling depth, mineralogical composition, soil biota, land use and management practices and the interaction between them that control* the total amount of SOC / SOCS in the soil profile (Hanamantappa *et al.,* 2024). Generally, in the study area, i.e., the semiarid region of Chitradurga district recorded lower SOCS, which was due to lower precipitation and higher temperature, which are not congenial for biomass (above and below) production, resulting in lower biomass production and addition coupled with higher temperature influenced higher oxidation and decomposition of organic matter makes the soil critical to maintaining higher SOCS. Precipitation and temperature are the two major factors of climatic conditions that act as a key driver of SOCS across scales, influencing organic carbon accumulation and decomposition through altering C input and decomposition and stabilization in any specific region (Zeng *et al.,* 2021). Land use and management influence soil to act as either a source or a sink to atmospheric carbon (Lal, 2004) and land management practices with less soil disturbance due to lesser cultural operations increase soil organic carbon accumulation by reducing soil erosion in the present study fallow land and plantations recorded higher SOCS compared to agricultural land. However, crop rotations, minimum / zero tillage, intercropping, organic farming, and crop residue management contribute to SOC/SOCS build-up in the soil. Correlation studies among soil properties of different landforms and land use (Table 4) show that SOCS highly and positively correlated with organic carbon content (r = 0.739), bulk density (r = 0.313) and clay (r = 0.054), whereas negatively correlated with pH, CEC, base saturation and calcium carbonate equivalent. SOCS are mainly controlled by C inputs, including residues, secretion and exudates of plant, animal and microbial and C outputs, such as mineralization, soil erosion and losses; thus, increasing the above and below-ground biomass helps to sequester more carbon from the atmosphere and further increases the carbon stocks in the study area (Prabakaran *et al*., 2023). Further, the type of vegetation influences the content of organic carbon through the influence of substrate, root exudate, litterfall, microbial activity, soil chemistry, root biomass and root turnover. Thus, to achieve sustainability in the carbon resource in any cultivated lands, suitable management practices such as crop residue incorporation, reduced tillage, cover crops, enrichment with organics, *etc*., have to be manifested (Prabakaran *et al.,* 2023) along with soil conservation measures to control erosion in order to prevent loss of C associated with clay and productive / fertile topsoil. The C stock production rate influences by different tree species present in the specific area depending upon their growth and biomass production capacity (Singh *et al.,* 2020). The SOCS varied significantly in the sub-surface due to several factors, including differential depths, gravel content, bulk density, soil types (mineralogy and texture), clay content, soil pH, soil moisture, temperature, structure, porosity, microbial community composition, topography, land use, nutrient management, and the dynamics of SOC. Notably, the proportion of microaggregate - associated SOC increased significantly in subsoils compared to topsoils, indicating that SOC in subsoils is crucial for long-term carbon stabilization (Zeng *et al.,* 2021).

Soil organic matter (SOM) and SOCS increase with higher clay content because the complexation of organic matter with clay slows down decomposition. Additionally, greater clay content in subsoil enhances the likelihood of aggregate formation, influencing the differential rates of SOCS in these layers. This variation can also be attributed to high root density, which increases micropores and facilitates the percolation of SOC in the form of dissolved organic carbon to deeper soil layers, largely due to elevated faunal activity. Furthermore, land use types and management practices aimed at soil organic carbon sequestration are critical in mitigating global warming by reducing carbon buildup in the atmosphere.

5 | CONCLUSIONS

The soil properties in the semiarid region of Chitradurga district, Karnataka, did not significantly vary across geology, landforms, and land uses. However, SOCS was influenced by climatic conditions and varied by land use, with the highest being fallow land and sapota plantations and the lowest being agricultural land due to intensive cultivation and reduced organic inputs. Overall, SOCS levels were low in this region, primarily due to lower precipitation and higher temperatures, which affected biomass production and increased oxidation of organic matter. The soils were generally low in organic carbon, alkaline, calcareous, and subject to moderate to severe erosion. Management practices are needed to improve soil health and productivity, including soil reclamation for alkaline soils, proper water management to address calcium salts, and adding organic inputs. Implementing soil conservation measures is essential to combat erosion and enhance regional agricultural sustainability.

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DATA AVAILABILITY STATEMENT

Data is available with the corresponding author and will be provided if its required.

CONFLICT OF INTEREST

There are no conflicts of interest

AUTHOR'S CONTRIBUTION

Chandrakala M., the present study's principal investigator, conducted the investigation and wrote the manuscript. Ranabir Chakraborty and the principal investigator contributed to the field soil survey. Parvathy, S., contributed to laboratory soil analysis. Seema, K.V., contributed to GIS work. Sunil P. Maske contributed to the literature search review. Ramamurthy, V., and Ramesh Kumar, S.C., have coordinated the work. Nirmal Kumar prepared the cLHS sampling strategy for the soil survey, and Obi Reddy G.P. contributed to delineating the landform map.

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ORIGINAL ARTICLE
Indian Journal of Soil Conservation

Assessment of green energy for vegetable cultivation in tribal areas of Koraput district, Odisha in the Eastern Ghats region

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ABSTRACT

Undulating topography and lack of irrigation compel tribal farmers of Koraput district in Odisha to leave their agricultural fields fallow during post-monsoon season. Using a solar irrigation system can be an appropriate alternative for farmers to go for vegetable cultivation during the post-monsoon season using stored subsurface water in stone-pitched *jhola kundi* (shallow dug well). In this study, 60 stone-pitched *jhola kundis* were constructed, and solar-powered irrigation pumps were installed in 2022 and 2023 to irrigate the farmer's fields. The diameter of these *jhola kundis* varies between 4.0 to 6.2 m, whereas depth ranges from 3.0 to 7.8 m. These *jhola kundis* are equipped with a one-horsepower (hp) surface-mounted solar-operated pump. The harvested water irrigates a nearly 145-ha area covering 207 farmers. Vegetable cultivation enhances farmers' monthly income from ₹ 4644 to 19676 and holds the potential for further income growth. At the same time, it helps increase the crop diversity index values to as high as 0.85. There is a saving of 48336 kWh^{-1} power per annum, considering 70% pump efficiency. Further, it helps reduce carbon dioxide emissions by 280 kg per ha of CO_2 per annum. Therefore, the promotion of this technique will not only help to achieve assured irrigation to crops but also protect the environment by reducing the emission of greenhouse gases.

HIGHLIGHTS

- Irrigation potential created by constructing 60 nos. of stone-pitched *jhola kundi* is 145 ha.
- It helps enhance farmers' monthly income threefold.
- Annual reduction in CO_2 emission is 280 kg/ha.

1 | INTRODUCTION

Koraput district is a tribal-dominated area situated on a section of Eastern Ghats in Odisha state and has a total geographical area of 8379 km^2. The district's total population is 13,79,647 as per Census 2011, of which 50.6% are scheduled tribes. Agriculture and forest products are the mainstays of the economy of the Koraput district, with around 83% of the population depends on it. The soil and climate in the district are favorable for taking up agro-horticultural activities. The cultivable land is 3 04,000 ha (only 36.28 %) with the irrigated area (*kharif*) of 143,673 ha (17.14% of total geographical area), irrigated area (*rabi*) 92,599 ha (11.05% of total geographical area) Agricultural Statistics, 2019). The sources of irrigation include canals (upper Kolab, lower Kolab, and Telengiri irrigation projects), lift irrigation points, deep bore wells, and diversion-based spring water (Agricultural Statistics, 2019). The major portion of the district is ecologically fragile hilly upland vulnerable to resource degradation and environmental stress. Though the district is bestowed with a good amount of rainfall (annual average rainfall: 1316 mm) (Dash *et al.,* 2020), however undulating topography, shallow soil depth, low soil organic carbon, and fine textured soil hinder infiltration of water into the soil. Additionally, irregular monsoon cycle often causes long dry spells and drought-like situations, render rainfed agriculture a high-risk endeavor, and contribute to low agricultural production. Small and marginal farmers with small land holdings (82.68% of farmers are under marginal and small land holdings in Koraput district) with single crops during *kharif* have faced food insecurity and reduced income from farmlands (Agricultural Statistics, 2019). Not only erratic monsoons but also the non-availability of water during post-monsoon season led most farmers to leave their fields fallow. The farmers also mainly cultivate paddy, finger millet, and other minor millet. As most of the district's area falls under rain-fed mixed farming and the dependency on rainfall is very high, water provision during the post-monsoon season is a prerequisite to enhance the economic conditions of small and marginal farmers. In this context, constructing water harvesting structures and efficiently utilizing stored water is required. Among various water harvesting structures, *jhola kundi* (shallow dug well) can be considered a viable irrigation source during the post-monsoon and summer seasons, and the harvested water in *jhola kundi* can be used for vegetable cultivation. *Jhola kundi* is a low-cost sub-surface water harvesting structure usually constructed on or adjacent to the *jhola* land (terraced low land) as this land has a favorable hydrological condition that ensures availability of water at, or near, the surface for most of the year (Panda *et al.,* 2010; Dash *et al.,* 2019). It is a circular shallow well dug manually with depth varying from 3 to 8 m and a diameter of about 3 to 5 m (Panda *et al.,* 2011, IISWC Annual Report, 2021). Traditional water lifting devices called Tenda or Krishak Bandhu pumps / diesel or solar-operated pumps can lift the water for irrigation.

In India, water for irrigation in agriculture is mainly pumped using either diesel or electric pumps. However, the increasing price, uneven distribution of diesel fuel and electric power, and adverse effect of emission of greenhouse gases have diverted the attention of researchers, policy-makers, and planners to go for eco-friendly and low-cost irrigation systems vis-a-vis solar-operated water pumps. In total, 72% of CO_2 contributes to human-emitted greenhouse gases, and the share of fossil fuel combustion is the maximum (IEA, 2012). Substituting diesel-operated pumps with solar-powered pumps can considerably reduce carbon emissions as the energy source for solar-operated pumps is solar radiation and is abundantly available in tropical countries like India. There is an availability of about 300 clear sunny days in a year with variations of solar insolation from 4 to 7 kWh $m^{-2}day^{-1}$ in India, depending upon the locations (Chandel *et al.,* 2017). In Odisha, the availability of solar radiation is ~5 kWh $m^{-2}day^{-1}$ occurs for nearly 300 days (www.oreda.com). Solar-powered water pumps have been proven to be technically feasible and economically viable, particularly for small-scale applications in the irrigation sector for vegetable cultivation (Badra, 2018; Ghosal *et al.,* 2021). Apart from this, solar-operated water pumping systems have been proven to be favorable to the environment concerning emissions and require very little maintenance and no cost involvement for the fuel (Chandel *et al.,* 2015).

Therefore, stone-pitched *jhola kundi* constructed and solar-powered irrigation systems were installed in *jhola kundis* across eight blocks of Koraput district to help farmers cope with water-related risks or uncertainties during winter and summer seasons and to avert the impending water crisis in crop production. This study assessed the impact of the *jhola kundi* - based solar-operated irrigation system on socio-economic and environmental benefits.

2 | MATERIALS AND METHODS

2.1 | Location and details of *jhola kundi* based solar powered irrigation system

Sixty stone-pitched *jhola kundis* were constructed, and solar-operated irrigation pumps were installed in eight blocks of Koraput district, Odisha, during 2022 and 2023. The location of these systems is presented in Fig.1, and their distribution in various blocks of the Koraput district is presented in Table 1. In the Koraput and Pottangi blocks, a maximum of 10 systems have been installed, whereas the Boipariguda and Lamataput blocks have only four systems. All these locations in the Koraput district receive a good amount of solar radiation for about 4 to 5 hours a day over nearly 300 days a year (Anonymous, 2013). The Google Earth image shows three of these systems located in Lingamguda village, Pottangi block, shown in Fig. 2. A total of 51 villages are covered, and 207 nos. of farmers have been using the stored water for vegetable cultivation during winter and summer seasons. The diameter of constructed stone-pitched *jhola kundi* ranges between 4.0 to 6.2 m, while its depth varies from 3.0 to 7.8 m depending on the location. The designed dimension of *jhola kundi* was based on previous research works by Panda *et al.* (2011). Each *jhola kundi* has a solar-operated surface-mounted irrigation pump (1 hp) with three solar panels. The capacity of each solar panel is 300 watts, and the suction head is 7 m. The cost of each system is ₹ 2,50,000/-, which includes a) construction of stone pitched *jhola kundi* (₹ 1,50,000/-) and installation of the solar-powered pump (₹ 1,00,000/-). The farmers generally irrigate their fields by conveying water through high-density polyethylene (HDPE) pipes and cultivate various vegetable crops.

2.2 | Environmental and socio-economic impact assessment

Various data on bio-physical and socio-economic parameters were collected through field visits, questioners, meetings, and Focused Group Discussions (FGDs) during pre- and post-installation of these systems. The total duration of the study includes 2 seasons for 30 nos. of the system and 1 season for the rest of the 30 nos. of the system. Periodic monitoring and measurement of water level in the *jhola*

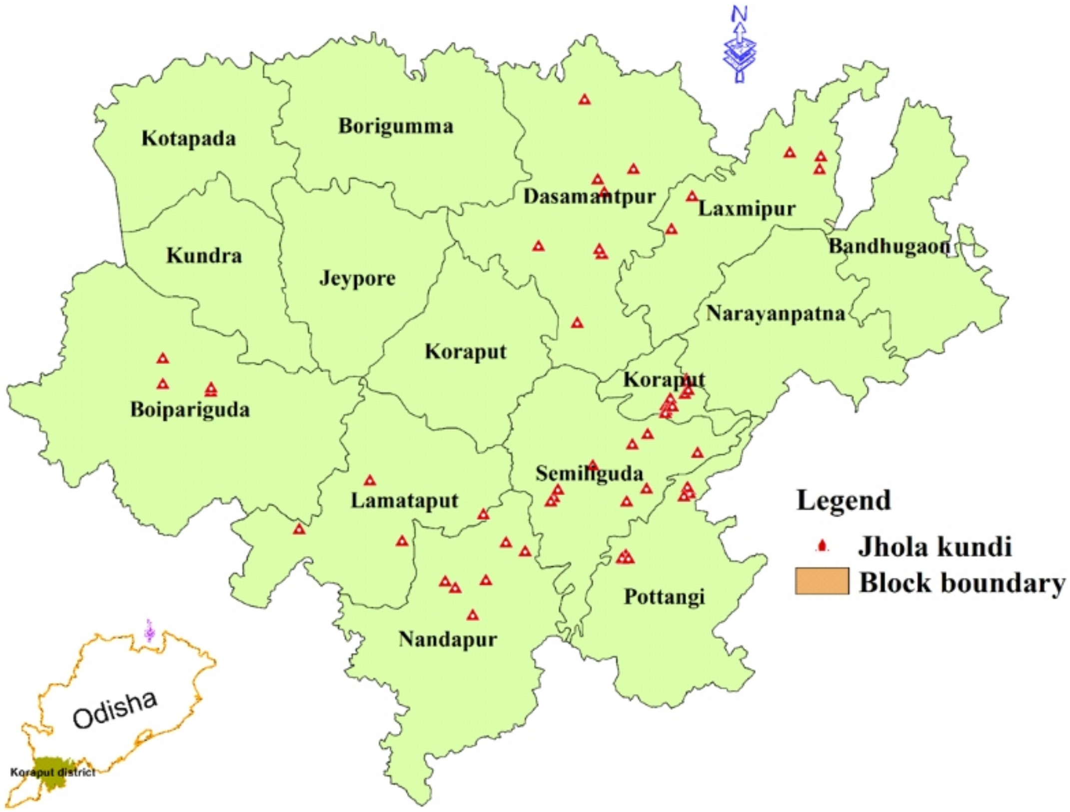

FIGURE 1 Map showing location of *jhola kundi* based solar powered irrigation system in Koraput district

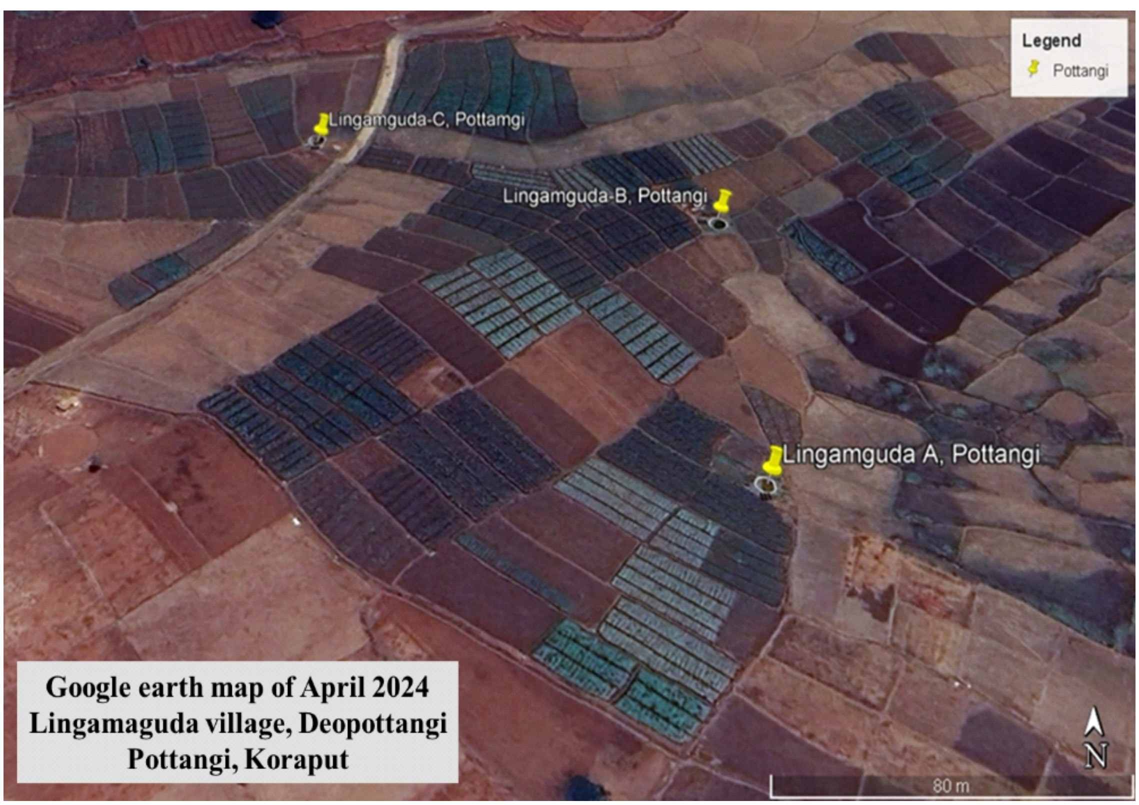

FIGURE 2 Google earth map showing installed *jhola kundi* based solar powered irrigation system in Lingamguda village, Koraput district

TABLE 1 Blockwise distribution of *jhola kundi* based solar powered irrigation system

Block name	*Jhola kundi* based solar operated irrigation system (No)	Beneficiary covered (No)	Villages covered (No)	Average area under cultivation (ha/farmer)
Boipariguda	4	9	2	0.35
Dasamantapur	9	36	8	0.49
Koraput	10	32	8	0.30
Lamataput	4	12	4	0.31
Laxmipur	5	15	5	0.42
Nandapur	9	27	8	0.39
Pottangi	10	42	7	0.50
Semiliguda	9	34	9	0.37
Total	60	207	51	

kundis, recuperation rate, discharge rate of solar-powered pump, and yield of crops were carried out. Information on the area under irrigation under each *jhola kundi* during the winter and summer seasons was collected. Crop-wise area under irrigation and crop yield were also collected from individual farmers. Apart from that, the environmental benefit of using a solar-powered irrigation system was also estimated. The various impact assessment indicators are presented below:

a) **Cropping pattern:** This refers to the proportion of land under cultivation of different crops at different times. It indicates the time and arrangement of crops in a particular land area. The cropping pattern before and after using solar-operated pumps in the villages was analyzed.

b) **Cropping intensity (CI):** Cropping intensity is the number of crops a farmer grows in a given agricultural year on the same field. It is another means of intensifying production from the same plot of land.

$$\textit{Cropping intensity (\%)} = \frac{\textit{Gross cropped area}}{\textit{Net sown area}} \times 100$$

c) **Crop diversification index (CDI):** Crop diversification refers to the distribution of land to grow various crops and is adapted to counteract the unfavorable consequences of current crop specialization and monoculture. It facilitates resource utilization, nutrient recycling, soil fertility restoration, and economic viability through value-added products and ecological enhancements (Acharya *et al.,* 2011). The level of crop diversification in an area can be measured using the crop diversification index. This index considers the number of crops grown in an area and the area under cultivation for each crop (Kumar and Gupta, 2015). For this study, the Simpson index (SI) is used and calculated by following the equation:

$$\mathrm{SI} = 1 - \sum_{i=1}^{n} p_i^2$$

Where, $p_i = \frac{A_i}{\sum A_i}$ is the proportion of the i^{th} activity in acreage. If SI is close to zero, it indicates that the region or area is near the specialization in growing a particular crop, and if it is close to one, then the zone is fully diversified in terms of crops.

d) **Net income:** Farmers' net income from vegetable cultivation during the winter and summer seasons was calculated by subtracting the cost of cultivation from gross income. The gross income was calculated by multiplying vegetable production with the selling price of those products in the local market.

e) **Environmental benefit assessment:** In India, diesel and electricity are the primary fuels used to operate diesel and electric pump sets for irrigation. Burning diesel in internal combustion engines and generating electricity in power plants contribute a lot to the emission of greenhouse gases into the atmosphere, causing more to the present concerns of global warming and climate change. In Odisha, nearly 3.00 lakhs and 2.00 lakhs of diesel and electric pumps are used, respectively, with the power rating ranging between 1 to 5 hp (Anonymous, 2017). It has been reported that a single one-hp engine consumes about 0.25 liter of diesel per hour (Ghosal *et al.,* 2021), and the burning of 1 liter of diesel releases about 3 kg of CO_2 into the atmosphere (Sharma and Maréchal, 2019). Similarly, the average carbon dioxide emission for electricity generation from coal-based thermal power plants is 1.58 kg kW^{-1} h^{-1} (Chel *et al.,* 2009). By knowing the annual working hours of this solar-powered irrigation pump and discharge rates, the mitigation of CO_2 emission by replacing diesel and electric pumps was calculated.

3 | RESULT AND DISCUSSION

This study installed 30 nos. of *jhola kundi*-based solar-powered irrigation systems in 2022 and the rest in 2023. The water level in these *jhola kundi* varied between 2.5 to 7.2 m depending on location and time. Similarly, the mean discharge rate of the pump ranged from 1.6 to 3.3 l sec^{-1}. The mean discharge rate of the solar pump was calculated by taking an average of discharge measured at 9.00 am, 12.00 pm, and 3.00 pm. There are several techniques to determine the potential yield of dug wells. The most commonly used techniques include a) the well recovery or recuperation, b) specific capacity, and c) the peak demand tests. Specific capacity and recuperation are science-based tests, whereas peak demand tests are more subjective. Therefore, in this study recuperation test was carried out to determine the potential well yield, by following standard procedure. The measured potential yield of *jhola kundis* ranged between 55 to 137 m^3 day^{-1}. However, in many cases, the stream water has been diverted and directly entered into the *jhola kundis* by farmers. Therefore, the stored water is adequate to supply water for vegetable cultivation. The creation of irrigation facilities increased the irrigated area. The details of the potential area under irrigation created in different blocks during the winter and summer seasons are presented in Fig. 3. The Total area irrigated during the summer season is 84 ha, while the same during the winter season is 61 ha, covering a total area of 145 ha. Among the blocks, the area under irrigation in Pottangi block is maximum (36.1 ha). In contrast, the Boipariguda block has a minimum irrigated area (5.4 ha), followed by Lamataput (6.4 ha), due to only 4 no. of systems installed in those two blocks.

Before the creation of irrigation facilities, rice and finger millet were the dominating crops cultivated during the rainy season by all farmers, while only a few farmers such as 54 and 6% cultivated vegetables during the winter

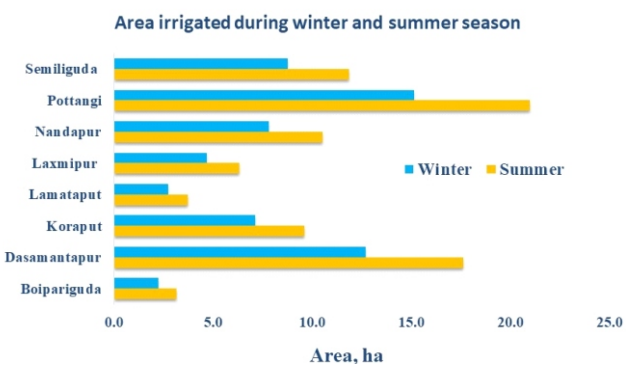

FIGURE 3 Block wise area created under irrigation

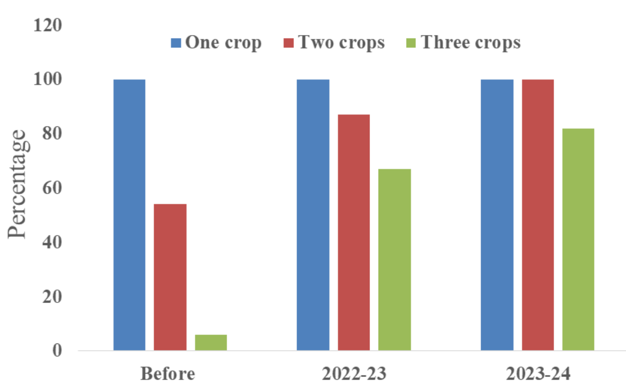

FIGURE 4 Cropping pattern in project operational area before and after creation of irrigation facility

and summer seasons, respectively, based on the availability of water (Fig. 4). The creation of irrigation facilities helped farmers to cultivate a different type of vegetables such as tomato, beans, chili, brinjal, bitter gourd, yam, cabbage, cauliflower, capsicum, etc. The creation of irrigation facilities has changed the cropping pattern as presented in Fig. 4. During 2022-2023, among the project beneficiaries, the percentage of farmers who cultivated vegetables during winter and summer was 87 and 67%, respectively. Similarly, during 2023-24, the percentage of farmers cultivating vegetables during winter and summer increased to 100 and 82%, respectively. The reason can be attributed to the late construction of *jhola kundis*. Overall, it can be stated that after the creation of irrigation facilities, many farmers were able to cultivate high-value vegetable crops, which helped farmers earn every week.

Farmers could cultivate and grow different kinds of vegetables, evidenced by the crop diversification index (Fig. 5) calculated for different blocks coming under the project operational area. The crop diversification index varied from 0.25 to 0.55, with a mean value of 0.40 before the creation of irrigation facilities, and increased to a mean value of 0.8. A maximum value of 0.85 was observed in the project operational areas of the Pottangi and Nandapur blocks, whereas a minimum value (of 0.73) was obtained in the Boipariguda block. The difference in crop diversification among the blocks may be related to the availability of vegetable seeds, market demand, and farmers' willingness to cultivate different vegetables.

With the creation of irrigation facilities, there was an increase in the cropping intensity with the inclusion of vegetable crops in the winter and summer seasons. In other words, the field has a crop throughout the year. The cropping intensity has increased from 137% to 272% in the project operational area. With the increase in cropping intensity in the study area, the income of farmers increased in comparison to their earlier level of income (Fig. 6). Earlier, per farmer's monthly net income ranged between ₹ 3274/- to

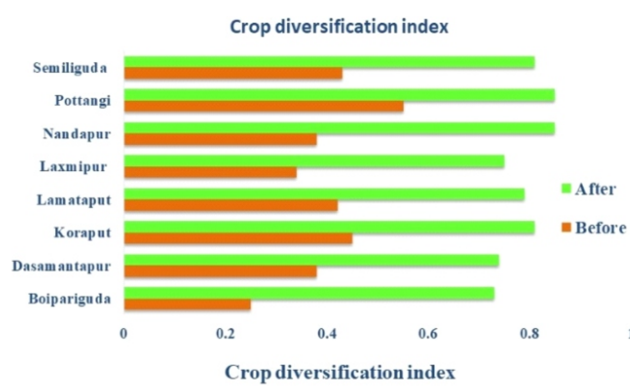

FIGURE 5 Crop diversification index in project operational area before and after creation of irrigation facility

₹ 5565/- with a mean value of ₹ 4644/-. With the construction of *jhola kundis*, the monthly income of project beneficiaries during the *rabi* and summer seasons was increased to a range of ₹ 13376/- to ₹ 22493/- with a mean value of ₹ 19676/-.

3.1 | Mitigation of CO_2 emission by the use of solar-powered pumps

In the study area, 60 nos. of solar-operated irrigation pumps were installed. Solar pumps are rapidly becoming more attractive than traditional electric and diesel-operated pumps. Further powered by renewable energy sources, solar pumps are especially useful in remote locations where a steady fuel supply or electricity supply is problematic. Apart from this, solar pumps are environment-friendly, with zero CO_2 emission. Considering the hypothesis that if 60 no. of diesel and electric pumps have the same horsepower, then the quantity of CO_2 emission from those pumps can be mitigated using these solar pumps. The environmental benefit of using solar pumps is presented in Table 2. There is a saving of 15900 liters of diesel fuel with a benefit of ₹ 15,90,000/- considering per liter diesel price as ₹ 100/-. Similarly, if an electric pump is used, the energy for cultivating vegetables in 145 ha of land is 48336 kWh. Overall, the annual reduction of CO_2 in using solar pumps per year is 40545 kg from 145 ha area, which is 280 kg ha^{-1} yr^{-1}.

4 | CONCLUSIONS

Solar-powered water pumping systems are gaining importance nowadays due to less maintenance and the use of renewable energy, and they can be used anywhere in rural and remote areas. Looking into the non-availability of water during the post-monsoon season in the Eastern Ghats highland region of Koraput district, the *jhola kundi* based solar operated irrigation system can be considered as a sustainable approach for the cultivation of vegetables, which helped farmers to increase their socio-economic conditions. By adopting this system, farmers' income increased threefold in the Koraput district, increasing the mean crop diversification index to 0.8. The present study's findings would provide insight to the state's farming community to adopt this technology to strengthen their agricultural production system with secured energy and water availability.

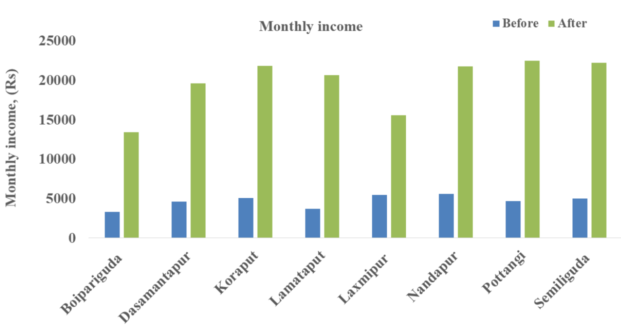

FIGURE 6 Monthly income of farmers in project operational area before and after creation of irrigation facility

TABLE 2 Environmental benefit of using a solar pump

Saving diesel fuel by replacing diesel pumps (liters)	: 15900
Saving of electric energy by replacing electric pump (kWh)	: 48336
Reduction in CO_2 emission per year (kg)	: 40545

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DATA AVAILABILITY STATEMENT

The data presented in this study are available upon request from the corresponding author.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR'S CONTRIBUTION

CJD: Conceptualization, data analysis, writing; JL: Data collection, analysis, review; MM: Conceptualization, guidance; HCHG and RD: Review and editing; GBN, GWB and PY: Data collection and analysis.

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ORIGINAL ARTICLE

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Effect of different tillage regimes and mulching practices on crop yields and water use efficiency of linseed (*Linum usitatissimum*) in South Gujarat conditions

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ABSTRACT

The productivity of linseed (*Linum usitatissimum*) can be significantly enhanced by adopting appropriate natural resource management technologies. However, there is limited research on conservation-based management practices specifically for linseed. This study, therefore, aimed to identify suitable conservation agricultural management practices that improve both crop yield and water use efficiency in linseed cultivation. The present research was conducted in Navsari district, Gujarat, within Agro-climatic Zone - 3 (South Gujarat Heavy Rainfall Zone - I) over three consecutive winter seasons from 2019-2022. Eight treatments involving the combinations of different conservation tillage practices were evaluated using a randomized block design with three replications. The results demonstrated that the maximum yield attributes were recorded under CT + RSM + SGM treatment [conventional tillage + rice straw mulching + sunn hemp (*Crotalaria juncea*) green manuring during the preceding *kharif* season)]. Except for the first year, this treatment was statistically superior to both reduced tillage (RT) and conventional tillage (CT). Similarly, maximum grain and stalk yields were recorded under the treatment CT + RSM + SGM, followed by CT + SGM [conventional tillage + sunn hemp green manuring (during preceding *kharif* season)] and RT + RSM + SGM [reduced tillage + rice straw mulching + sunn hemp green manuring (during preceding *kharif* season)]. Water use efficiency (WUE) was also significantly improved under CT + RSM + SGM treatment. Based on these findings, it is recommended that linseed growers adopt the conventional tillage combined with rice straw mulching and sunn hemp green manuring during preceding *kharif* as an effective tillage and mulching strategy to enhance the crop performance and WUE.

HIGHLIGHTS

- Conventional tillage combined with paddy straw mulching and sunn hemp green manuring during the preceding *kharif* season helps improve linseed yield.
- Conservation agricultural management practices applied in conventional and reduced tillage control soil moisture depletion and improve WUE.
- Green manuring during *kharif*, followed by paddy straw mulching for linseed cultivation, is recommended for the black soil region.

1 | INTRODUCTION

Linseed (*Linum usitatissimum* L.) is a highly nutritious and emerging oilseed crop known for producing high-quality vegetable oil and fibre. It is an excellent vegetarian source of Omega - 3 essential fatty acids, particularly Alpha-Linolenic Acid (ALA), containing twice the amount found in fish oil (Sarkar and Sarkar, 2017). Globally, linseed or flax is one of the oldest oilseed crops, widely cultivated across Asia, America, and Europe for oil, fibre, and seed production. India ranks as the fourth-largest vegetable oil producer in the world, following the USA, China, and Brazil. The demand for edible oils is continuously rising in India due to population growth and improved living standards. Linseed is a major winter (*rabi*) oilseed crop in India, after rapeseed mustard. It is a valuable source of complete protein, high levels of linolenic acid, carbohydrates, vitamins, and minerals, and is cultivated for both seed and fibre production.

Conservation agriculture (CA) is practised on ~ 125 million hectares globally (Kiboi *et al.*, 2017). CA-based management practices have enhanced crop yields and net returns, improved soil fertility and biodiversity, increased WUE, and mitigated greenhouse gas emissions (Giller *et al.,* 2015). Additionally, CA also reduces pests and diseases by integrating crop rotations, which disrupts disease cycles that affect crops (Mourtzinis *et al.,* 2017). The area under CA represents 12.5% of global total cropland, with distribution nearly equal between industrialized regions (52%) and developing regions (48%) (Kassam *et al.,* 2018).

Tillage involves mechanical manipulation of the soil to enhance conditions for crop production. It contributes up to 20% to crop productivity among various production factors (Ali *et al.*, 2017). Proper tillage can alleviate the soil-related constraints, whereas improper tillage can lead to adverse effects such as soil structure degradation, accelerated erosion, depletion of organic matter and fertility, and disruption of water, organic carbon, and nutrient cycles. Conservation tillage is a practice in which at least 30% of the soil surface is covered by plant residues (Ali *et al.*, 2017). In recent years, reduced tillage has become widely adopted globally to control soil erosion and maintain soil fertility. Rani *et al.* (2019) also reported that soils under reduced tillage exhibit higher aggregate stability and water infiltration rates than those under plough tillage. However, limited data on linseed performance under reduced tillage systems are available.

Mulching enhances water productivity and crop yield by increasing water retention. It extends the moisture availability period, reduces water evaporation losses, and helps maintain soil temperature. Upon degradation, organic mulches contribute organic matter to the soil, improving its nutrient status. Mulching impacts crop growth and yield directly by supplying essential nutrients and indirectly by improving the soil physical properties such as aggregate stability and porosity, which enhance soil quality and stimulate plant growth (Kiboi *et al.*, 2017). Rice straw mulch is a protective layer of organic material applied to the soil surface. It helps reduce moisture loss by minimizing evaporation, decreasing plant water loss, suppressing weed growth, improving soil conditions, and providing habitat for earthworms and soil-dwelling natural enemies.

Despite these benefits, limited information exists on the impact of various CA management practices on the yield and water use efficiency of linseed. Therefore, there is a pressing need to identify and implement effective conservation agricultural-based management practices to enhance both the production and water productivity of linseed crops.

2 | MATERIALS AND METHODS

The present experiment carried out at the Engineering farm, Navsari Agricultural University, Navsari, Gujarat, India, comes under Agroclimatic zone - 3 (20º55'41.38" N and 72º 53'41.18"E), South Gujrat Heavy Rainfall Zone-I) during three consecutive winter seasons, 2019-20 to 2021-22. Soils of this region are heavy textured (clay content 58%) with good water holding capacity, non-saline (EC 0.28 dS/m), pH 7.5 (1: 2.5 soil water) and high inorganic carbon (0.77%), available phosphorus (60.52 kg/ha), available potassium (495.52 kg/ha) and medium in available nitrogen (266.8 kg/ha). The experiment consisted of eight treatment combinations of different conservation tillage practices: CT-conventional tillage (Two ploughing followed by laddering); RT - Reduced tillage (One ploughing followed by laddering); CT + RSM - Conventional tillage + Rice straw mulching (dose in t/ha); RT + RSM - Reduced tillage + Rice straw mulching; CT + SGM - Conventional tillage + sunn hemp green manuring (during preceding *kharif* season); RT + SGM - Reduced tillage + sunn hemp green manuring (during preceding *kharif* season); CT + RSM + SGM - Conventional tillage + Rice straw mulching + sunn hemp green manuring (during preceding *kharif* season) and RT + RSM + SGM - Reduced tillage + Rice straw mulching + sunn hemp green manuring (during preceding *kharif* season). The experiment was replicated three times under a randomized block design. The linseed (local variety) sowing was done with the recommended seed rate (20 kg/ha) during the last fortnight of October. The experimental plot size was 25 m^2, and crop spacing was maintained at 30 cm × 10 cm (Kalal *et al.,* 2023). The recommended doses of fertilizer were used N:P:K: 40:20:45, 50% N, 100% P and K as basal and the remaining 50% N was used after 45 DAS. All other cultivation practices were similar for all the treatments. Two irrigations were applied as per the crop water requirement during all seasons. Five plants per plot were selected to measure growth parameters and yield attributes. Crop yield was recorded after harvest, and data were converted to obtain productivity for a one-hectare land area.

The gravimetric method took the soil samples for moisture content determination at 15 and 30 cm depth (Tripathi *et al.,* 2018). Measurements were taken 30 days after sowing during the growth period. Soil moisture content (SMC in %) was calculated using the equation below (Sharma *et al.,* 2015).

$$SMC(\%) = \frac{Weight\ of\ wet\ soil - Weight\ of\ dry\ soil}{Weight\ of\ dry\ soil} \times 100 \quad ...(1)$$

Irrigation water was applied using the surface irrigation method. The amount of water applied in different treatments was measured using a Parshall flume. The total water used during the cropping season was calculated, and water use efficiency was then calculated by dividing the grain yield (kg/ha) by the total amount of water (mm) applied in the field (Kumari *et al.,* 2018). The rainfall was received 37.05, 38.96 and 76.99 mm during 2019-20, 2020-21 and 2021-22, respectively. Rainfall + irrigation should be used as the total amount of water applied.

$$WUE = \frac{Grain\ yield}{Total\ amount\ of\ water\ applied\ in\ the\ field} \quad ...(2)$$

The data gathered in each observation were statistically evaluated using the analysis of variance technique suggested by Gomez and Gomez (1984). A critical difference (CD) was computed to assess the significance of treatment means at the 5% level of probability.

3 | RESULT AND DISCUSSION

3.1 | Growth Attributes

The growth parameters of linseed (plant height and number of branches per plant) were significantly influenced by the various conservation practices, except for the first year (Table 1). The treatment CT + RSM + SGM significantly enhanced these growth attributes compared to CT and RT. Throughout the study, treatment RT consistently resulted in the lowest plant height and number of branches per plant, although both parameters showed improving trends over time. In contrast, CT demonstrated consistent trends across the years. Anjum *et al.* (2014) similarly observed higher plant growth under conventional tillage compared to reduced tillage in maize. The enhanced plant growth was attributed to greater soil moisture retention throughout the growth period, coupled with lower soil temperatures. The increase in plant growth with more intensive tillage may be due to improved nutrient uptake and moisture availability by the plants.

3.2 | Yield Attributes

Different conservation practices significantly influenced the number of capsules per plant in linseed, except during the first year. In contrast, these practices non-significantly affected 1000-grain weight (test weight) and harvest index (Table 1). CT + RSM + SGM markedly increased the number of capsules per plant compared to CT and RT. The lowest number of capsules per plant was consistently observed under RT throughout the study, though its performance showed potential for improvement over time. CT, however, exhibited stable trends across all years of the study. The lowest yield attributes under reduced tillage may be attributed to increased soil bulk density, which negatively impacted root growth. In contrast, conventional tillage treatments likely enhanced water and nutrient availability by improving moisture movement through the soil profile, thereby facilitating nutrient uptake in the rhizosphere and promoting better plant growth and performance. These findings align with Shahid *et al.* (2016), who reported a significant effect of tillage on yield attributes like the number of rows per cob, with conventional tillage resulting in 15.40 rows compared to 13.90 rows under the minimum tillage.

3.3 | Crop yields

Significant variations in linseed grain and stalk yield were observed across the different conservation practices, except in the first year. The highest grain yield was recorded under the treatment CT + RSM + SGM, which was significantly greater than that of CT, RT, CT + RSM and RT + RSM during the second and third years of the experiment (Table 2). The lowest grain yield was consistently observed under RT across all years. Experimental plots treated with paddy straw mulching (CT + RSM, RT + RSM, CT + RSM + SGM and RT + RSM + SGM) produced higher grain yields compared to non-mulched treatments (CT, RT, CT + SGM and RT + SGM). Similarly, stalk yield was significantly higher under CT + RSM + SGM than CT, RT, CT + RSM and RT + RSM, with the lowest stalk yield recorded under RT. Mourtzinis *et al.* (2017) reported a 16% increase in maize grain yield under conventional tillage compared to reduced tillage systems.

3.4 | Soil moisture depletion and Water use efficiency (WUE)

After the first irrigation, year-wise soil moisture content was recorded as 19.2%, 21.2%, and 20.2% during the first,

TABLE 1 Effect of different conservation practices on growth and yield attributes of linseed

Treatment	Plant height at harvest (cm)			No. of branches plant^{-1}			No. of capsules plant^{-1}			Test weight (g)		
	1styear	2nd year	3rd year	1styear	2nd year	3rd year	1styear	2nd year	3rd year	1styear	2nd year	3rd year
CT	59.9	58.9	57.6	6.5	6.6	6.6	49.9	49.097	50.1	6.6	6.5	6.4
RT	57.2	57.4	57.6	6.2	6.4	6.3	47.0	47.1	49.1	6.4	6.6	6.4
CT + RSM	61.1	62.5	62.6	7.1	7.9	7.9	51.3	52.0	53.3	6.8	6.7	6.6
RT + RSM	60.4	62.3	62.4	6.8	8.0	8.2	49.3	51.4	53.1	6.6	6.8	6.6
CT + SGM	61.1	65.8	67.4	6.8	8.5	8.6	50.9	53.7	54.3	6.8	6.9	6.7
RT + SGM	60.2	65.2	66.6	6.4	8.3	8.5	49.0	52.1	53.7	6.7	70	6.7
CT + RSM + SGM	63.1	67.4	69.3	7.3	8.8	9.0	52.0	570	58.4	70	6.8	6.8
RT + RSM + SGM	62.6	66.5	68.2	7.2	8.8	9.0	50.7	55.7	56.8	6.7	6.8	6.8
CD ($p = 0.05$)	NS	6.7	7.2	NS	1.2	1.8	NS	5.7	5.7	NS	NS	NS

TABLE 2 Effect of different conservation practices on grain and stalk yield of linseed

Treatment	Grain yield (kg ha^{-1})			Stalk yield (kg ha^{-1})		
	1styear	2nd year	3rd year	1styear	2nd year	3rd year
CT	1046	1014	1005	1501	1569	1537
RT	946	958	969	1443	1487	1468
CT + RSM	1079	1059	1108	1626	1879	1887
RT + RSM	1050	1129	1147	1541	1895	1912
CT + SGM	1057	1228	1288	1595	2042	2105
RT + SGM	1013	1183	1225	1514	1949	1999
CT + RSM + SGM	1084	1269	1341	1790	2150	2215
RT + RSM + SGM	1062	1198	1260	1699	1984	2052
C.D. ($p = 0.05$)	NS	152.0	160.0	NS	324.0	302.0

second, and third years, respectively. Soil moisture depletion was the lowest under RT + RSM + SGM, with values of 22.0%, 16.7%, and 16.6% in the first, second, and third years, respectively, followed by CT + RSM + SGM (Fig. 1). Treatments without paddy straw mulching (CT, RT, CT + SGM and RT + SGM) exhibited the higher soil moisture depletion as compared to those with paddy straw mulching (CT + RSM, RT + RSM, CT + RSM + SGM and RT + RSM + SGM). The lowest WUE was observed under RT, with 6.9, 6.9, and 5.5 kg/ha/mm values during the first, second and third years, respectively. In contrast, the highest WUE was recorded under CT + RSM + SGM, significantly outperforming CT, RT and CT + RSM in the second year. CT, RT, CT + RSM and RT + RSM in the third year (Fig. 2). Treatments incorporating green manuring (CT + SGM, RT + SGM, CT + RSM + SGM and RT + RSM + SGM) showed higher WUE compared to those without green manuring (CT, RT, CT + RSM and RT + RSM). The lower WUE under reduced tillage, compared to conventional tillage, may be attributed to decreased water storage capacity (Xiao *et al.,* 2019). Reduced tillage often leads to lower infiltration rates than deep-ploughed conventional tillage, resulting in lower crop yield and WUE.

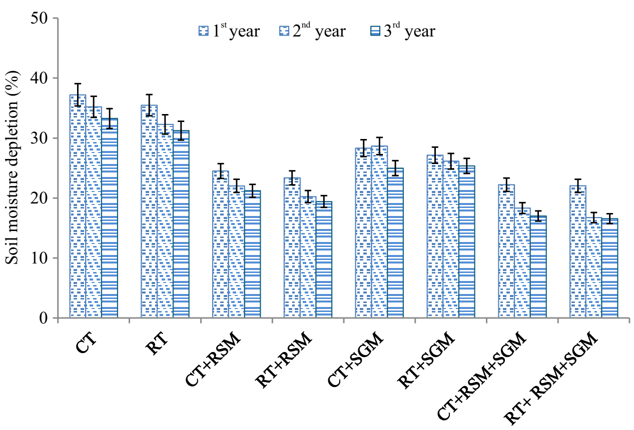

FIGURE 1 Effect of different conservation practices on soil moisture depletion of linseed

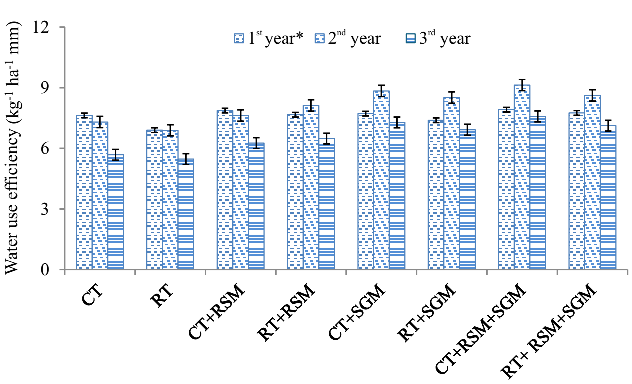

FIGURE 2 Effect of different conservation practices on water use efficiency of linseed (*denoted NS @ p=0.05)

5 | CONCLUSIONS

Based on the results, the overall yield was the maximum under conventional tillage combined with paddy straw mulching and sunn hemp green manuring during the preceding *kharif* season. Additionally, soil moisture depletion and WUE were the most favourable under conservation agricultural management practices applied in conventional and reduced tillage, compared to treatments without conservation measures. Thus, it may be recommended that linseed cultivators in black soil regions adopt conservation agricultural management practices such as green manuring (during the *kharif* season) and paddy straw mulching in combination with conventional tillage to improve crop yield, enhance water use efficiency, and reduce the soil moisture depletion.

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DATA AVAILABILITY STATEMENT

Available with authors on request.

CONFLICT OF INTEREST

We have no conflict of interest.

AUTHOR'S CONTRIBUTION

This work was carried out as research project work of Reena Kumari. Yogesh Garde helped in data analysis. Babloo Sharma and Pratibha Kumari improved paper writing and literature, improving language.

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ORIGINAL ARTICLE
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Water harvesting structure-farm pond for increasing crop yields and farm income in rainfed semi-arid ecosystem of Karnataka

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ABSTRACT

This study evaluated the impact of farm ponds constructed under the Krishi Bhagya Scheme in the Northern Dry Zone of Karnataka from 2022 to 2024. A total of 320 farmers were selected for data collection, divided into two groups: farmers with or without farm ponds. Each group comprised 160 farmers, who were chosen using a multi-stage stratified random sampling technique. Various statistical methods were used to analyse the data, including descriptive statistics, tabular analysis, and t-tests. The findings indicated that cropping intensity significantly increased among farmers with ponds (157%) compared to those without (142%). This improvement was attributed to effective on-farm rainwater conservation and the harvesting of surplus runoff in ponds, which provided supplemental irrigation during critical periods. Additionally, farmers with ponds experienced greater crop yields and farm income than the control group, resulting in a percentage increase in income from 17% to 48%. Employment generation, measured in man-days, also improved among farmers with ponds, showing a substantial increase in work opportunities, particularly during the rabi season (69%) compared to the *kharif* season (31%). The construction of farm ponds also influenced the number of livestock maintained, particularly cows, sheep, and goats. The ponds provided essential drinking water and fodder, ensuring alternative livelihood opportunities in rainfed regions. Consequently, adopting farm ponds fosters sustainable production and promotes efficient natural resource management in these areas.

Key words:
Farm pond
Life-saving irrigation
Rainfed farming
Runoff harvesting
Rainwater recycling

HIGHLIGHTS

- Farm pond helps farmers diversify their cropping pattern and integrate different farming systems with agriculture, such as dairy, to increase on-farm and off-farm income in Semi-arid rainfed regions.
- The area under irrigation and cropping intensity was increased for farmers with farm ponds compared to control due to on-farm rainwater conservation and harvesting surplus runoff with farm ponds for supplemental life-saving irrigation.
- The crop yields and farm income for farmers with farm ponds were increased compared to control due to protective life saving irrigation, particularly during critical crop growth stages with farm ponds.
- Farmers with farm ponds were more resilient to drought and sustaining income than control due to harvesting excess runoff and used for farming and other economic activities.

1 | INTRODUCTION

Agriculture is the backbone of the Indian economy, with nearly 55% of the population relying on it as their primary source of income and livelihood. Rainfed agriculture accounts for more than 50% of the net sown area and plays a significant role in producing food grains, particularly coarse cereals, rice, pulses, and oilseeds in India (Rao *et al.,* 2019). However, this sector faces numerous bio-physical and socio-economic challenges. The limited resource base has negatively impacted crop and livestock productivity (Venkateswarlu, 2011). Additionally, the irrigation potential in these areas is not fully utilized, resulting in significantly lower crop productivity compared to regions with irrigated agriculture. Therefore, effective strategies and planning are essential to optimize the natural resource base, enhance crop productivity, and achieve the goal of doubling farmers' income in rainfed areas. Fragile agroecosystems with low productivity characterize rainfed farming and are largely practised in arid, semi-arid, and dry sub-humid regions. Low productivity in this region is mainly due to marginal and erratic rainfall exacerbated by high runoff and evapotranspiration losses. Sufficient availability of soil moisture during crop growth is a limiting factor, and soil degradation is a critical factor that results in low productivity. These regions receive an average annual rainfall of 500 to 700 mm, which is highly erratic and unevenly distributed during cropping seasons. There is an abundant scope and opportunities for harvesting excess runoff in the rainfed region of different states of the country (Wani *et al.,* 2003). Therefore, proper management and utilization of surplus runoff is crucial to increase rainfed farm productivity. In addition, farm-level adoptions of rainwater harvesting structures were highly effective in rainfed farming and had a multiplier effect on farm income (Shalander Kumar *et al.,* 2016).

In Karnataka, Agriculture is predominantly rainfed and the state is experiencing recurring droughts and floods simultaneously in different regions. A glance into the rainfall pattern of the state reveals that for every decade, three to four years experience severe drought, sometimes consecutively. The non-availability of irrigation coupled with prolonged dry spells in the rainfed area may lead to crop failure and low productivity. Supplementary irrigation in rainfed agriculture through farm ponds reduces the risk of total crop failure due to dry spells and substantially improves water and crop productivity (Biazin *et al.,* 2012). Realizing the importance of water in the climate change scenario, the Government of Karnataka has implemented the Krishi Bhagya Scheme during 2014-15 to ensure irrigation for sustainable production through on-farm rainwater conservation practices. Water harvesting farm ponds are essential in improving crop productivity and farm income in rainfed regions in climate change situations (Dupdal *et al.,* 2021). Most of the study area, *i.e.,* the Northern dry zone of Karnataka, is characterized by a semi-arid climate with low rainfall, which is highly unpredictable and unevenly distributed in cropping seasons. Crop yields are very poor and unstable due to low and uncertain rainfall and inefficient crop management (Adhikari *et al.,* 2009). Thus, rainwater harvesting ponds helps to conserve and harvest surplus runoff for protective irrigation during critical crop growth stages to improve rainfed productivity. Further, farmers can integrate different farming systems with agriculture, horticulture, fisheries and dairying to enhance on-farm (farming, crop production) and off-farm (extension services, processing, packaging, storage, distribution and retail sale etc.) income in dryland areas (Dupdal *et al.,* 2020). However, economic viability and long-term sustainability of farm ponds were the major concerns for the farmers. Keeping this in view, the present study attempted to analyze the impacts and profitability of farm ponds constructed under the Krishi Bhagya Scheme in the Northern dry zone of Karnataka.

2 | MATERIALS AND METHODS

The present study was conceptualized to study the impact of farm ponds constructed under the Krishi Bhagya Scheme implemented by the Government of Karnataka to enhance the rainfed region crop productivity through efficient rainwater management. Under the scheme, more than two lakh farm ponds were constructed in the farmers' fields with a combined water storage capacity of 1472.31 lakh cubic meters. The Scheme encompasses a farm pond with polythene lining and installing a sprinkler with a diesel pump set (5HP) to promote micro-irrigation and increase water use efficiency. Therefore, the current study evaluates the change in cropping patterns, crop productivity, and farmers' incomes with and without farm pond interventions.

2.1 | Study Area

Ballari and Vijayapura districts under the northern dry zone of Karnataka were chosen for the present study as they fall under a semi-arid region with low and deficit rainfall. Ballari district is located in the eastern part of Karnataka and lies between 15°30' and 15°50', north latitude and 75°40' and 77°11' East longitude. The district receives a mean annual rainfall of about 633 mm, which is non-uniformly distributed over the district. Predominant soil types are red and deep black soils. The main occupation of the district is agriculture, and more than 75% of the population depends on agriculture and allied activities for their livelihood. The major crops of the district were paddy, chilli, maize, sorghum, sunflower, cotton and chickpea. Vijayapura district, located in the northern part of Karnataka, lies between 150 50' and 170 28' North latitudes and 74°54' and 76°28' East longitudes. The mean annual rainfall of the district is 594 mm, with 52% of annual rainfall received during the *rabi* season. This zone received low annual unimodal rainfall and comprised mostly medium to deep black soils with diversified cropping patterns (Dupdal *et al.,* 2022). The important crops were pearl millet, groundnut, pigeon pea, green gram, maize, sorghum, sunflower, safflower and chickpea.

TABLE 1 Water stored in selected sample farm ponds in the study area

Size of farm pond	No. of sample	Water storage (m^3) @ 2 fillings
15*15*3	40	35280
21*21*3	40	78480
28*28*3	40	15070
30*30*3	40	175680
Total	160	304510

2.2 | Data Source

For analyzing the impact of farm ponds, farmers with and without farm ponds were selected within the same village. Farmers were selected based on a multi-stage random sampling technique across the northern dry zone of Karnataka. A total of 320 farm household data was collected through pre-tested interview schedules during 2022-2024. Of 320 farm household samples, 160 were farmers with farm ponds, and 160 were farmers without farm ponds selected for a comparative study. For data collection, dryland districts were selected purposively in the northern dry zone of Karnataka. Under each district, one taluk and two villages were selected for primary data collection. The selected taluka were Ballari taluk in Ballari district and Vijayapura taluk in Vijayapura district and selected villages were K. Veerapura and Joladarasi in Ballari taluka and Nagatan and Hunsyal in Vijayapura taluk. The primary data on cropping patterns, crop yields, and income were collected from sample farmers with and without farm ponds. Further, data relating to employment status and livestock components were collected from farmers with and without farm ponds.

2.3 | Statistical Tools Used

Descriptive statistics such as frequency, percentage, tabular analysis and t-test were used to study the impact of farm ponds on cropping patterns, crop productivity and returns, and employment accrued among the beneficiary farmers in the study area compared to control farmers.

3 | RESULT AND DISCUSSION

3.1 | Socio-economic Characteristics of Sample Farm Households

The socioeconomic characteristics of farmers with and without farm ponds revealed that nearly 53% of control farmers were in the old age groups, while 45% of farmers with ponds were in middle-aged groups (Table 2). The education of farmers had implications for technology adoption and its usage. A higher level of education among farmers helped them access more advanced technology and information than their counterparts. Less than one-third of the farmers with ponds were illiterate. In comparison, more than one-third of control farmers were illiterate, and only five per cent of farmers attained graduation, while 10% of farmers with ponds attained graduation. Farming experience was higher for farmers with ponds (55%) than control farmers (30%). The majority of sample farmers in both categories were under a small size of land holding with <2 hectares followed by a large size of holding (> 2 ha). Farmers with ponds possessed more livestock (48%) than control farmers (38%) since farm ponds provided sustained water availability for fodder production and drinking for animals. The off-farm employment among control farmers (43%) was higher than that of farmers with ponds (28%) as farm ponds provided supplemental irrigation, increasing employment opportunities and man months in agriculture/crop cultivation among farmers with ponds. Further, with the adoption of farm ponds risk, the ability and accessibility to institutional credit increased among farmers with ponds (50%) compared to control farmers (38%).

3.2 | Farm Pond and its Impact on Cropping Pattern and Cropping Intensity

The impact analysis of farm ponds on cropping patterns revealed that the area under irrigation increased due to on-farm conservation and harvesting of rainwater for protec-

TABLE 2 Socio-economic characteristics of sample farm households

S.No.	Particulars	Farmers with ponds		Farmers without ponds	
		f	*%*	*F*	*%*
1.	Age (years)				
	Young (<35)	36	23	28	18
	Middle (35-50)	72	45	48	30
	Old (>50)	52	33	84	53
	Total	160	100	160	100
2.	Education (No.)				
	Illiterate	44	28	64	40
	Primary	64	40	72	45
	High school	32	20	16	10
	Graduation	20	13	08	05
	Total	160	100	160	100
3.	Farming experience (years)				
	Low (<15)	24	15	40	25
	Middle (16-25)	48	30	72	45
	High (>25)	88	55	48	30
	Total	160	100	160	100
4.	Social category (No.)				
	SC/ST	64	40	56	35
	OBC	36	23	40	25
	General	60	38	64	40
	Total	160	100	160	100
5.	Land holding type (No.)				
	Marginal (< 1 ha)	36	23	40	25
	Small (<1-2 ha)	68	43	64	40
	Large (>2 ha)	56	35	56	35
	Total	160	100	160	100
6.	Possession of livestock				
	Yes	76	48	60	38
	No	84	53	100	63
	Total	160	100	160	100
7.	Off-farm employment				
	Yes	44	28	68	43
	No	116	73	92	58
	Total	160	100	160	100
8.	Access to institutional credit				
	Yes	80	50	60	38
	No	80	50	100	63
	Total	160	100	160	100

Source: Field Survey Data, 2022

tive irrigation, particularly utilized during critical crop growth stages. The area under chickpea (28.26 ha) and onion (19.83 ha) were higher among farmers with ponds as compared to control farmers (19.73 ha) and (6.93 ha), which was due to the adoption and harvesting of excess runoff water with farm ponds resulting in increased water availability for life saving irrigation and also in-situ soil moisture conservation (Table 3). The study also revealed a difference

TABLE 3 Impact of farm ponds on cropping pattern and Cropping Intensity

Crop	With farm ponds		Without farm ponds	
	Area (ha)	Percent to the total area	Area (ha)	Percent to the total area
Redgram	17.17	7.45	18.11	9.30
Cotton	14.92	6.48	14.61	7.50
Maize	14.43	6.26	15.34	7.88
Jowar	11.66	5.06	13.81	7.09
Bajra	10.57	4.59	13.44	6.90
Onion	11.77	5.11	13.47	6.92
Fallow land	33.17	14.40	24.16	12.41
Total *kharif* area	113.69	49.34	112.94	58.00
Chickpea	28.26	12.26	19.73	10.13
Safflower	12.06	5.23	10.81	5.55
Coriander	10.69	4.64	4.7	2.41
Jowar	15.73	6.83	10.13	5.20
Sunflower	11.06	4.80	8.87	4.56
Onion	19.83	8.61	6.93	3.56
Wheat	10.88	4.72	5.55	2.85
Fallow land	8.22	3.57	15.07	7.74
Total *rabi* area	116.73	50.66	81.79	42.00
Gross cropped area	230.42	100.00	194.73	100.00
Net cultivated area		146.86		137.1
Cropping intensity (%)				
Mean	157.82		142.13	
Std. Error Mean	8.23		5.47	
t-value	7.196*			

**Significance at P<0.01.*

in grossed cropped area (15%) for farmers with farm pond compared with control. The difference in the gross cropped area was mainly attributed to the increase in relative cropped area in the *rabi* season as compared to the *kharif* season; thus difference in cropping intensity to the tune of 157% for farmers with farm ponds as compared to control (142%) was observed and difference in cropping intensity between farmers with and without farm pond was found statistically significant at less than 0.01 level of probability. Desai (2007) and Dupdal (2023) in their studies revealed that the construction of farm ponds had brought about a perceptible change in cropping intensity by increasing the area under *rabi* crops in the case of farmers with ponds as compared to farmers without farm ponds.

3.3 | Impact of Farm Ponds on Crop Yields and Farm Income

The findings of the impact of the adoption of farm ponds for rainwater harvesting and supplemental irrigations had differences in the crop yields and net income of farmers with farm ponds (Table 4 and Fig. 1). There was a difference in crop yields particularly coriander (23%), onion (21%) and maize (18%) over cultivation of crops without irrigation from farm pond under rainfed situations. The 't' test showed

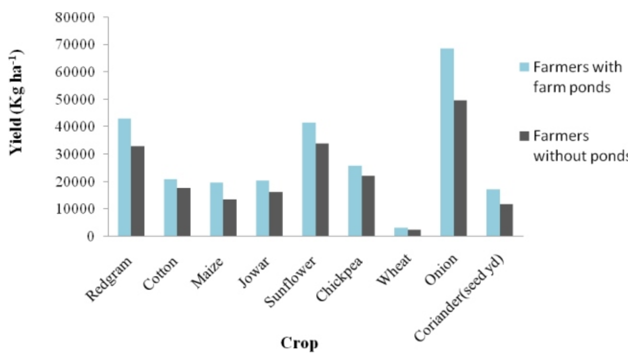

FIGURE 1 Impact of farm pond on farmer's net income with and without pond

TABLE 4 Economics of farmers with and without farm ponds

Crop	Farmers with farm pond			Farmers without farm pond			Additional income to farmers with farm pond (₹ ha^{-1})	% difference over control	t-value
	Yield (q ha^{-1})	COC (₹ ha^{-1})	Net returns (₹ ha^{-1})	Yield (q ha^{-1})	COC (₹ ha^{-1})	Net returns (₹ ha^{-1})			
Redgram	12.47	39244	43058	10.62	37321	32771	10287	31	4.275*
Cotton	9.43	36450	20884	8.66	34964	17689	3196	18	1.854
Maize	30.09	39328	19709	25.42	39345	13529	6180	46	3.800
Jowar	12.91	20265	20265	11.64	18679	16125	4140	26	3.526**
Sunflower	10.81	27677	41507	9.35	25949	33891	7616	22	1.274*
Chickpea	10.33	28144	25882	9.24	26284	22041	3841	17	3.964**
Wheat	12.7	20150	6838	11.80	19413	5662	1176	21	0.316
Onion	181.75	58752	68473	150.26	45505	49677	18796	38	0.876*
Coriander	5.76	23075	17245	4.69	21166	11664	5581	48	2.508**

***Significant at P<0.01, *Significant at P<0.05.*

a significant difference in farmers' yields with farm ponds compared to control farmers. The difference in farmers' yields with ponds was mainly due to increased protective irrigation, particularly during critical crop growth stages and improved soil moisture. The field bunds constructed in the farmer's fields increased the soil moisture and reduced the cracks in the fields laid out with farm ponds over the control conditions. Results revealed that due to the difference in crop yields of farmers with ponds, additional income was ₹ 18796 ha^{-1} for onion and ₹ 10,286 ha^{-1} for redgram. Similar findings were reported by Kumar *et al.* (2016), Raizada *et al.* (2018), Gireesh *et al.* (1997) and Kumar *et al.* (2024).

The percent difference in farmers' income with farm ponds ranged from 17 to 48% for different crops over control farmers, and net income realized was higher (30%) than farmers without farm ponds. The results align with the findings of Rao *et al.* (2019), who reported that income gains resulted from improvement in crop yield, change in cropping pattern towards high-value crops, increase in cropping intensity and expansion of cultivated area where the ponds were located. This study found in conformity with studies of Dupdal *et al.* (2021) and reported that farm pond intervention enhanced 25-30% of crop productivity as harvested rainwater available for providing one or two protective irrigations to crops at critical growth stages during dry spells and drought. Rao *et al.* (2017) and Reddy *et al.* (2018) reported similar results for increasing crop productivity and net returns with farm pond irrigation. The study was also in line with the findings of Umesh *et al.* (2024), reporting that tank rejuvenation of selected traditional community tanks helped to improve the livelihood of 50 to 70% of small and marginal farmers through increasing crop yields in Yadgir district of Karnataka.

TABLE 5 Impact of farm ponds on employment among beneficiary farmers (Man days/farm)

Particulars	With farm ponds	Without farm ponds	% difference	t-value
Kharif	90	85	6	0.3
Rabi	40	08	400	10.8**
Total	130	93	40	2.7**

*Note: ** indicates 1% level of significance.*

TABLE 6 Share of farm-households owning livestock and small ruminants (Nos.)

Livestock	Farmers with ponds	Farmers without ponds	% Change
Cow	57	31	83.9
Buffalo	17	13	30.77
Sheep	23	14	64.3
Goat	43	25	72.0
Bullock	15	13	15.38
Poultry	48	51	-5.9

3.4 | Farm Pond and its impact on employment among beneficiary farmers

The results of employment generated due to the adoption of farm ponds revealed that there was a difference in man-days for farmers with the adoption of farm ponds (130 man days/ farm) as compared to control (93 man days/farm) (Table 5). The difference in man-days for beneficiary farmers was attributed to an increase in man-days, particularly during the *rabi* season compared to the *kharif* season. The excess runoff water harvesting followed by supplemental irrigation with a farm pond increased the area under irrigation, which demanded more labour and employment opportunities in the farm compared to the control condition. The 't' test showed a significant difference in the employment generated for farm pond beneficiaries and control farmers. The study findings align with Kumar *et al.* (2016), who reported that farm ponds led to the diversification of the cropping system and an increase in crop yield, which helped improve employment generation.

3.5 | Share of Farm-households Owning Livestock and Small Ruminants

Livestock rearing is one of the alternative livelihood enterprises in the village, and it plays a vital role in sustaining and strengthening farmers' income. It also helps reduce rural poverty and nutritional security and is resilient to drought and climate variability. In the study area, there exists a per cent difference in the share of cows (83.9%), goats (72%) and sheep (64.3%) for farmers with pond over control, implying that the farmers with pond are more resilient and sustaining compared to the control farmers (Table 6).

The percentage difference in livestock population among beneficiary farmers was mainly due to the availability of green fodder and drinking water for animals with the support of farm ponds. Even during the drought period, it was easy for the farmers to fetch water for the animals after the construction of farm ponds.

5 | CONCLUSIONS

Sustainable agriculture production in the rainfed regions is challenging under climate change, mainly due to unpredictable and erratic rainfall, frequent droughts followed by prolonged dry spells and crop failures. However, these vagaries can be overcome by farm-level adoption of farm ponds for rainwater harvesting and efficient utilization and management of excess runoff water for increasing rainfed productivity. It helps the farmers diversify their cropping system and integrate different farming systems with agriculture, such as dairy, to increase on-farm and off-farm income in rainfed areas. It also helps efficiently utilise and manage natural resources in the rainfed region. It is evident from the study results that there was a difference in cropping pattern cropping intensity and crop yields for the adoption of farm ponds. The area under irrigation was increased due to on-farm rainwater conservation and harvesting utilized for supplemental life saving irrigation. There is a difference in crop yields and farm income for farmers with farm ponds compared to control due to protective life saving irrigation during critical crop growth stages with farm ponds. Further, results also revealed that the percent gain in income of farmers with farm ponds ranged from 17 to 48% over control farmers, and net income realized was higher than farmers without farm ponds. The employment generation in terms of man days was higher for farmers with pond than control farmers. This was mainly attributed to an increase in man-days, particularly during the *rabi* season compared to the *kharif* season. Due to the adoption of farm ponds, there was an increase in livelihood opportunities such as dairy through livestock rearing as farm ponds served as a source of drinking water and green fodder for the livestock even during drought periods.

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DATA AVAILABILITY STATEMENT

Data are available for reasonable reasons from the first author.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR'S CONTRIBUTION

RD: Conceptualization, Formal analysis, Methodology, Writing - original draft. BSN: Data curation, Writing - review and editing. MNR: Data curation, Writing - review, and editing. RKN: Data curation, Writing - review, and editing. BKR: Supervise, validate, and write - review and editing.

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ORIGINAL ARTICLE
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Combating land degradation: Global challenge, local solutions

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Strategies and approaches

ABSTRACT

Land degradation is a critical global challenge that undermines food security and threatens ecosystem services and livelihoods. Driven by unsustainable land use practices, climate change, and natural phenomena, degradation manifests through soil erosion, fertility decline, salinization, acidification and desertification, with drylands regions particularly vulnerable. This review comprehensively analyzes the methods used to assess land degradation, highlighting regional disparities and critical hotspots. Effective mitigation strategies such as conservation agriculture, agroforestry, and soil and water conservation techniques are explored, emphasizing community-based and participatory approaches for combating land degradation. The significance of policy frameworks, including the United Nations Convention to Combat Desertification (UNCCD) and Land Degradation Neutrality (LDN), is underscored in fostering sustainable management to address sustainable development goals (SDGs). Technological advancements, including GIS, remote sensing, and precision agriculture, are pivotal in enhancing monitoring, conservation planning, and management. Despite these advancements, challenges such as socio-economic constraints, climate variability, and policy implementation gaps remain. The paper advocates for integrated, multidisciplinary strategies that balance short-term actions with long-term sustainability to reverse degradation trends and promote ecosystem resilience, aligning with global sustainability goals.

HIGHLIGHTS

- Land degradation threatens food security, ecosystem services and livelihood.
- SLM is essential to reduce soil erosion and reverse land degradation.
- Adoption of multi-pronged approach in tackling land degradation.
- Reversing land degradation helps in achieving LDN and SDGs

1 | INTRODUCTION

Land degradation is a significant global threat that poses risks to food security, ecosystem services, and biodiversity, with anthropogenic activities like urbanization, deforestation, drastic land use change, improper land management practices, and climate change serving as key contributors (Anālayo *et al*., 2023). This phenomenon involves physical, chemical, and biological processes that lead to the deterioration of soil quality and productivity, with nearly half of the world's cultivated land currently under various stages of degradation (Abdel Rahman, 2023). Various approaches and indicators are utilized to evaluate land degradation, highlighting considerable regional disparities and identifying critical hotspots, particularly in arid and semi-arid regions (Jiang *et al.,* 2024). Mitigation efforts focus on sustainable land management (SLM) or sustainable soil management (SSM) practices, such as conservation agriculture involving no-till / reduced tillage, crop rotation, and residue retention to ensure permanent soil cover, in conjunction with community involvement and global cooperation (Chaudhary, 2024). Addressing land degradation requires the integration of multiple scientific disciplines and using standardized assessment methods to achieve (LDN and support the SDGs (Nedd and Anandhi, 2024).

Combating land degradation is vital for improving food and nutritional security, environmental quality, and socio-economic progress. This issue, driven by unsustainable land use practices (e.g. clearing forest areas, non-adoption of appropriate soil and water conservation measures and non-replenish of soil nutrients, bare soil surface outside the cropping cycle, and low addition of organic manure), climate change, and natural disasters, results in decreased agricultural productivity and biodiversity loss, thereby intensifying poverty and food insecurity on a global scale (Ali *et al.*, 2024). In India, approximately 120.7 M ha are affected by land degradation, primarily due to soil erosion and deforestation (Jinger *et al*., 2023). Implementing strategies such as agroforestry, sustainable cropping and grazing practices, and integrated land use planning can restore degraded lands, enhance soil quality, and boost carbon sequestration (Chaudhary, 2024). Moreover, tackling land degradation is crucial for achieving the SDGs, as it supports improved living conditions, creates job opportunities, and mitigates the effects of climate change (Gibson, 2022). Therefore, a multidisciplinary approach incorporating community involvement and innovative management techniques is essential to effectively address land degradation and build community resilience to climate change (Badapalli *et al.*, 2023).

This review aims to examine the global extent and impact of land degradation, highlighting its effects on food security, ecosystem services, and livelihoods. It aims to evaluate existing methods and indicators for land degradation, focusing on identifying regional disparities and critical hotspots. Additionally, we identify and analyze effective mitigation strategies, including SLM practices and community-based approaches that have shown success in addressing land degradation (Fig. 1). We also explore the role of policies, technological advancements, and scientific innovations in combating land degradation and achieving LDN. Besides, the scope of this review includes a comprehensive analysis of the forms and drivers of land degradation - both anthropogenic and natural - alongside an assessment of sustainable management practices such as conservation agriculture, regenerative agriculture, agroforestry, soil and water conservation, and integrated land-use planning.

2 | UNDERSTANDING LAND DEGRADATION

2.1 | Definition and Types of Land Degradation

Land degradation refers to the decline in land quality and soil health caused by human activities and natural processes, resulting in reduced soil fertility and biodiversity and disrupted ecological balance (Teng and Zhou, 2020). This phenomenon includes various forms of land degradation, such as soil erosion, desertification, salinization, acidification, contamination, and land destruction, each driven by factors like unsustainable agricultural practices, deforestation, and pollution (Zaitsev *et al*., 2022; Teng and Zhou, 2020). For example, erosion can be triggered by water and/or wind and accelerated by tillage, while desertification involves the conversion of fertile land into arid regions (Saljnikov *et al*., 2022). The widespread occurrence of these degradation forms is particularly concerning, with large areas of European agricultural land affected by multiple degradation pathways (Prăvălie *et al.,* 2024). According to Dalal (1996), soil fertility degradation occurs primarily due to soil erosion (via water and wind), overgrazing, intensive cultivation of farmlands using inappropriate practices, poor addition / return of organic residue / manures, loss of soil organic matter from arable lands, nutrient removal via crop produce/residue burning, acidification, salinization, sodification, and flora, fauna and microbial biodiversity loss, and excess accumulation of heavy metal load and pesticides. Therefore, addressing land degradation necessitates a multidisciplinary strategy incorporating SLM practices and effective environmental policies to alleviate its effects.

Soil erosion and the resulting loss of soil fertility / soil fertility degradation are pressing environmental challenges, intensified by both natural factors and human activities such as deforestation, intensive farming, and unregulated construction (Dalal and Bridge, 1996; Dalal, 1998; Barman *et al*., 2024) (Fig. 2). The physical removal of top- fertile soil leads to nutrient depletion, adversely affecting agricultural productivity and ecosystem health, as key nutrients such as nitrogen,

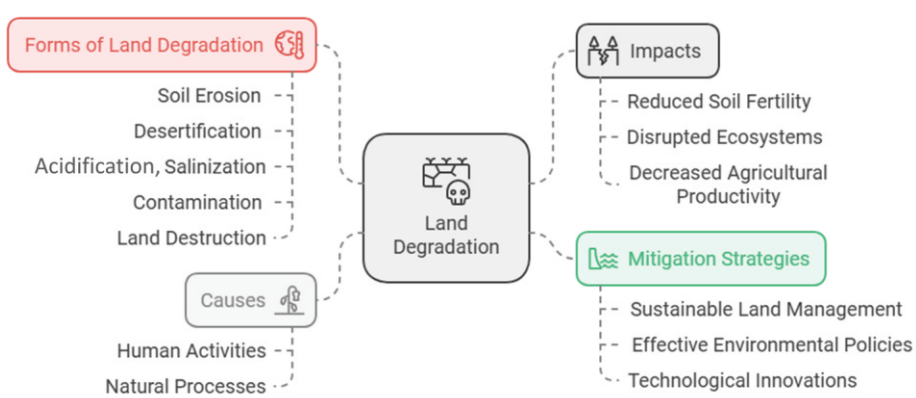

FIGURE 1 Forms of Land degradation and mitigation strategies (Source: Authors)

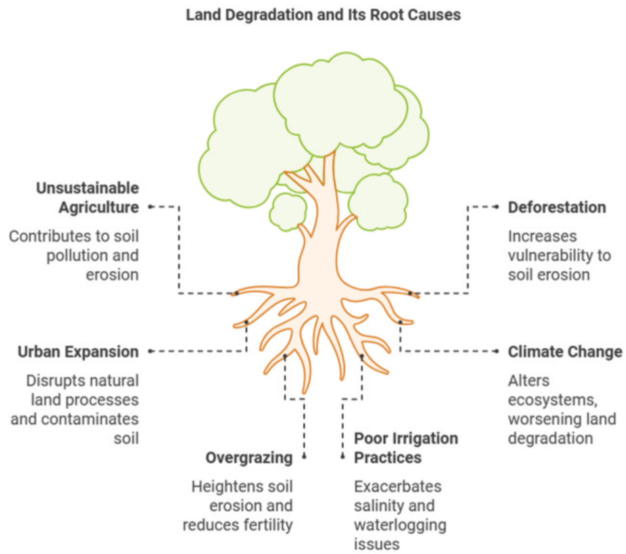

FIGURE 2 Interconnected issues to land degradation (Source: Authors)

phosphorus, and potassium are lost more rapidly than they can be replenished (Musa *et al*., 2024). For example, in Northeast China, soil fertility declined by 4.46% between the 1990s and 2010s, with minimal declines observed in cultivated lands, emphasizing the impact of land-use practices on soil health (Xiong *et al*., 2023). Strategies like cover cropping / green manuring have been shown to improve soil fertility by increasing organic matter and nutrient availability, mitigating some of the adverse effects of erosion. Additionally, specific agricultural activities, such as tuber crops harvesting (e.g., sugar beet, potato), have been recognized as significant but often overlooked contributors to soil erosion and loss, underlining the need for comprehensive soil conservation measures (Saggau *et al.,* 2024). Tackling these interconnected issues requires a multifaceted strategy involving SLM practices and technological innovations (Barman *et al*., 2024).

Long-term salinization and waterlogging severely hinder agricultural productivity in arid regions by adversely affecting crop growth and yields. Salinity stress has been found to decrease the nutritional quality and yield of crops, causing physiological changes that lead to reduced photosynthesis and impaired nutrient uptake, especially in crops like maize and sunflower (Zhang *et al*., 2024). When combined, salinity and waterlogging intensify these adverse effects by osmotic stress, disrupting ion homeostasis and reducing stomatal conductance, further diminishing crop yields (Sachan *et al*., 2022). Poor irrigation practices, such as insufficient drainage, exacerbate soil salinity issues, currently affecting around 952 M ha worldwide (Ashford, 2023). To address these challenges, effective management strategies are crucial, including establishing optimal irrigation-to-drainage ratios to maintain soil health and ensure sustainable agricultural productivity in these susceptible regions (Peng *et al*., 2024).

The primary factors driving desertification and the expansion of arid lands in the 21st century are strongly tied to increasing greenhouse gas (GHG) emissions, thus, global warming and rising atmospheric aridity. Studies have shown that global drylands expanded by approximately 3.67% between 1950 and 2014, with around 4.5% of this growth attributed to GHG emissions, indicating a significant human impact on dryland dynamics (Gu, 2023). As aridity increases, ecosystems transition through various stages of vulnerability, resulting in soil degradation and vegetation loss, which heighten desertification risks, particularly in regions like Africa and East Asia (Sun, 2024). Key factors such as the diversity of vegetation cover and cattle density have been identified as significant predictors of desert expansion, emphasizing the intricate relationship between ecological and socioeconomic factors in driving these changes (Wu *et al*., 2022). Consequently, the interaction between climate change, land use practices, and ecological thresholds plays a critical role in the ongoing process of desertification.

2.2 | Agents of Land Degradation

The primary human activities driving global land degradation involve various practices that significantly impact soil health and ecosystem function. Unsustainable agricultural methods, such as the overuse of pesticides and excessive amounts of fertilizers, contribute to soil pollution and the degradation of agroecosystems, affecting an estimated 33% of global soils (Zalesny *et al*., 2021). Overgrazing and deforestation worsen soil erosion and heighten vulnerability to wind erosion, particularly in arid regions, leading to sand and dust storms (Zucca *et al*., 2022). Urban expansion and industrial activities, including mining and waste disposal, also contribute to soil contamination and disrupt natural land processes (Zalesny *et al*., 2021). Socio-political pressures and climate change create feedback loops that amplify land mismanagement, causing declines in soil productivity and biodiversity (Anālayo *et al*., 2023). These factors highlight the intricate link between human actions and environmental degradation.

Natural factors contributing to global land degradation include climate change (enhanced global warming is human induced, mostly using fossil fuels such as natural gas and coal), soil erosion, and regressive pedogenic processes. Climate change exacerbates land degradation by altering ecosystems and diminishing biological productivity, particularly in vulnerable regions like arid and semi-arid areas. Increased temperatures and shifts in precipitation patterns lead to soil salinization, nutrient imbalances, and erosion driven by wind and water (Roy *et al*., 2022). Soil erosion, primarily caused by natural agents such as water and wind, significantly reduces the topsoil layer critical for agricultural productivity (Farooq *et al*., 2023). Additionally, regressive pedogenic processes, including forming calcium carbonate and subsoil sodicity, impair soil health and crop yields, especially in semi-arid tropical regions (Pal, 2017). These natural factors interact with human activities, complicating efforts to manage and mitigate land degradation effectively.

2.3 | Impact of Land Degradation on Ecosystem and Human Livelihoods

Land degradation significantly affects both ecosystems and human livelihoods, leading to a reduction in essential ecosystem services that support community well-being. For instance, in Majuli, India, the degradation of cultural ecosystem services demonstrates how environmental decline can have irreversible consequences for rural populations, worsening their hardships during natural disasters like floods (Saikia & Goswami, 2024). In Ethiopia, shifts in land use have resulted in considerable economic losses, with degraded watersheds experiencing a decline in ecosystem service values by millions of dollars, primarily due to the loss of arable and grazing lands (Mekuria *et al.,* 2023). Furthermore, intensive agricultural practices contribute to soil degradation, compromising soil health and its ability to support life, thereby threatening food security and public health on a global scale (Sprunger, 2023). In India, land degradation impacts more than 120 M ha, underscoring the urgent need for sustainable practices like agroforestry pasture and perennial crops to restore productivity and enhance ecosystem services critical for food and livelihood security (Pandey, 2023; Jinger *et al*., 2023). Thus, tackling land degradation is vital for the sustainability of both ecosystems and human communities.

3 | GLOBAL PERSPECTIVES ON LAND DEGRADATION

3.1 | Hotspots of Land Degradation Worldwide

Global hotspots of land degradation span various regions and profoundly impact ecosystems and human livelihoods. Approximately 29% of the Earth's land area is estimated to be affected, with approximately 3.2 billion people residing in these regions, highlighting an urgent need for targeted interventions (Le *et al*., 2016). The southern Gobi Desert illustrates severe land degradation caused by climate change and human activities such as unsustainable farming practices and overgrazing, which further accelerate desertification and the formation of sand dunes and dust (Kim *et al*., 2022; Zucca *et al*., 2022). Additionally, soil erosion poses a critical risk, with anticipated increases in erosion rates leading to significant economic losses and challenges to food security, particularly in vulnerable regions like Africa and Asia (Sartori *et al*., 2024). To effectively address ongoing land degradation, it is vital to employ a combination of assessment methods to accurately identify these hotspots and develop informed management strategies (Jiang *et al*., 2024).

3.2 | Policies and Global Initiatives to Combat Land Degradation

Global initiatives and policies aimed at addressing land degradation focus on SLM and restoration practices, which are essential for improving agricultural productivity and enhancing ecosystem services. The United Nations Convention on Combating Desertification (UNCCD) requires signatory nations, including India, to achieve LDN by 2030, underscoring the importance of comprehensive national policies and localized implementation strategies (Sharma and Prakash, 2023; Pricope *et al*., 2022). Numerous programs have been launched to tackle degradation, emphasizing community involvement and incorporating socio-ecological frameworks for effective monitoring (Chaudhary, 2024; Haregeweyn *et al*., 2022). Although challenges persist, including rising rates of land degradation, recent data show a modest increase in forest cover and a decrease in degraded land due to effective policy interventions (Edrisi *et al*., 2022). The collective global efforts highlight the necessity for collaboration, research networks (national and international organizations), and the adoption of innovative practices coupled with informed policy decisions to combat land degradation and foster resilience among vulnerable communities (Pricope *et al*., 2022). The UNCCD (estd in 1994) is regarded as a groundbreaking sustainable development treaty that tackles both environmental and socio-economic issues (Chasek, 1997). It advocates for a Global Governance approach, fostering multi-actor networks and encouraging civil society participation in efforts to combat desertification (Rechkemmer, 2004). The UNCCD emphasizes the importance of public involvement in assessing and rehabilitating land degradation, promoting a bottom-up approach that integrates local insights with scientific expertise (Stringer *et al*., 2007). Nonetheless, the national-level implementation of participatory practices has been challenging, highlighting the necessity for better communication among researchers, practitioners, and policymakers (Stringer *et al*., 2007). Despite these obstacles, the UNCCD continues to be a vital strategic tool for development cooperation, serving as a framework for policies addressing desertification, drought, and SLM (Squires, 2017). In 2015, the 12th session of the Conference of the Parties (COPs) UNCCD COP[12] adopted 35 decisions related to desertification, land degradation, and drought. These included how to pursue UNCCD (LDN) within the framework of the SDGs and how to align UNCCD goals and the actions of Parties with the SDGs.

SDG 15.3 addresses land degradation and encourages land restoration to achieve LDN, which is essential for preserving ecosystem services and biodiversity. This goal holds particular significance in light of the growing global population and economic development, which places increasing demands on land resources for agriculture and livestock production, resulting in environmental harm and loss of biodiversity (Schillaci *et al*., 2022; Fitawek and Hendriks, 2024). The UNCCD has developed an indicator framework to monitor progress, focusing on the ratio of degraded land to the total land area (Schillaci *et al*., 2022).

Recent evaluations have demonstrated that higher spatial resolution data can provide a more precise assessment of land degradation, identifying up to 40% more degraded areas than previously recognized (Schillaci *et al*., 2022). Consequently, achieving SDG 15.3 requires comprehensive approaches that integrate climate-smart agricultural practices and foster community engagement to combat land degradation while ensuring food security (Fitawek and Hendriks, 2024).

The LDN is an essential principle focused on reconciling land degradation with restoration efforts, ensuring no net loss of land-based natural capital, thereby contributing to the fulfillment of SDGs. Introduced under the UNCCD, LDN underscores the need for comprehensive evaluation of land systems that integrate biophysical and socio-economic factors to guide planning and monitoring initiatives (Kust *et al*., 2017; Cowie *et al*., 2018). The framework advocates a hierarchical approach to addressing land degradation, emphasizing the steps of avoid, reduce, and reverse, which encourages the adoption of SLM practices and restoration efforts tailored to specific land types (Cowie *et al*., 2018; Kesavan *et al*., 2022). However, several challenges arise in implementing LDN, including the need for effective indicators, establishing baseline conditions, and addressing technical distinctions between restoration and rehabilitation (Thomas *et al*., 2023; Kesavan *et al*., 2022). Practical applications of LDN are illustrated in case studies from Madagascar and Italy, which highlight the importance of engaging multiple stakeholders and employing adaptive management strategies to achieve successful results (Chasek *et al*., 2019; Kesavan *et al*., 2022) (Fig. 3).

4 | LOCAL SOLUTIONS AND COMMUNITY - BASED APPROACHES

4.1 | Agroecological and Sustainable Farming Practices

Agroecological and sustainable farming techniques play a crucial role in addressing desertification and land degradation, especially in arid and semi-arid areas. Effective strategies encompass agroforestry, conservation agriculture, cover cropping, and sustainable grazing, all of which improve soil health and enhance ecosystem resilience (Ali *et al*., 2024). The significance of soil microbiome is gaining recognition, as they aid in nutrient cycling, carbon sequestration, and soil stabilization, thus boosting land productivity and reducing the impacts of desertification (Islam *et al*., 2024). In Africa, employing participatory methods alongside Indigenous and Local Knowledge (ILK) has proven successful in restoration efforts, resulting in enhanced vegetation and improved livelihoods for communities (Ben-Enukora and Ejem, 2024). In India, a shift from conventional, input-heavy farming to practices like zero-till drilling and the application of biopesticides has shown potential in mitigating land degradation (Chaudhuri *et al*., 2023; Jayaraman *et al*., 2021; Jayaraman and Dalal, 2021). Collectively, these approaches underscore the importance of comprehensive policies and community involvement to promote SLM and effectively tackle desertification (Nwer *et al*., 2021) (Fig. 4).

4.1.1 | *Conservation Agriculture*

Conservation agriculture (CA) is one of the crucial approaches to tackling land degradation while addressing the challenges of environmental sustainability and food security. By utilizing techniques such as minimal soil disturbance, maintaining permanent soil cover, and implementing crop rotation, CA improves soil health, boosts soil organic carbon (SOC) levels, and fosters biodiversity (Jayaraman and Dalal, 2021; Jayaraman *et al.,* 2021; Naorem *et al*., 2023). This helps to alleviate the negative impacts of traditional agricultural practices, which often lead to soil erosion and loss of fertility (Francaviglia *et al*., 2023). Studies suggest that CA can enhance crop productivity by anywhere from 3.8% to 76.2% and significantly improve water productivity, thus contributing to SDGs and efforts to mitigate climate change (Kumawat *et al*., 2023; Francaviglia *et al*., 2023). Additionally, CA practices have demonstrated effectiveness in restoring soil organic matter and enhancing soil structure, both essential for preserving ecosystem services and building resilience to climate change (Mondal *et al*., 2024). Nevertheless, the widespread adoption of CA is hindered by socio-economic and technical challenges, which must be

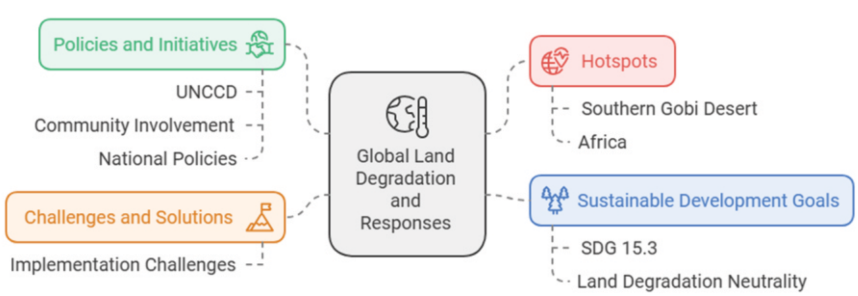

FIGURE 3 Adoption of multi-pronged approach in addressing land degradation (Source: Authors)

addressed through supportive policies and educational initiatives to fully realize its potential for rehabilitating degraded lands (Francaviglia *et al*., 2023).

4.1.2 | *Organic Farming and Permaculture*

Organic farming and permaculture are gaining recognition as effective methods for addressing land degradation while improving soil health and biodiversity. Organic farming focuses on sustainable techniques, including crop rotation, the application of animal manures, and biological pest management. These practices work together to enhance soil structure, fertility, and microbial activity, thereby lessening the negative environmental impacts associated with conventional agriculture (Raj *et al*., 2024). In contrast, permaculture advocates for a comprehensive design framework that incorporates ecological principles, leading to significantly greater soil carbon storage and biodiversity when compared to traditional farming systems (Fiebrig *et al*., 2020). For example, permaculture sites have shown a 27% increase in soil carbon levels and recorded 201% rise in earthworm populations, both indicators of improved soil quality and ecosystem health (Krebs *et al*., 2024). Both approaches not only enhance immediate agricultural yields but also promote long-term sustainability by rehabilitating degraded lands and bolstering resilience to climate change (Pinto *et al*., 2023).

4.2 | Soil and Water Conservation Techniques

4.2.1 | *Contour Farming, Terracing, and Check Dams*

Contour farming, terracing, and the construction of check dams are effective techniques for addressing land degradation, especially in at-risk agricultural areas. Check dams are commonly employed for soil conservation and erosion control; they improve water retention and reduce sediment buildup, ultimately boosting agricultural productivity and ecosystem vitality (Lucas-Borja, 2023). In the Moldavian Plateau, the decline of contour farming practices has intensified soil erosion, underscoring the urgent need for effective soil conservation strategies to combat degradation (Niacsu *et al.,* 2021). Likewise, terracing stabilizes slopes and minimizes runoff, which is vital in regions experiencing significant land degradation (Chaudhary, 2024). In regions with high rainfall, such as the Nilgiris hills of Tamil Nadu, inward bench terracing with a longitudinal gradient of 2.5% to 1% is recommended to ensure safe water disposal (Madhu *et al.,* 2021). It was found that 5% outward sloped bench terraces with rosemary achieved the highest water conservation efficiency (96%), while 10% outward sloped bench terraces with grass (permanent soil cover) and recommended nutrient management practices had the best soil conservation efficiency (98%) and nutrient retention. Therefore, the combination of these practices, along with community involvement and supportive policies, is crucial for effective SLM and restoration efforts. Initiatives in India aimed at achieving LDN by 2030 exemplify this approach (Sharma and Prakash, 2023). These methods enhance soil health, ensure water security, and bolster agricultural resilience in degraded environments.

4.2.2 | *Water Harvesting Structures and Micro-Irrigation*

Water harvesting techniques and micro-irrigation are vital in addressing land degradation, especially in arid and semi-

FIGURE 3 Adoption of multi-pronged approach in addressing land degradation (Source: Authors)

arid areas. In Jordan, micro-catchment water harvesting has been shown to increase soil moisture levels and foster the growth of native plant species, which in turn enhances soil microbial diversity and boosts overall ecosystem health (Tatsumi *et al*., 2021). These systems effectively capture and concentrate rainwater, reducing runoff and erosion while improving water availability for agricultural crops (Thakur and Grendler, 2022). In India, research has highlighted the capacity of water harvesting structures to recharge groundwater, with notable differences in recharge potential influenced by geomorphological and catchment factors (Raskar *et al.,* 2020). Additionally, using low-impact runoff harvesting systems can potentially rehabilitate degraded rangelands by replicating natural hydrological processes, thereby promoting vegetation recovery and enhancing soil stability (Stavi *et al.,* 2020). Together, these strategies help mitigate land degradation and encourage SLM practices.

4.3 | Reforestation and Afforestation Initiatives

Numerous studies have evidenced that reforestation and afforestation efforts are essential strategies in the fight against land degradation. These programs boost agricultural output and enhance environmental health by restoring vital ecosystem services and promoting biodiversity. For example, Greece's Agricultural Land Afforestation Program seeks to combat soil erosion and desertification by providing compensation for income losses during non-productive periods (Grillakis and Christoforidi, 2023). Similarly, Senegal's reducing emissions from deforestation and forest degradation (REDD) initiative focuses on tree planting and agroforestry practices to strengthen ecosystem resilience and encourage community involvement in forest management (Dieng *et al*., 2023). Additionally, global forest restoration initiatives have shown substantial socio-economic advantages, including carbon sequestration and protection of watersheds (Prati and Pomero, 2022). In India, a comprehensive strategy that combines local governance with national policies aims to achieve LDN by 2030, addressing the various factors contributing to land degradation across its diverse agro-climatic regions (Sharma and Prakash, 2023). These initiatives highlight the need to integrate ecological, economic, and social aspects into SLM practices (Chaudhary, 2024).

5 | ROLE OF TECHNOLOGY AND INNOVATION IN COMBATTING LAND DEGRADATION

5.1 | Remote Sensing and GIS Applications

Remote sensing and GIS technologies are vital in the fight against land degradation, offering powerful methods for monitoring and evaluating environmental changes. Research has shown that satellite imagery, including Sentinel-2 and Landsat, is effective in mapping the extent of degradation and identifying signs of agricultural stress, such as soil erosion and crop vitality (Ebrahimi *et al*., 2024). For example, Ebrahimi *et al*. (2024) developed degradation maps using spectral indices, while Al-Mulla *et al*. (2024) demonstrated the rapid assessment capabilities of remote sensing in agricultural monitoring. Furthermore, machine learning algorithms improve the identification of land degradation trends, enabling timely responses and promoting SLM practices (Hediyalad *et al*., 2024). GIS tools also enhance spatial analysis of soil erosion and support planning conservation strategies, emphasizing the importance of integrating these technologies to tackle land degradation issues (Chokshi, 2023). In summary, the synergy of remote sensing, GIS, and machine learning offers a robust framework for effective land management and conservation initiatives.

5.2 | Use of Soil Amendments and Organic Matter Addition

The application of soil amendments and organic matter is an essential approach to address land degradation, improve soil quality, and encourage sustainable agricultural practices. Organic materials such as compost, crop residue, biochar, and manure significantly enhance the physico-chemical properties of soil, including nutrient retention, microbial activity, and organic matter levels, which are crucial for rehabilitating degraded soils (Rani and Kapoor, 2024; Larsen *et al.,* 2024; Matisic *et al*., 2024). For example, incorporating compost and biochar has been found to boost soil dissolved organic carbon while decreasing CO_2 emissions, promoting healthier plant growth and resilience in compromised ecosystems (Larsen *et al*., 2024). Additionally, these organic amendments improve water retention, optimize pH levels, and facilitate carbon sequestration, contributing to the long-term health and productivity of the soil (Matisic *et al*., 2024; Aboukila *et al.,* 2024). Utilizing a range of organic materials, including agricultural and urban waste, not only speeds up soil restoration but also fosters sustainable practices by recycling nutrients and minimizing dependence on chemical fertilizers (Bharti *et al*., 2023). In summary, the thoughtful use of organic amendments is crucial for rehabilitating degraded lands and securing sustainable agricultural futures.

5.3 | Digital Solutions: Precision Agriculture and Monitoring Tools

Digital technologies, especially precision agriculture and monitoring tools, are vital in the fight against land degradation by improving soil health management and maximizing resource utilization. Innovations such as IoT sensors, remote sensing, and machine learning algorithms enable real-time soil condition monitoring, allowing farmers to make well-informed decisions about irrigation and fertilization, which can significantly enhance crop yields and land productivity (Naorem *et al.,* 2024; Levin, 2024). For example, Earth Observing System data analytics (EOS DA) supports effective benchmarking of crop health and monitoring of degraded soils, thereby fostering sustainable farming practices (Oymatov *et al.,* 2023). Furthermore, tools like the Multi-Layered Land Degradation Tracer (ML-LDT) leverage machine learning to predict land degradation patterns, offering valuable insights for implementing effective interventions (Kim, 2023). Overall, these digital advancements signify a significant shift toward sustainable agricultural practices, effectively tackling the issues of declining soil quality and rising environmental challenges (Anshu and Kumar, 2024).

6 | Challenges and Limitations in Addressing Land Degradation

Climate change-driven land degradation and desertification threaten food production systems and ecosystem services. Several challenges arise in the implementation of LDN, including the need for effective indicators, establishing baseline conditions, and addressing technical distinctions between restoration and rehabilitation. Making people and productive landscapes resilient to drought is a core mandate of the UNCCD, which is fully supported by the national and international organization through its strategy, and relevant programs and projects.

Challenges such as poor funding for government-aided projects, socio-economic conditions, climate change-driven land use change, not adopting appropriate soil and water conservation measures / SLM / land use policy, lack of coordination between national and international organizations despite the sincere efforts made by UNCCD in tackling the serious issue of land degradation. Countries / regions / projects need to keep the balance (trade-off) between short-term benefits and long-term sustainability while addressing land degradation.

7 | FUTURE DIRECTIONS AND RECOMMENDATIONS

UNCCD is committed to a bottom-up approach to combating desertification and land degradation, involving the participation of local people and farming communities. This review article highlights the following future directions and the way forward.

- Land degradation comprises physical, chemical, and biological degradation, so a holistic approach is required to tackle this issue (i.e., reduce, reverse, and restore land degradation).
- Multi-dimensional preventive/combating strategies with co-beneficial activities are essential to addressing land degradation vis-à-vis focusing on major land use sectors of the region / country.
- Identifying (areas and degradation processes analysis) and mapping degraded areas using latest tools and techniques, setting target areas and devising 'Sustainable Land Management (SLM) / Landscape Restoration Approach (LRA)' is the need of the hour.
- Restoration efforts should be based on suitable nature-based eco-restoration models with a focus on sustainable natural resource management and livelihood improvement of the farming community (Sometimes, indigenous nature-based local solutions may be tapped for reversing land degradation). Besides, protecting ecologically productive land from other uses via appropriate legal mechanisms (a need for soil law and Governance, national land use policy) (NASS, 2022; Desai, 2023).
- A farmer-centric approach (participatory-public-private partnership, in a PPP mode) is required to address land degradation issues. We need to consider biophysical conditions, different agroclimatic conditions, major soil types, and land use while developing strategic solutions.
- Voluntary targets to achieve LDN involving a multi-ministerial / multi-disciplinary approach- needs priority and funding by each nation / country to safeguard land resources for providing food and nutritional security to growing populations.
- In 2011, the International Union for the Conservation of Nature (IUCN) and the Government of Germany launched the Bonn Challenge, targeting the restoration of 150 M ha of deforested and degraded land by 2020 and 350 M ha by 2030. India took the challenge and pledged to restore 26 M ha of degraded land by 2030. Therefore, our efforts, targets, vision, and actions should be top priorities to achieve the restoration of degraded lands.

5 | CONCLUSIONS

Land degradation and desertification are the major threats to the food production system, economic stability, community viability, and the environment. About 29% of the Earth's land area is affected, with ~ 3.2 billion people residing in these regions, necessitating an urgent need for sustainable interventions. Natural and anthropogenic factors contributing to global land degradation include climate change, soil erosion, and regressive pedogenic processes. Land degradation has been exacerbated by climate change-driven extreme events and human activities such as unsustainable farming practices (deforestation / overgrazing), further accelerating desertification and forming sand dunes and dust. Additionally, soil erosion poses a critical risk, with anticipated increases in erosion rates leading to significant economic losses and challenges to food security, particularly in vulnerable regions such as Africa and Asia. Climate change exacerbates land degradation by altering ecosystems and diminishing biological productivity, particularly in vulnerable regions like arid and semi-arid areas. Increased temperatures and shifts in precipitation patterns lead to soil salinization, soil acidification, nutrient imbalances, and erosion-driven most-fertile topsoil loss by wind and water.

Therefore, SLM is essential to reducing soil erosion, reversing land degradation, and achieving LDN. Moreover, the Sustainable Development Goal (SDG, 15.3) addresses land degradation and encourages land restoration to achieve LDN, which is essential for preserving ecosystem services and biodiversity. Thus, a comprehensive approach is required that integrates climate-smart agricultural practices, ensuring permanent soil cover and fostering community engagement to combat land degradation while ensuring food and nutritional security.

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DATA AVAILABILITY STATEMENT

Not applicable.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR'S CONTRIBUTION

Conceptualization - SJ, AN, RCD; writing - original draft preparation, AN, SJ, RCD, NKS and MM; writing - review and editing, SJ, AN, RCD, NKS and MM, visualization, AN, SJ, RCD and MM. All authors have read and agreed to the published version of the manuscript.

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ORIGINAL ARTICLE

Indian Journal of Soil Conservation

Evaluating ecologically important bamboo species for the pulp and paper industry

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ABSTRACT

Bamboo is used worldwide to rehabilitate degraded lands because of its fast growth, effective rooting system, and ability to prevent soil erosion. The pulp and paper industry has been experiencing an acute shortage of raw materials for the last two years. In such a scenario, bamboo could significantly bridge the supply gap, thereby relieving the paper industry. Keeping the above in view, Kuantum Papers Limited, Punjab, has recently focused on using bamboo in its production system to cater to its needs. The mill's current share of bamboo in its total furnishing is around 10-15%, around 85 tons per day. The present study, therefore, focused on evaluating ecologically important bamboo species viz., *Bambusa balcooa, Bambusa vulgaris, Bambusa tulda, Dendrocalamus hamiltonii, Dendrocalamus strictus,* and *Melocana baccifera* in terms of their suitability to meet industry demands for strength, fiber quality, and yield for pulp production. These species were procured from different parts of the country. Results revealed that the properties of the species vary to some extent even after keeping all the conditions constant, like cooking temperature, time, and steaming temperature. The brightness of unbleached pulp for *B. tulda* was highest (23.7), and for *B. balcooa* was lowest (19.2). The screen pulp yield was highest in *M. baccifera* (51.4%) and lowest in *D. hamiltonii* (44.9%). The highest viscosity in unbleached pulp was observed in *B. Tulda* (27.9 cP) and lowest in *M. baccifera* (26.7 cP). The physical strength properties also vary from species to species. Burst Factor (BF) was highest in *D. hamiltonii* (52.77) and lowest in M. *baccifera* (35.67). The breaking length was highest in *D. hamiltonii* (6780 m) and lowest in *M. baccifera* (4900 m), whereas the tear factor was highest in *B. tulda* (105) and lowest in *B. balcooa* (79). The comparison between these varieties highlights the importance of understanding regional variation to optimize their utilization. Based on the study, specific recommendations can be made for cultivating bamboo on degraded lands to optimize environmental rehabilitation and industrial yield.

Key words:

Bamboo
Green gold
Physical strength properties
Pulp and paper industry
Tear factor

HIGHLIGHTS

- Bamboo is used worldwide for the rehabilitation of degraded lands.
- *M. baccifera* provided the highest screened pulp yield with the lowest breaking length and burst factor.
- *D. hamiltonii* and *B. tulda* are best suited for high-strength paper applications.
- *B. vulgaris* shows versatility, offering moderate to high strength and yield, making it an adaptable choice for various paper types.

1 | INTRODUCTION

Bamboo, commonly known as "Green gold" and "Poor man timber," is a widely used raw material in manufacturing industries due to its wide range of exploitable characteristics like fast growth and high fiber characteristics (Raikundlia and Sawlikar, 2022). In India, bamboo is grown on 15.69 M ha of land, It can grow from the seaside to an altitude range of 4000 m and tolerate a temperature range from 20^0-45^0C (Sharma *et al.,* 2009). The altitude range between 770-1080 m is the most suitable condition for its occurrence (Tewari *et* *al.,* 2019). It belongs to the subfamily Bambusoideae under the Poaceae family (Kaushal *et al.,* 2021). About 25% of bamboo species occurring worldwide are found in India (Chaudhary *et al.,* 2024). Bamboo has multiple other commercial and environmental significance. Its high demand in industry has created much attention among farmers and commercial growers, providing them a good source of income and employment opportunities to locals. It emerges as an essential raw material for pulping and papermaking to mitigate the shortage of wood resources, a major concern of pulp and paper industries (Chen Z *et al.,* 2018). It has high ash, low lignin, and excellent cellulose content, which helps to make excellent pulp yield (Shamsuri, 2021). Despite bamboo's numerous commercial and environmental benefits, it has not yet achieved the same level of acceptance among farmers as more commonly cultivated species like Eucalyptus, Poplar, and Shisham (Shrivastav and Tomar, 2020). Despite India being abundant in natural bamboo resources, it is a net importer of bamboo. Globally, the market for sustainable products has been on the rise, as there has been an increasing awareness about sustainable consumption. Although the demand for bamboo has been high since post covid, industries like pulp and paper that use it as raw material are facing challenges in procuring it, especially the industries located in the Northern part of India. The global demand for paper, which was 242.79 Mt in 1990, increased to 402 Mt in 2011, and the industrial demand for raw materials was 153 M cu m, against which internal market supply was only 60 M cu m. In contrast, the global consumption of paper and paperboard totaled 417 Mt in 2021. Consumption is projected to continue rising over the coming decade to reach 476 Mt by 2032; therefore, there is a need to promote species like bamboo that proliferate and have short rotation periods (Sharma *et al.,* 2024).

Bamboo's dense root systems stabilize soil and mitigate erosion, making it a valuable asset in restoring degraded lands (Kaushal *et al.,* 2020). Bamboo offers strength properties to the paper and makes it better than the one made without adding bamboo; it has a long fiber length, making it suitable for pulping (Netto *et al.,* 2024). It has lower ecological footprints, and its ability to use various paper-making processes underscores its suitability as a viable alternative to conventional pulp sources. While research on the role of bamboo in rehabilitating degraded lands is well-documented, studies specifically addressing bamboo's pulp quality parameters are limited. Recognizing this gap, our study focuses on screening ecologically important bamboo species such as, *Bambusa balcooa, Bambusa vulgaris, Bambusa tulda*, *Dendrocalamus hamiltonii*, *Dendrocalamus strictus,* and *Melocana baccifera* to evaluate their suitability to meet industry demands for strength, fiber quality and yield for pulp production. This dual focus will contribute valuable insights into species-specific pulp qualities and support sustainable resource management by highlighting bamboo's potential as a raw material that aligns with environmental restoration objectives.

2 | MATERIALS AND METHODS

The study focused on evaluating the physical and chemical properties of different bamboo species, *viz., Bambusa balcooa, Bambusa vulgaris, Bambusa tulda*, *Dendrocalamus hamiltonii*, *Dendrocalamus strictus,* and *Melocana baccifera*. The bamboo species used for the study studies were procured from different sources from Nagaland (*M. baccifera, D. strictus* and *B. tulda)*, Assam (*B. balcooa*), Himachal Pradesh (*D. hamiltonii*) and Uttarakhand (*B. vulgaris*). The details of the collected bamboo samples, along with climatic and soil conditions, are given in Table 1.

The physical and chemical tests on collected samples were done in the quality control laboratory (DSIR Approved) of Kuantum Papers Limited, Saila Khurd, Hoshiarpur, Punjab. Before converting the raw material into chips form, the material was checked for its suitability for pulping. Raw materials' quality directly affects the final product's quality and physical appearance. Equal amount of chips after proper chipping was taken taken and cooked in the sodium hydroxide solution as per the details given in (Table 2).

The pulping of different species of bamboo collected was carried out using Autoclave bomb digester followed by bleaching in ODoEopD1P sequence. The observations at

TABLE 1 Climatic and soil conditions of the different locations

Species	Location	Altitude (above MSL)	Average rainfall (mm)	Temperature Range (°C)	Soil
Melocana baccifera	Farmer Field, Mariani (Nagaland)	1025 m	1800 - 2500	21-40	Fine clay, clay loamy, and the fine loamy clay
Dendrocalamus strictus	Farmer Field, Mariani, (Nagaland)	1025 m	1800-2500	21-40	Fine clay, clay loamy, and the fine loamy clay
Bambusa tulda	Farmer Field, Mariani, (Nagaland)	1025 m	1800-2500	21-40	Fine clay, clay loamy, and the fine loamy clay
Bambusa balcooa	Farmer Field, Pathsala (Assam)	1960 m	1660-1830	20-30	Sand (coarse to fine) and clay
Dendrocalamus hamiltonii	Farmer Field, Arla, Palampur (HP)	1254 m	2909-3800	16-22	Loam to clayey-loam
Bambusa vulgaris	FRI Nursery, Dehradun (Uttarakhand)	640 m	2051-2200	0-33.8	Sandy loam to sandy clay loam

each stage were carried out using standard methods, as mentioned below:

1. Optical Properties *i.e.* Brightness Measured as per TAPPI (Technical Association of the Pulp and Paper Industry) Test Method (T-218) using Instrument Konica Minolta.
2. Viscosity of pulp measured using TAPPI Test Method (T-230), Capillary viscometer Method.
3. Screened Yield and Black Liquor characteristics were measured using the CPPRI Laboratory Manual of Testing Procedures 2001.
4. Physical Strength properties, i.e., Tear, Tensile, and Bursting Strength, measured using TAPPI Methods.
5. Freeness of pulp measured using Degree SR, Schopper Reigler (ISO-5267).

3 | RESULT AND DISCUSSION

The results for all the tested species are summarized in Table 3-6. The properties of these samples were observed and analyzed from the initial stage to the final stage. *B. tulda* exhibited the highest brightness at 23.70±0.52%, followed closely by *D. strictus* at 23.30±0.99%, with *B. balcooa* having the lowest brightness at 18.20±0.78%. The screen pulp yield was highest in *M. baccifera, which* achieved the highest yield at 51.40±0.40%, while *D. hamiltonii* had the lowest at 44.90 ±1.94%. Viscosity values for unbleached pulp were fairly consistent across species, ranging from 26.70±0.01 cP for *M. baccifera* to 27.90±0.02 cP for *B. tulda* (Table 3).

TABLE 2 Pulping parameters and cooking chemicals for treating different bamboo species

Parameters		Unit
Pulping parameters	Raw Material O.D.	500 gm
Cooking chemical (White Liquor)	Active alkali as NaOH	21%
	Steaming Time	120 min
	Cooking Temp	165°C
	Cooking Time at 165°C	120 min

The characteristics of black liquor extracted from different bamboo species revealed differences in chemical parameters, including pH, chloride content, organic and inorganic composition, and silica content (Table 4). The pH levels range from 11.90±0.51 in *B. tulda* to 12.4±0.20 in *D. hamiltonii*, indicating slightly alkaline properties across all species. Chloride content as Cl varies, with *B. balcooa* showing the highest level at 3.40±0.11%, while *M. baccifera* has the lowest at 2.45±0.01%. Regarding organic and inorganic content, *B. balcooa* displays the highest organic content at 65.84±1.10 %, while the lowest is *B. tulda* with a value of 59.07±0.95. Conversely, *M. baccifera* has the highest inorganic content (40.03±0.62%), whereas the lowest is B. balcooa, with a value of 34.16±2.97%. Silica content is highest in *D. hamiltonii* at 0.90±0.04% and lowest in *B. vulgaris* at 0.36±0.09% (Table 4).

At the refining stage, the characteristics of six bamboo species revealed key differences in terms of Schopper degree (°SR), BF (burst factor), breaking length, and tear factor (Table 5). All species exhibited similar Degree SR values, with *B. balcooa*, *D. hamiltonii*, and *B. vulgaris* slightly higher at 31, compared to 30 for the other species. The BF (Burst Factor) values ranged from 35.67±1.78 for *M. baccifera* to 52.77±1.70 for *D. hamiltonii*, indicating superior strength of *D. hamiltonii* under pressure. *D. hamiltonii*

TABLE 3 Characteristics of unbleached pulp of different bamboo species

Bamboo species	Brightness (%)	Screened Pulp Yield (%)	Viscosity (cp)
Melocana baccifera	20.70±0.25^{b}	51.40±0.40^{a}	26.70±0.01^{e}
Dendrocalamus strictus	23.30±0.99^{a}	50.20±0.57^{ab}	27.80±0.01^{b}
Bambusa tulda	23.70±0.52^{a}	48.20±0.26^{bc}	27.90±0.02^{a}
Bambusa balcooa	18.20±0.78^{c}	46.40±0.53^{cd}	26.80±0.06^{d}
Dendrocalamus hamiltonii	19.90±0.50^{bc}	44.90±1.94^{d}	26.90±0.02^{c}
Bambusa vulgaris	19.10±0.36^{bc}	46.30±0.46^{cd}	27.80±0.02^{b}
CD (0.05)	1.93	2.79	0.09

TABLE 4 Characteristics of black liquor extracted from different bamboo species

Bamboo species	pH	Chlorides component (%)	Organic composition (%)	Inorganic composition (%)	Silica content (%)
Melocana baccifera	12.00±0.05^{a}	2.45±0.01^{c}	59.97±0.62^{c}	40.03±0.62^{ab}	0.62±0.06^{b}
Dendrocalamus strictus	12.10±0.10^{a}	2.74±0.01^{b}	61.06±0.98^{bc}	38.94±1.13^{abc}	0.56±0.03^{b}
Bambusa tulda	11.90±0.51^{a}	2.82±0.01^{b}	59.07±0.95^{c}	40.93±0.94^{a}	0.65±0.03^{b}
Bambusa balcooa	12.20±0.23^{a}	3.40±0.11^{a}	65.84±1.10^{a}	34.16±2.97^{c}	0.81±0.02^{a}
Dendrocalamus hamiltonii	12.40±0.20^{a}	2.55±0.03^{c}	64.71±1.15^{ab}	35.29±1.04^{bc}	0.90±0.04^{a}
Bambusa vulgaris	12.20±0.25^{a}	2.83±0.05^{b}	62.67±2.05^{ab}	37.33±1.07^{abc}	0.36±0.09^{c}
CD(0.05)	NS	0.17	3.81	4.69	0.15

TABLE 5 Characteristics of different varieties of bamboo at the Refining Stage

Bamboo species	Schopper degree (°SR)	Burst Factor (BF)	Breaking Length (m)	Tear Factor
Melocana baccifera	30.00±0.58[a]	35.67±1.78[c]	4900.00±100.00[c]	85.00±7.64[bc]
Dendrocalamus strictus	30.00±1.00[a]	45.75±1.96[b]	6007.00±314.93[b]	100.00±6.35[ab]
Bambusa tulda	30.00±0.57[a]	37.75±0.42[c]	5100.00±104.01[c]	105.00±2.65[a]
Bambusa balcooa	31.00±0.57[a]	48.86±1.05[ab]	6417.00±84.50[ab]	79.00±2.08[c]
Dendrocalamus hamiltonii	31.00±1.16[a]	52.77±1.70[a]	6780.00±72.34[a]	101.00±3.22[a]
Bambusa vulgaris	31.00±1.73[a]	45.80±1.67[b]	6098.00±154.07[b]	104±5.13[a]
CD(0.05)	NS	4.75	502.55	15.40

TABLE 6 Characteristics of different varieties of bamboo at P Stage

Bamboo species	Brightness (%)	Viscosity (cP)	Bleach Pulp Yield (%)
Melocana baccifera	85.50±0.38[b]	7.32±0.04[c]	49.16±0.38[a]
Dendrocalamus strictus	86.40±0.47[ab]	7.62±0.08[c]	47.75±0.24[a]
Bambusa tulda	86.70±0.42[ab]	7.03±0.09[c]	45.60±0.35[b]
Bambusa balcooa	87.50±0.4[a]	8.72±0.04[b]	43.30±0.75[c]
Dendrocalamus hamiltonii	86.50±0.40[ab]	9.24±0.03[b]	42.50±0.68[c]
Bambusa vulgaris	87.20±0.18[a]	12.3±0.60[a]	43.30±0.32[c]
CD(0.05)	1.21	0.79	1.53

showed the highest breaking length at 6780±73.24 m, indicating better fiber strength, followed by *B. balcooa* at 6417±84.50 m. Comparison of tear factor indicates that *B. tulda* had the highest tear factor of 105±2.65, followed closely by *B. vulgaris* (104±5.13) and *D. hamiltonii* (101± 3.22). The lowest tear factor of 79±2.08 was recorded in *B. balcooa,* indicating comparatively lower resistance to tearing. Overall, *D. hamiltonii* stands out for its superior BF, breaking length, and tear factor, making it particularly robust at the refining stage (Table 5).

The bamboo species display brightness, viscosity, and bleach pulp yield differences at the P stage. *B. balcooa* and *B. vulgaris* showed the highest brightness levels at 87.50± 0.40% and 87.20±0.18%, respectively. In contrast, *M. baccifera* showed a slightly lower brightness of 85.50± 0.38% (Table 6). Viscosity measurements vary significantly, with *B. vulgaris* showing the highest viscosity at 12.30±0.60 cP, followed by *D. hamiltonii* at 9.24±0.03 cP. In contrast, *B. tulda* has the lowest viscosity at 7.03±0.09 cP, indicating potential differences in fiber strength and flexibility between species. *M. baccifera* had the highest bleach pulp yield of 49.16±0.38%, while *D. hamiltonii* had the lowest yield at 42.50±0.68 %. Overall*, M. baccifera is the* optimal species for higher pulp yield, and *B. vulgaris* and *D. hamiltonii* for strong fiber characteristics through higher viscosity values.

Overall, the results revealed that *M. baccifera* provided the highest screened pulp yield (51.4%), but its strength properties were lower, with the lowest breaking length (4900 m) and burst factor among the species. This yield advantage makes it ideal for cost-effective, high-volume paper production where strength requirements may be more moderate. *D. strictus* had a high tear factor (100) and a moderate screened yield (50.2%), making it a balanced option for paper requiring strength and durability. *B. tulda* recorded the highest tear factor (105) and brightness in unbleached pulp (23.7), making it ideal for high-strength applications and quality paper that requires a brighter base. *B. balcooa* had the lowest tear factor (79) and lower brightness (19.2) and thus remains useful due to its moderate strength properties, which may suit cost-effective production for general-purpose paper. *D. hamiltonii* exhibited the highest burst factor (52.77) and breaking length (6780 m), highlighting its potential for high-strength applications, although it had the lowest screened yield (44.9%). *B. vulgaris* showed strong physical properties with a high tear factor (104) and moderate pulp yield, comparable to *D. strictus*, and thus is essential for its adaptability across applications, blending strength and yield effectively. Bamboo is a sustainable alternative for pulp and paper production, adding to the existing body of research that underscores bamboo's rapid growth and wide availability (Hidayati *et al.,* 2019). Similar studies confirm the commercial potential of bamboo, analyzing fiber dimensions and chemical and pulping properties across different species and countries. However, a comprehensive assessment across lesser-studied bamboo species is still needed to understand their suitability for papermaking fully. Results conform with the findings of Chaurasia *et al.* (2016) on *Melocanna baccifera* and Junior *et al.* (2019) on *Bambusa vulgaris*, who revealed that bamboo exhibits promising properties similar to traditional wood fibers.

The chemical composition of bamboo poses unique challenges and advantages for the pulping process. As Chen *et al.* (2019) noted, high ash and silica content can lead to equipment wear and increased recovery costs. Bamboo's high lignin levels (27-29%) require longer cooking times and more chemicals for effective delignification (Mansouri *et al.,* 2012; Rowell *et al.,* 2012). The high extractives content, such as organic and inorganic in bamboo, also reflects the presence of low molecular weight carbohydrates and other constituents, affecting the efficiency of the pulping process (González *et al.,* 2013). In mechanical testing, bamboo fibers generally showed slower tensile strength development than softwood pulps, likely due to bamboo's thicker-walled fibers that resist internal fibrillation (Khantayanuwong *et al.,* 2021). However, the tear strength of bamboo pulp was found to increase with the initial beating time, indicating the potential for durable paper products (Scott and Abbott, 1995). Further research has shown that bamboo's age and culm section influence its pulping properties. Suhaimi *et al.* (2022) and Yoon *et al.* (2006) demonstrated that younger bamboo yields more pulp, and the cellulose content is highest in the top section of older culms, enhancing its potential for pulp production. Silica, while problematic for equipment, remains underexplored in mitigation, suggesting a future research avenue (Liese and Tang, 2015). Chemical pre-treatments, such as sodium hydroxide soaking, have improved pulp yield, SR degree (freeness), and brightness (Ainun *et al.,* 2018). Such advancements may reduce dependency on harsh bleaching processes, making bamboo a more viable alternative to wood in papermaking. The findings collectively indicate that optimized handling of bamboo's unique properties holds significant potential as a sustainable raw material for the paper industry. This diversity in properties across species allows the pulp and paper industry to tailor bamboo use to specific product needs, supporting specialized, high-strength papers and more general-purpose paper production while emphasizing sustainability.

5 | CONCLUSIONS

Integrating bamboo into the paper industry can lead to both environmental sustainability and the industry's long-term viability. From a technical perspective, bamboo fibers possess several properties that make them highly suitable for paper production. Bamboo for paper making generally employs lower chemicals during the pulping process due to low lignin content than the woody raw material. This helps reduce production costs and maximize production efficiency. Data from various bamboo species illustrate the potential of bamboo as a versatile resource for the pulp and paper industry, each species bringing unique qualities suited to different paper applications. *D. hamiltonii* and *B. tulda* are best suited for high-strength paper applications, while *M. baccifera* excels in pulp yield, making it more suitable for high-volume production. *B. vulgaris* shows versatility, offering moderate to high strength and yield, making it an adaptable choice for various paper types. Overall, it can be concluded that integrating bamboo into the pulp and paper supply chain creates a model of sustainable resource management that benefits the industry, environment, and society. As industries and governments prioritize sustainability, the role of bamboo in paper production will likely widen, contributing to a greener and more resilient future for the planet.

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DATA AVAILABILITY STATEMENT

The data generated and analyzed during the current study are available from the corresponding author upon reasonable request.

CONFLICT OF INTEREST

The authors have declared that there is no conflict of interest.

AUTHOR'S CONTRIBUTION

SKS carried out the research over the period and recorded data, whereas SKC and VKS arranged testing and analyzed the data. SC proofread the compiled documents and made corrections. KS laid out the research and analysis methods for this research, constantly proofreading and making additions and deductions. VA analyzed and compiled the data statistically. GK and BKN supervised the field research work.

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