Review Article

Comprehensive Assessment of Soil Erosion using USLE and Sustainable Management Strategies

Abstract

Continuous soil erosion from all parts of world through water and winds have become a severe concerns for soil scientists and geologists due to its adverse effect on soil productivity, water bodies siltation and deterioration of water quality. Therefore, it becomes most important to locate erosion-prone regions of any landscape and take the best measures to solve the issues of erosion. USLE and its modified models i.e. RUSLE (Revised Universal Soil Loss Equation) versions and MUSLE (Modified Universal Soil Loss Equation) are most commonly used for estimation of soil erosion. In India, soil erosion is a major serious concern which varies in its intensity depending on the country's different agro-climatic zones. USLE as well known model for evaluating soil deterioration is used in this review to provide an understanding of its parameters and how this approach is useful in soil erosion assessment. In addition, an overview of the current situation of erosion status in India which is being altered by regional variations like climate and land uses. Literature also dictates and discusses the potential advantages of better erosion control approaches, such as increased agricultural output and long-term land sustainability and looks at what might be possible in the future if the things get managed. The study also looks at crop selection and land use systems, emphasizing how crucial it is to choose crops that are suitable for the land vulnerability to erosion in order to prevent the further deterioration. Lastly, it emphasize on a thorough explanation of the USLE's parameters which are essential for precise erosion prediction including slope factors, soil erodibility, rainfall erosivity and conservation techniques. The study summarizes the knowledge on soil erosion in India and the necessity of customized, area-specific soil conservation plans to guarantee long-term agricultural outputs and sustainable agricultural goals.

Keywords: Soil erosion, sustainability goal, crop selection, USLE, RUSLE

Introduction

India, encompassed by different rivers and seasonal monsoons, has many soils formed through various natural processes such as precipitation, weathering, climate influences, and various complex soil geo-morphological interactions (Pal *et al.*, 2021). In India, more than 60 percent of people depend on agriculture to fulfill their needs and keep their socio-economic status up to a threshold level. So, it becomes quite apparent that higher dependency on agriculture to make returns will exploit the land areas and marine systems, thus causing serious problems like soil erosion, land degradation, mineral mining, and polluted water bodies. The national average erosion in India is estimated at 21 tons per hectare per year. The erosion phenomenon affects nearly 30 percent of the total area in a milder form. However, 3 percent would be affected by catastrophic soil loss (IIT New Delhi, 2024). This devastating loss can be directly attributed to anthropogenic interventions such as deforestation and intensive agricultural practices.

Controlling the extent of soil erosion is crucial in India because of the country's dependency on the agricultural sector, which employs around 158 million people. Therefore, it is vital for the economy. Generally, when the soil erodes initially, the fertile topsoil is lost which reduces the crop yields and threatens the food security in the country. In the past, natural erosion by wind and water has produced some of the World's most fertile soils, such as those in the Indo-Gangetic Plains, Nile Deltas and China Plateaus. However, the accelerated erosion caused by anthropogenic activities has severely triggered the ecosystem services and led to landscape fragmentation (Bhattacharyya *et al.*, 2016). India's diverse landscapes present unique challenges, from the arid deserts of Rajasthan to the lush wetlands of Kerala. Each region faces specific issues, such as water scarcity, soil degradation, and varying climate impacts, which require tailored approaches to address them effectively. As we move forward, embracing adaptive, localized strategies will be crucial in ensuring sustainable development and resilience in these varied environments. By prioritizing community-driven solutions, we can better navigate the complexities of India's diverse ecological tapestry and foster a more sustainable future. Soil erosion causes sediment accumulation in river basins and reservoirs every year, thus lowering their capacity to store water and affecting power generation efficiencies and irrigational facilities. Soil erosion occurs in various forms, such as sheet erosion, water erosion, mass erosion, landslides and terrace failures. The intensification of landslides due to human-based activities has been driven by numerous factors like vegetation removal, road or building construction, illegal mining and the development of hydropower projects (Mishra *et al.*, 2022). India's varying climatic features and landscape variability, from mountains to coastal plains, create a challenging situation for soil conservationists deliberately working on land and natural resources reclamation projects. Additionally, engaging communities and encouraging stakeholder collaboration are vital to supporting participatory erosion control methods and building resilience in specific vulnerable landscapes. Therefore, the present review discusses and highlights the extent of soil erosion and its assessment in different agro-climatic regions of India.

Overview of USLE & RUSLE

Soils provide numerous ecosystem services and goods, *i.e.*, a) producing food, fiber and other biomass; b) interacting with the environment through water filtration, carbon storage and nutrient transformation; c) serving as a biological habitat; d) supplying raw materials; e) contributing to physical and cultural heritage; e) serving as a foundation for human-made structures like buildings and roads (Poesen, 2018). Soil erosion is a severe and escalating issue in India with far-reaching consequences on agriculture, the environment and the economy. Implementing effective soil erosion control measures is crucial to mitigate such previous matters addressed.

This model of soil erosion measurement was proposed by Wischmeier & Smith in 1978. It is a globally acceptable approach and used as a tool in soil erosion research, as it offers a systematic approach to measuring erosion rates and identifying thematic areas susceptible to erosion. By integrating the meteorological data, soil properties, land use patterns, and agriculture conservation practices, USLE helps evaluate the soil loss potential and pinpoints various critical areas for erosion control and land management. Addressing the extent of soil erosion is crucial for achieving sustainable development goals and environmental stewardship. Reducing erosion risks demands a comprehensive strategy comprised of land-use planning, soil conservation techniques, reforestation projects and sustainable farming practices. USLE approach was primarily used at plot scale for agricultural plots in the United States of America in 1978, and since then, this approach has provided promising results on erosion measurement.

RUSLE, an updated version of USLE was introduced, and this model included detailed soil erosivity maps for precise erosion estimation. This model also added the variations in soil erodibility caused by moisture imbalances caused by precipitation and freezing actions. RSULE method is a computer based model programmed to handle complex datasets from farm and measures the soil loss that occurred per unit area in a yearly period. The MUSLE is an extension that works at a finer resolution by using the runoff and peak flow rate to estimate event-based soil loss (Sadeghi *et al.*, 2014). RUSLE method is globally known for its low data requirements and simple result interpretations. These simpler interpretations encourage the policymakers to think and retaliate for maximum possible solutions from both agricultural and non-agricultural points of view. The RUSLE as an empirical model, briefly discussed in numerous reviews of soil erosion modeling and model types that have been published. Components of this model are frequently integrated into more intricate conceptual or physics-based soil erosion models (Aksoy and Kavvas, 2005).

USLE parameters

Soil erosion models aid in land use planning and management by elucidating the areas vulnerable to soil erosion, estimating potential erosion rates, and identifying possible causes of soil erosion. The Universal Soil Loss Equation estimates the long-term average annual soil loss (tons per unit area) from sheet and rill erosion by considering six essential factors related to climate, soil, topography, vegetation and management practices (Pham *et al.*, 2018).).
USLE is given as:

$$A= R\times K\times L\times S\times C\times P$$

Where A = Average annual soil loss (tons/ha/year); R = Erosivity caused by rainfall (It represents the effect that rainfall has on soil erosion and was included after observing sediment deposits after an intense storm); K = Soil erodibility factor (It means the influence of different soil properties on the slope's susceptibility to erosion); L = Slope length factor; S = Slope steepness and topographic factor (L and S factor, which is the ratio of the anticipated soil loss from a field slope to the initial USLE unit plot, shows how the slope's length and steepness affect sheet, rill, and inter-rill erosion by water); C = Crop management factor (Ratio of soil loss between a field under "clean-tilled continuous fallow" and one with a specific cover and management); P = Practice support factor (Ratio of soil loss in a field with up slope and down slope tillage to that under a certain soil conservation technique (such as terracing or contouring).

Although USLE was initially used for agricultural land at the small farm plot scale, it has been applied in numerous nations under a wide range of geo-climatic zones. The original USLE is more accurate for soils of a medium in texture and slopes (<400 fts in length) with a 3-18 percent gradient. Despite the name suggesting that the model can be applied to all soils, it is maintained with regular cropping practices which are well represented in plot scales (Wischmeier and Smith, 1978). Therefore, it is necessary to carefully parameterize the model and be aware of the increased uncertainty in model predictions when applying the USLE family of models to soils and sites that exceed these boundaries. Factors used by USLE are geographic. These factors can be quickly and efficiently calculated using a geographical information system (GIS), which incorporates various data layers such as watershed boundaries, slope, rainfall distribution, land use, management practices and soil types. By combining these data layers, GIS enables the calculation of soil erosion for each pixel (Chandramohan and Durbude, 2002). The USLE was initially developed to estimate the soil erosion on gently sloping cultivated land in the Mid-West, USA (Renard *et al.,* 1997). The RUSLE has been designed with a structure similar to the USLE, incorporating several enhancements in identifying input factors using an updated database in the United States.

Limitations of (R)USLE

The (R)USLE model's limited application to areas outside of the United States of America is the most frequently mentioned drawback (Sadeghi et al., 2014). Soil erosion research conducted on US agricultural land served as the foundation for the original USLE. However, estimates of average annual soil loss may become more imprecise when applied to various climatic regimes and land cover situations other than the US region (Kinnell, 2010). Upscaling the original USLE to the catchment or regional scale is not without its uncertainties (Naipal *et al.,* 2015). Additionally, Wischmeier and Smith (1987) cautioned that extrapolation error could result from applying the (R)USLE under circumstances dissimilar from the agricultural conditions under which the model was developed. The incapacity of models to capture the intricate relationships involved in soil loss, the scarcity of long-term, trustworthy data for modelling and the absence of soil erosion observational data for model validation, particularly in data-scarce environments are the main causes of the uncertainties surrounding the (R)USLE and, it can be argued, soil erosion modelling in general.

Nutrients depletion through erosion

Deterioration of soil attributes associated with soil productivity and the quality of natural resources is commonly called land degradation (Shubham *et al.,* 2023). Furthermore, soil compaction, erosion, loss of biodiversity, acidification, alkalization, depletion of soil nutrients and decrease in soil organic matter (SOM) are some of the typical examples (Acharya *et al.,* 2009). There are numerous physic-chemical and biological processes which are either directly or indirectly brought on by anthropogenic activities cause land degradation. One of the biggest problems facing land managers is land degradation, which includes soil erosion, and it affects around 60 per cent of the world's land surface. For instance, soil erosion is a severe issue that have raised serious worries all around the world (Guerra *et al.,* 2017). Over the years, agricultural soils have been continuously degrading to severe extent and the necessity to use the forest resources to meet the people demand for basic food has grown. As per the reports global population is projected to outreach 9.6 billion people by 2025, and to full fill the basic food requirement of such outnumbered population, agricultural production would needed to increase by 70 per cent (Shubham *et al.,* 2023). However, soil fertility has been severely weakened by farming practice like intensive farming and overuse of synthetic chemicals and as result soil erosion has been become a persistent issue for both the environment and agricultural sector (Gardner *et al.,* 2003). Here’s a table summarizing the erosion status across various Indian states:

Table 1: Summerizing the erosion status across various Indian states

State	Erosion Rate (t/ha/year)	Key Factors	Key Factors
Himachal Pradesh	30-50	High	Heavy rainfall, deforestation, steep slopes
Uttarakhand	25-45	Significant	Landslides, extreme weather events
Maharashtra	10-25	Moderate to High	Agricultural practices, deforestation
Karnataka	10-20	Varies (Moderate to High)	Monsoon rains, land-use changes
Rajasthan	5-15	Moderate	Wind erosion, water scarcity
Tamil Nadu	5-15	Moderate	Urbanization, agricultural expansion
Punjab	2-5	Generally Low	Intensive agriculture, localized issues
Haryana	2-5	Generally Low	Intensive agriculture, localized issues
Gujarat	10-20	Varies (Moderate)	Coastal erosion, sea-level rise
Bihar	10-20	Moderate	Flooding, sediment deposition
Uttar Pradesh	5-10	Moderate	Riverbank erosion, flooding
Odisha	20-30	High	Heavy rainfall, deforestation

This table provides a snapshot of the erosion status in different Indian states, highlighting the key factors contributing to soil erosion in each region. According to an estimate, soil erosion causes 1.7 mm of topsoil to be lost annually, yet it takes nearly 100 years to form one centimeter of soil (Gautam, 1993). Different rates of soil erosion are caused by variations in topography, changes in land use and cover, uneven rainfall distribution and demographic differences within the nation. The majority of soil minerals for plant nourishment are concentrated in the surface layers, and also impacted the most (Quansah *et al.*, 2000). Planning for the implementation of adaptive measures is necessary because the increased risks of soil erosion hazards brought on by climate change would have comparable detrimental effects on crop growth and yields, particularly in the tropics and sub-tropics, where the impacts of climate change would be more severe and small landholders with limited resources would not be able to adjust to the sudden changes in climate (Cline, 2007).

Extent of erosion through water and wind in India

There are several ways that nutrients might be lost. While less soluble nutrients like phosphorus are more likely to be lost with sediments moving in eroding soil and runoff water, soluble nutrients like potassium and nitrate can be lost in runoff and drainage water. The growth and life cycle of plants depends on the majority of the 17 essential nutrients. The primary nutrients that replenish soil fertility are N and P, which are lost due to water erosion together with Ca, Mg, K, and organic matter (Bertol & Miquelluti, 2003). Although total erosion prevention is unachievable, it can be reduced, and erosion management methods typically preserve or boost soil production. Transport of productive soil or erosion-induced reduction in productivity. They usually remove around three times as many nutrients from the soil as are still present. The average nitrogen content of a ton of fertile surface soil is 1-6 kilogram, 1-3 kg of phosphorus, and 2-30 kg of potassium; in contrast, the average nitrogen content of soil on eroded land is 0.1-0.5 kg per ton (Hopkins *et al.*, 2001).

Organic matter, clay partials, or soil in sand, silt, and clay ratio is disturbed with reduced fertility due to negligible loss from wind erosion (Mandal *et al.*, 2012). There are three distinct ways that silt is transported in wind erosion: creep, saltation, and suspension. The saltating grain bombardment starts the particles moving in creep, yet they are big enough to stay in constant contact with the soil surface. Since creep mostly moves coarse sand, which is low in nutrients, it is thought to not produce appreciable nutrient losses. Additionally, creep transit distances range from a few centimeters to several meters. The majority of saltating particles bounce just over the soil's surface before rising to a height of two meters. They can be moved between a few hundred and several hundred meters. From Bielders *et al.* (2002), we discover that the nearby bush acts as a sink for the majority of the silt and, consequently, the majority of the nutrients when wind erosion takes place in farmed areas. When the fallow is replanted for farming, water erosion may cause this sediment and the nutrients it contains to return, depending on the local terrain. Nitrogen dynamics and soil organic carbon (SOC) are impacted by topsoil loss that ultimately affects the soil's capacity to sequester carbon (Mendez *et al.*, 2006). One of the most critical steps in preserving soil quality and production is the conservation and maintenance of SOC contents. The small SOC pool of desert soils has also declined more quickly as a result of progressive land use trends shifting from natural rangeland ecosystems to arable farming in dryland areas and this decrease will only accelerate in the context of desertification processes linked to global climate

Advances in soil erosion modeling, climate impact on erosion patterns and GIS applications in erosion management

Several studies on advanced soil erosion modeling have increasingly focused on integrating technology and interdisciplinary approaches to improve predictions and management strategies. Here are some key trends and findings:

1. **Machine Learning and AI Integration:** Researchers use machine learning algorithms to enhance traditional soil erosion models like the Universal Soil Loss Equation (USLE) and its revised versions (RUSLE). These models are being combined with AI techniques to analyze large datasets, allowing for more accurate predictions of erosion under various climate scenarios.
2. **Remote Sensing and GIS:** Remote sensing technologies and Geographic Information Systems (GIS) are being employed to map erosion-prone areas. Studies have

demonstrated the effectiveness of using satellite imagery to assess land use changes, vegetation cover and rainfall patterns, which are crucial for understanding erosion dynamics.

3. **Impact of Climate Change:** Recent studies have highlighted how climate change alters erosion patterns. Increased rainfall intensity and changes in seasonal precipitation are causing shifts in erosion rates. Researchers are developing models that incorporate climate projections to predict future erosion scenarios.
4. **Integrated Watershed Management:** There's a growing emphasis on integrated approaches that consider the entire watershed. Studies are focusing on how land management practices, such as agroforestry and conservation tillage, can be modeled to assess their impact on soil erosion at a landscape scale.
5. **Soil Erosion Risk Assessment:** Advanced modeling techniques are being used to conduct risk assessments, identifying areas at high risk for soil erosion. This helps prioritize interventions and resource allocation for conservation practices.

Such studies focus on specific regions, such as the Himalayas, the Western Ghats, and Mediterranean regions, to understand localized erosion issues. These studies often include community engagement and participatory approaches to develop context-specific management strategies.

Selection of erosion-resistant cropping systems

The soil serves as a reservoir of water and nutrients, meeting the demands of plants throughout their growth and serving as a vital substrate for animal activity and plant growth. One of the soil's key roles is to collect water and hold onto it so that the plant roots may use it. The plants need a steady flow of water for photosynthesis, turgor maintenance, cooling and nutrient transportation (Bazilevskaya *et al.,* 2013). The unique properties of soil are derived from a combination of minerals and organic matter across the earth's surface. India's varied soil types have produced various agricultural techniques, with multiple crops and cropping systems tailored to specific soil types and climates (table 2). Soil conservation and management techniques are essential for the nation to maintain agricultural production and food security. India's huge geographical and climatic variances result in a broad spectrum of soils.

Table 2. Selection of Crops according to Soil types in different states of India

Types of Soils	States where found	Rich in	Lacks in	Crops grown
Alluvial soils	Mainly found in the plains of Gujarat, Punjab, Haryana, UP, Bihar, Jharkhand, etc.	Potash and Lime	Nitrogen and Phosphorous	Large variety of *rabi* and *kharif* crops such as wheat, rice, sugarcane, cotton and jute

Black soils/Regur soils	Deccan plateau: Maharashtra, Madhya Pradesh, Gujarat, Andhra Pradesh, Tamil Nadu, Valleys of Krishna, and Godavari.	Lime, Iron, Magnesia, Alumina and Potash	Phosphorous, nitrogen and organic matter	Cotton, sugarcane, jowar, tobacco, wheat and rice
Red soils	Eastern and Southern parts of the Deccan Plateau, Orissa, Chattisgarh, and Southern parts of the middle Ganga Plains	Iron and Potash	Nitrogen, phosphorus, sulphur and humus	Wheat, rice, cotton, sugarcane and pulses
Laterite soils	Karnataka, Kerala, Tamil Nadu, Madhya Pradesh, Assam and Orissa hills	Iron oxide and potash	Organic matter, nitrogen, phosphate and calcium	Cashew nuts, tea, coffee and rubber
Arid and Desert	Western Rajastan, North Gujarat and Southern Punjab	Soluble salts and phosphate	Humus and Nitrogen	Only drought resistant and salt-tolerant crops such as barley, rape, cotton, millets maize and pulses
Saline and Alkaline soils	Western Gujarat, Deltas of Eastern Coast, and Sunderban area of West Bengal, Punjab and Haryana	Sodium, potassium, and magnesium	Nitrogen and calcium	Barley, cotton, sugar beet, sugarcane, sorghum and rice,

Scenario of soil erosion extent in Indian agro-climatic zones

In India, soil erosion is a pervasive environmental issue that varies in intensity among states due to a variety of anthropogenic, climatic and geographic causes. Water erosion is the largest percentage of India's estimated 147 Mha of land that is degraded to varying degrees. Deforestation, unsustainable farming methods, heavy monsoon rains, and other natural causes are all directly related to the problems caused by soil erosion (Anonymous, 2024). Because of the high rainfall erosion during the monsoon season, soil erosion is particularly severe in North-Eastern states like Assam, Meghalaya, and Arunachal Pradesh (table 3). Heavy rainfall in these areas erodes the nutrients-rich topsoil, resulting in severe soil loss. The problem is made worse by the steep slopes and the common loamy and silt loamy soils, which are more prone to erosion. According to district-level data, Meghalaya's East Khasi Hills and other regions see some of the nation's highest erosivity levels due to heavy rains (Mongabay, 2024). Because of the steep terrain and seismic activity, the soil in the Himalayan region, including states like Jammu and Kashmir, Himachal Pradesh and Uttarakhand, is highly vulnerable to erosion. The issue is made worse by landslides and slope instability, which cause soil displacement, especially during the monsoon season. Deforestation and uncontrolled development further jeopardize the delicate ecosystems in these regions by upsetting the natural soil structure and making them more susceptible to erosion (Anonymous, 2023).

Table 3. Indian states cultivable area impacted by soil erosion

State	**Area (*in hectare*)**
Andhra Pradesh (including Telangana)	8093
Arunachal Pradesh	666
Assam	3248
Bihar	851
Chhatisgarh	3733
Delhi	28
Goa	1
Gujarat	984
Haryana	306
Himachal Pradesh	982
Jammu and Kashmir	1369
Jharkhand	3219
Karnataka	7522
Kerala	490
Madhya Pradesh	12262
Maharashtra	8799
Manipur	122
Meghalaya	302
Mizoram	-
Nagaland	46
Orissa	2227
Punjab	229
Rajasthan	19029
Sikkim	45
Tamil Nadu	2308
Tripura	109
Uttar Pradesh	13075
Uttarakhand	1018
West Bengal	1332
Total	92400

(Source: Anonymous, 2023)

Management practices of soil erosion in India

Because it is necessary for all life on Earth, soil is nature's most valuable resource. Prosperous agriculture, the cornerstone of economic growth and a higher standard of living in a community can only be ensured by a fertile soil base. Therefore, soil management and conservation are essential to ensuring that economic development is sustainable. All such actions that aid in preventing soil erosion and depletion are included in soil conservation. There are many different approaches that can be used to preserve this critical resource.

Management practices:

Management practices:

1. **Contour tillage:** Water erosion processes are accelerated on sloping farms by conventional tillage, which involves ploughing up and down the hill. The use of cultivation and tillage direction with respect to a field's contour lines, also known as contour farming, is a conservation method for lowering water erosion. The method is predicated on the idea that ridges created by tillage and seeding create an oriented roughness. Oriented roughness is improved by reducing the angle (0–90°) between contour lines and agricultural direction, which can lessen soil erosion and surface runoff (Stevens et al., 2009)
2. **Contour bunding:** For hilly, sloping, and marginal terrain where soil erosion is a concern, contour bunding is a tried-and-true sustainable land management technique (ICIMOD, 2013). In many areas, contour bunding significantly lowers soil erosion and surface runoff in agricultural watersheds. Runoff observations on 55 hectares of agricultural watershed treated with contour bunds in the Dehradun region revealed that the volume and peak of runoff were decreased by 62 and 40 per cent, respectively (Ram Babu *et al.,* 1980). Strip planting in a 2:1 maize to cowpea ratio was just as successful as graded contour bunding in reducing runoff by 43 to 37 per cent and soil loss by 21 to 11 t/ha (Bhardwaj, 1994).
3. **Strip cropping:** It is generally acknowledged that it is crucial for reducing runoff erosion and preserving soil fertility. Several good agricultural techniques, such as crop rotation, contour cultivation, appropriate tillage, stubble mulching, and cover crops, are used in strip cropping. To increase productivity and net return, soybeans grown as a strip crop (2:8 rows of maize and soybean) at a 4 percent slope with maize decreased runoff by 42 percent and soil loss by 54 per cent. Since soybeans are a crop that effectively resists erosion, they should either be cultivated in strips with maize in a ratio of two rows of maize to eight rows of soybeans, or they should be grown in place of maize (Singh *et al.*, 1979).
4. **Afforestation:** Forests are the most effective technique to preserve soil for future growth. Trees should not be cut down carelessly, and efforts should be made to replace trees in new locations. The five-year plan increased the minimum amount of forest land that is deemed healthy for soil and water conservation nationwide from 20 to 25 percent to 33 percent. It is advised that 20 percent of plain areas have forest cover, whereas 60 percent of hilly and mountainous regions should have forest cover (Saroha, 2017).

Conclusion

Assessment through USLE assesses the severe status of soil erosion in India's various agro-climatic zones. The significance of elements such as crop cover, slope length, rainfall erosivity and soil erodibility in determining erosion rates is shown by examining several USLE characteristics. Because of India's diverse agro-climate, erosion patterns vary, with wind erosion being more common in arid areas and water-induced erosion predominating in humid ones. Because eroded soils lose vital elements necessary for crop productivity, nutrient depletion from soil erosion is still a significant concern. In order to support sustainable land use, our review also emphasizes how crucial it is to choose crops appropriate for the soil type and erosion susceptibility in various zones. Crop rotation, mulching, terracing, contour farming, and other efficient management techniques have demonstrated promise in reducing erosion and preserving soil health. Future USLE applications can significantly enhance soil erosion estimation and facilitate focused interventions if they are improved to account for local differences and real-time monitoring technology. To protect soil resources and guarantee long-term agricultural viability, ongoing work toward adaptive soil conservation solutions catered to India's varied agro-climatic zones is essential.

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