Plant Bulletin, Vol 4, (2) 2025: 127-136 ISSN: 2959-3379 (Print), 2959-3387 (Online)

Review Article

Soil Erosion Challenges: Environmental Health and Sustainable Agriculture Solutions

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ABSTRACT
Soil erosion represents one of the most significant global threats to environmental integrity, agricultural productivity, and food security. Current estimates suggest that over 75 billion tonnes of soil are lost annually, with approximately one-third of the world's arable land classified as moderately to severely degraded. Besides decreasing the soil fertility, this process changes the hydrological cycles, enhancing the emission of greenhouse gases, and impacting national economies that rely on agriculture adversely. The current study is a synthesis of peer-reviewed materials, world soil data, and quantitative evaluations aimed at assessing the theory, cause, and effects of soil erosion as well as evaluation of the developing mitigation measures. Review uses an integrative structure integrating comparative case study, GIS-based modeling, and policy review to determine current gaps in the research field and evaluate the success of current interventions to protect the soil. The results indicate that current erosion control measures are scattered and regionally specific whereby there is inadequate integration of remote sensing, microbial stabilization of soils, and socio-economic assessment processes. To bring any meaningful improvements, new research and management approaches should be holistic and data-intensive, combining powerful models with participatory land-management and policy models. The general objective of this review is to improve the knowledge about the multifaceted mechanisms of soil erosion processes, to advance new, interdisciplinary approaches that will build soil erosion resilience and protect agricultural performance and environmentally sustainable stewardship, both locally and globally.
Keywords: Soil erosion, Sustainable agriculture solutions, Environmental health, Erosion control strategies

INTRODUCTION

Soil erosion-the detachment, transport, and deposition of soil particles by natural agents such as wind and water are one of the most pressing environmental challenges contributing to global soil degradation. It poses severe threats to terrestrial and aquatic ecosystems by degrading fertile topsoil and contaminating freshwater systems (Tripathi et al., 2020). Among the various forms of erosion, water-induced soil erosion remains the most detrimental type, affecting vast regions both locally and globally. Annual average soil loss rates range from 0 to as high as 7638 tonnes per hectare per year (Mandal & Roy, 2024). Although soil erosion occurs naturally through geomorphological processes, its severity has been substantially amplified by anthropogenic activities such as deforestation, overgrazing, unsustainable farming practices, and improper land management (Chi et al., 2019). The impacts of soil erosion extend beyond the physical loss of topsoil; it strips away the most nutrient-rich layer of soil, leading to declines in soil fertility and productivity (Rashmi et al., 2022). This degradation undermines agricultural sustainability and contributes to declining crop yields, particularly in developing countries where land

Article History
Received: September 16, 2025, Accepted: October 19, 2025, Published: November 04, 2025.

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resources are already under pressure (Montgomery, 2007). The consequences are both on-farm such as reduced soil aggregation, organic matter, and nutrient content and off-farm, including sedimentation of water bodies, contamination with agrochemicals, and loss of aquatic biodiversity (Shahane & Shivay, 2021). These effects also lead to shortened reservoir lifespans, diminished water quality, and economic losses through decreased agricultural productivity and increased maintenance costs of water infrastructure (Rashmi et al., 2022).

Wind erosion, while less widespread than water erosion, poses significant problems in arid and semi-arid regions, especially during periods of intense wind and dry, bare soil conditions (Jafari et al., 2017). Approximately 91% of global soil loss occurs in Africa and Asia, with India and China being among the most affected countries (Borrelli et al., 2017). In Pakistan, both wind and water erosion severely threaten sustainable development, with wind erosion rates exceeding 15,000 $t \cdot km^{-2} \cdot yr^{-1}$ in desert regions such as Kharan and Thar, and water erosion rates ranging from 2,500 to 5,000 $t \cdot km^{-2} \cdot yr^{-1}$ in the Potohar Plateau and surrounding areas (Yang et al., 2023; Zeeshan et al., 2024). In East Africa, water erosion results in an estimated 4 billion tonnes of annual soil loss, reducing agricultural productivity and threatening food security (Gomiero, 2016). Globally, water erosion alone accounts for more than 55% of total land degradation, affecting approximately one-sixth of the Earth's surface (Varghese, 2023).

Recent world evaluations show that about a third of the global soils are getting eroded and this negatively affects the stability of ecosystems and leads to a loss of agricultural GDP of 8% per year in the developing countries. Although erosion processes have been studied extensively, detailed analyses comprising physical, biological, and socio-economic aspects are not extensive. Thus, the objectives of the review study include (i) synthesizing the available information on soil erosion processes and effects globally, (ii) assessing the effectiveness of technological and ecological mitigation strategies and (iii) understanding research and policy gaps which limit the process of sustainable land management.

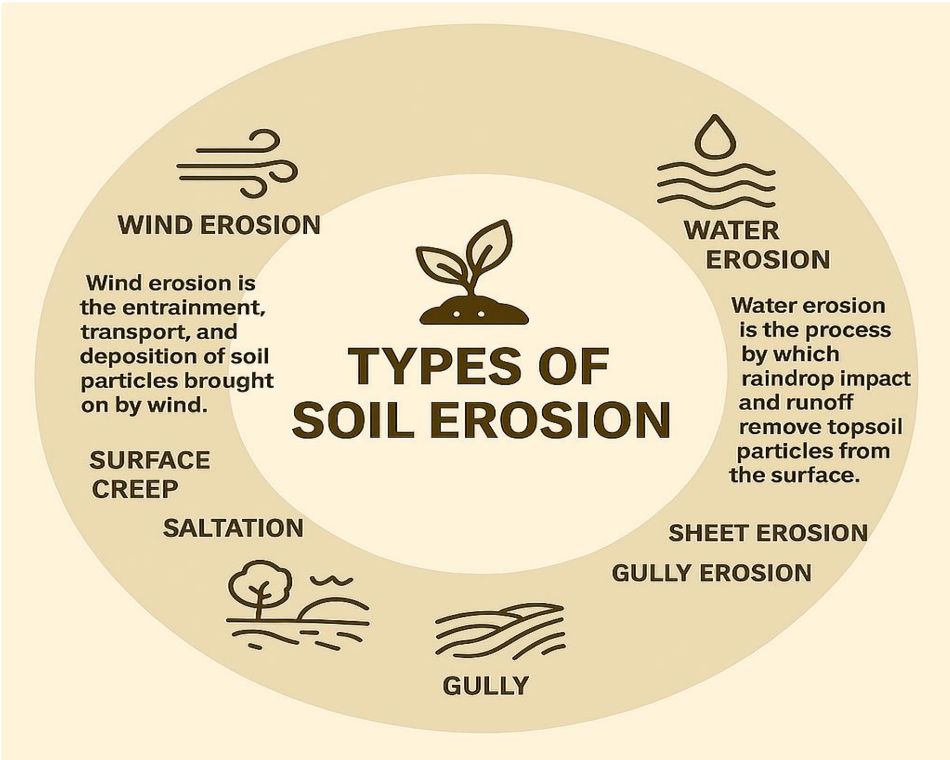


Figure 1. Types of soil erosion.

Processes and Types of Soil Erosion

Soil erosion occurs through four main mechanisms: water, wind, tillage, and mass movement. (i) Water erosion including sheet, rill, and gully types-accounts for roughly 55 % of global soil loss. (ii) Wind erosion predominates in arid regions and is responsible for ~17 % of degradation. (iii) Tillage erosion arises from mechanical soil displacement on slopes, often surpassing water erosion under intensive mechanization. (iv) Mass movement (landslides, slumping) represents localized but high-magnitude loss on steep terrains.

Wind erosion

Wind erosion is the entrainment, transport, and deposition of soil particles brought on by wind. Bringing nutrient-rich, fine-grained top soil particles to the atmosphere, water bodies, and other areas of land, it severely degrades the environment on a worldwide scale, lowering crop yield and raising health risks (Nieder et al., 2018). Deflation and abrasion are the two major impacts of wind erosion. In the arid climates of northern China, wind erosion is the primary cause of soil deterioration and extensive desertification. Creep (5-25 %), saltation (50-75 %), and suspension (3-40 %) are the three transport modes of particles during wind erosion (Guo et al., 2014).

Water Erosion

Water erosion is the process by which raindrop impact and runoff remove topsoil particles from the surface. About 55 % of the land is eroded due to water erosion, which is the most prevalent type of soil degradation process (Issaka & Ashraf, 2017). There are various types of water erosion, such as sheet erosion (which removes a thin layer of material from the soil) rill erosion (soil erosion that is primarily brought on by precipitation or water build-up) (Farooq et al., 2023). This kind of erosion takes the shape of tiny channels created by collecting stream water, which starts a flow from loose and weak spots in the soil and drags the dirt along with it, and gully erosion that is a more advanced form of rill erosion (Singh & Hartsch, 2019).

Soil Erosion Effects on Agriculture

Modern civilizations inhabit a world that has been developed, with roughly 38% of its land area being used for agriculture. A sustainable agricultural system can meet the demands of humanity (Balkrishna et al., 2021). Soil erosion is one of the primary causes of soil degradation along with loss of soil structure, soil compaction, low organic matter, inadequate internal drainage, soil acidity problems, and salinization (Hossini et al., 2022). Some farms have seen a 50% drop in productivity as a result of soil erosion and desertification. Historical soil erosion has caused yield losses in Africa ranging from 2 to 40%, with a mean loss of 8.2% throughout the continent (Rhodes, 2014). Soil erosion-degraded areas are susceptible to the depletion of organic matter and nutrients in the topsoil, resulting in increased water body pollution, reduced crop yields, and the degradation of wildlife habitats (Hassan, 2017). Soil erosion removes soil, organic carbon (OC), nutrients, soil productivity and its capacity to support life is reduced. The mechanisms of sheet erosion, which preferably transport the fine soil particles carrying the majority of nutrients and organic matter, are frequently specifically linked to the loss of organic matter and soil nutrients (de Nijs & Cammeraat, 2020). Erosion is depleting the soil's fertility and potentially the soil's overall composition. Erosion results in the loss of rich topsoil, the removal of SOM and plant nutrients, and a decrease in the productivity of the soil for agricultural purposes. Erosion diminishes soil fertility by depleting organic carbon, nitrogen, and phosphorus stocks, thereby reducing yield potential by 5-40 % depending on crop and region. Annual global loss of 0.3% of total cereal output due to erosion-related nutrient depletion (Yaseen et al., 2025). Long-term studies indicate yield reductions of up to 8% in Sub-Saharan Africa. Roughly 80 % of farmlands experience mild to serious erosion (Musa et al., 2024).

Soil Erosion Effects on Environment

Across the globe, soil erosion is a major environmental problem that poses varying degrees of threat to the ecosystem depending on the location. In most of the world, soil erosion is a serious environmental and economic issue that threatens land, freshwater, and the oceans (Guerra et al., 2020).

Effects on Air

Air is a crucial component of human life on earth. Basically, clean air is essential for better life and, in the absence of clean air, life on this planet will become intolerable and can be fatal (Reader, 2021). Currently, soil erosion brought on by wind and dust emissions is a problem for many soils worldwide. In dryland areas, one of the major causes of atmospheric particulate matter (PM) is dust emission brought on by wind erosion of agricultural soil (Katra, 2020). The origin area's topsoil characteristics, particularly the makeup of the aggregates that hold the majority of the dust particles, influence the amount of dust released during aeolian (wind) soil erosion (Katra, 2020). Aerosols that pollute the air have the potential to endanger not just human health but also the environment. Aerosols of mineral dust are an essential part of the Earth's system (Yaseen et al., 2025). They are tiny suspended soil particles (less than 20 μm) that are discharged by powerful winds in areas where the soil is erodible (Nieder et al., 2018). Mineral dust in the atmosphere is primarily produced by desert and semiarid environments. The presence of mineral dust in the atmosphere affects the climate and the ecosystem (Schepanski, 2018). Many elements of human and other habitats are impacted by atmospheric dust, including air quality, public health, the melting of snow and ice, the transport of nutrients over large expanses of land and water, and air temperature where and when dust plumes move throughout the world (Ghalib et al., 2025). Wind erosion enhances sand and dust pollution, influences soil carbon dioxide (CO_2) emissions to some degree, and speeds up the melting of the snow mantle and the snowline rise (Kamali et al., 2020).

Effects on Water

Although water is an essential component of the ecosystem, both natural and man-made activities are degrading surface and groundwater quality. Atmospheric, hydrological, topographical, climatic, and lithological elements are examples of natural variables that impact the quality of water (Shukla et al., 2023). Among the anthropogenic practices that degrade water quality are mining, raising livestock, producing and disposing of trash (industrial, agricultural, and municipal), increasing sediment runoff, and soil erosion brought on by changes in land use (Akhtar et al., 2021). Erosion contains nutrient-enriched fine soil particles. Many phosphorus (P) particles from erosive soils are transported to water bodies together with the eroded soil. Soil erosion and surface runoff from dry land cause the majority of watershed eutrophication (Lal, 2020). Eutrophication is a natural process that excessive much inorganic nutrients, like phosphorus and nitrogen, to promote growth of sea grass and other aquatic plants (Ghalib et al., 2025). These are absorbed by urban, industrial, and agricultural effluents in aquatic bodies. Freshwater lake eutrophication is a worldwide issue that negatively impacts aquatic habitats (Devlin & Brodie, 2023).

Agricultural field erosion and nutrient loss are detrimental to farmers and are linked to eutrophication, which can result in costly drinking water purification expenses, expenditures in lake or shoreline rehabilitation, or losses for the tourism sector (Khedr et al., 2022). Moreover, soil erosion and runoff processes regulate the mechanisms of pesticide mobilization and transfer from agriculture to river systems and pose a possible danger to aquatic ecosystems (Mishra, 2023). Runoff and erosion can carry water and sediment downhill on sloping agricultural areas. Rainfall characteristics, including intensity, amount, and duration, have a significant influence on the development of runoff and the particle transport (Meyer, 2020). The primary mechanism by which sediment is delivered to rivers is soil erosion; during this early stage, dislodged soil particles undergo transformation into sediments under the action of an erosion agent (Yaseen et al., 2024). The quantity of sediments can impair hydraulic structure performance and reservoirs potential storage capacity (Singh & Hartsch, 2019).

Effects on Soil

The world's most intricate and varied ecosystem is found in soils. In addition to providing humans with 98.8% of their food, soils also store carbon, control greenhouse gas emissions, prevent flooding, and sustain our growing cities (Qadir et al., 2024). Erosion has been shown to alter the natural characteristics of soil and remove vegetation cover, which negatively impacts the biomass, quantity, and composition of microorganisms (Yaseen et al., 2024). Degradation of the soil and the loss of its nutrients, structure, and SOC can result from soil erosion (Zhu et al., 2010). The redistribution of soil carbon is largely influenced by soil erosion, especially that portion of carbon that is tightly bonded to soil aggregates. Moreover, the link between soil erosion, deposition, and SOC is well acknowledged yet contentious (Kirkels et al., 2014).

Over the course of two years, it has been observed that increased wind erosion dramatically alters the soil texture in a typical desert grassland in southern New Mexico. One of the most significant factors contributing to desertification and land degradation in China's arid, semi-arid, and certain sub-humid areas is wind erosion (Lyu et al., 2020). Salinization, wind erosion, and water erosion are the main direct physical processes that cause desertification. Where there is enough slope for rainwater to flow downhill, erosion is depleting the soil's fertility and in many cases the soil's overall composition (Jafari et al., 2022). A major danger to the long-term viability of the agricultural sector's sustainable growth is the imbalance of nutrients and organic matter in the soil, which exacerbates soil degradation and, eventually, raises doubts about the potential of raising crop productivity even further (Zeeshan et al., 2024). According to a recent assessment, the expanses of land degradation vary from country to country and have a highly unclear influence on the world economy, ranging from 40 to 490 billion US dollars (Nkonya et al., 2016).

Table 1. Soil erosion effect on different aspects of agriculture.

Aspect	**Effects of Soil Erosion**	**References**
Agriculture	• 38% of land used for farming is at risk • 50% productivity loss in some farms • Yield losses in Africa: 2-40% (avg. 8.2%) • 80% farmlands face mild to severe erosion • Loss of topsoil, SOM, nutrients → reduced fertility	(Van Huyssteen & du Preez, 2023)
Environment	• Global environmental threat • Land, freshwater, and oceans at risk • Degradation of ecosystems and biodiversity	(Cazzolla Gatti, 2016)
Air	• Wind erosion causes dust emissions (PM < 20 µm) • Dust affects climate, air quality, and health • Accelerates	(Maji & Sonwani, 2022)

	snow/ice melting • Reduces air quality → respiratory health risks • Contributes to CO_2 emissions from soils	
Water	• Nutrient-enriched sediments (P, N) → eutrophication • Degradation of surface & groundwater • Pesticide runoff into rivers • Sediment load reduces reservoir/storage capacity • Increased water purification and rehabilitation costs	(Falkenmark et al., 2013)
Soil	• Loss of nutrients, SOC, structure, and biodiversity • Alters soil texture and vegetation cover • Contributes to desertification (China, New Mexico) • Salinization + erosion = land degradation • Economic impact: $40-490 billion annually	(AbdelRahman, 2023)

Strategies to control soil erosion

The goal of contemporary soil erosion control strategies is to prevent topsoil loss and preserve soil quality for environmental protection, landscaping, and agriculture. Here are a few contemporary methods for managing soil erosion:

Vegetation

By absorbing the energy from raindrops and raising surface roughness to lower surface runoff velocity, vegetation can lower the risks of soil erosion. When compared to engineering approaches in terms of soil and water conservation, soil erosion can be reduced through restoration of vegetation techniques especially during times when there is a lot of precipitation which has the ability of causing water erosion (Cantalice et al., 2017). It is important to use historical data to examine how physical surroundings operate. The choice of planting also significantly determines the success of restoration and habitats management of soil erosion under semi-arid conditions (Ramzan et al., 2025). Cover crops are sown, like grasses, to minimize runoff and erosion or even to remove them completely (Smithson et al., 2013).

Soil Netting

Geotextiles such as polyester mat (PM), jute mat (JM), and polyester net (PN) can stop erosion and improve the soil's capacity to support plants on slopes (Kumar, 2023).

Terracing

Terracing was among the first methods of soil and water conservation. It is prevalent in hilly and mountainous regions that are strained in terms of population. To expand surface area under cultivation and save soil and water on the slopes, terraces are constructed along the lines of contours (Chen et al., 2017). It entails constructing flat or inclined works on hills or slopes to regulate the flow of water in the land as well as making water to infiltrate into the soil. It reduces runoff and the deposition of sediments through the reconstruction of the landscape and encouraging vegetation growth (Morbidelli et al., 2018). One of the methods to reduce soil erosion is constructing radical terraces. Most considerable outcomes in combating water erosion were reached through zig terraces (Rutebuka et al., 2021).

Rock Fibers

Rock blankets are formed by covering the top soil with small aggregates randomly spread over the top surface. There is wide use of rock blankers on steep terrain where the ratio does not exceed 2:1 and where re-vegetation is difficult to accomplish (Vaitkus et al., 2012). One of the applications which can be performed along with this option is called rock-joint planting. They will assist the soil to be even more balanced (Deb & Verma, 2025). Geotextile can be used in some cases where there is overlaying of rock blanket to check on the soil erosion with regard to the slope. So, unless there are out of place rocks, the rock blankets require minimal maintenance (Kumar, 2023).

Contour Farming

Water **e**rosion is the most serious process leading to the weakening of arable soils. This process can be mitigated by conservation practices such as minimi**z**ation of tillage activities or contour farming (Kumar & Pandey, 2024). Under this procedure, the crops are sown along with the natural contours of land. It reduces the soil erosion and assists in slackening water flow. Contour farming has been found to be helpful in curtailing soil erosion on steep lands in the mountains (Tiwari et al., 2024).

Microbially driven soil stabilization

In the recent years, a significant amount of research has been dedicated to microbe mediated soil development plan through microbe-initiated carbonate solidification (MICP) due to its flexibility, environmental sustainability predicted potential and possible cheap cost (Coban et al., 2022). The wandering acrobat then proceeds to demonstrate a flight of fancy (Zeeshan et al., 2024). MICP is an exclusive way of making the soil stronger and can reduce the probability of wind erosion of sandy soils (Wang et al., 2022).

Mulching

Mulching involves the placement of organic or synthetic materials on the soil around plants to create a favorable environment that facilitates their growth, development, and eventual positive yields and to prevent soil erosion (El-Beltagi et al., 2022). Residue mulching has been resorted to, in order to enhance soil organic carbon (SOC) and prevent soil erosion and degradation. Due to the fact that the soil cover was more than 30%, the rates of soil erosion were considerably lower (Liu et al., 2019). Compared to the bare soil in which no mulching was undertaken, the plot in which mulching was applied helped to reduce the amount of runoff by 15.5% and sediment yield by 40.7% (Gholami et al., 2013). Straw mulching is one of the most commonly adopted techniques amongst the farmers because it is dirt cheap and easy to practice and because it is eco-friendly (Imran et al.). On the contrary, a comparative technique revealed that applying sawdust and straw mulch on a skid trail lowered the runoff by 72.8% and 36.5% respectively when compared to untreated trails (Iqbal et al., 2020).

Stone Bunds

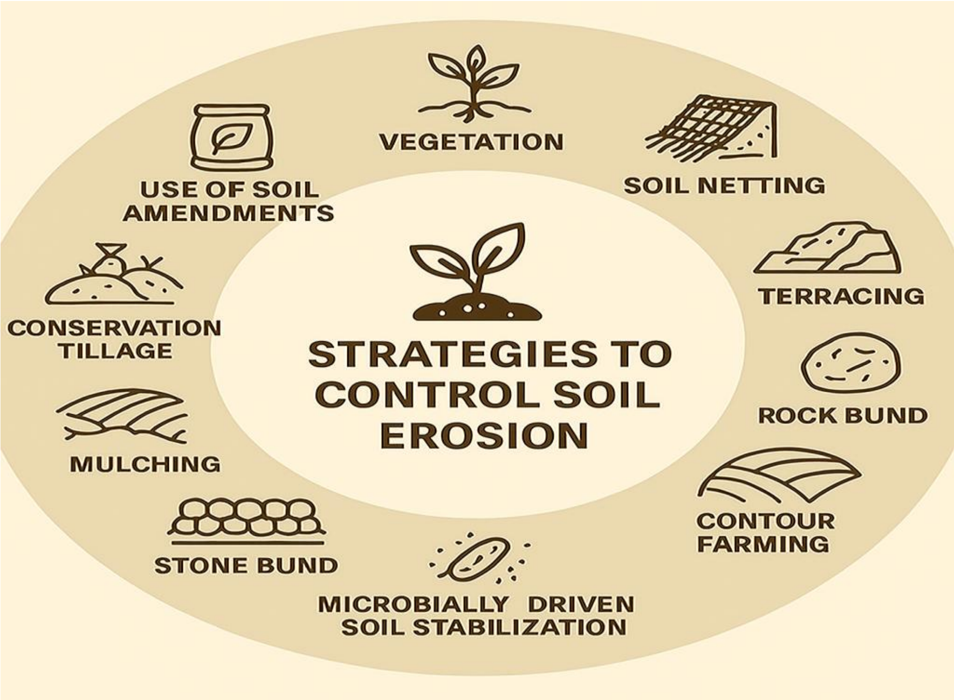
It was in Tigray, northern Ethiopia, in 1981 that stone bunds were first used to improve soil and water conservation (Zaman et al., 2025). Use of stone bunds resulted in Increased infiltration, a 68% reduction in soil loss from rill and sheet erosion, and marginally higher crop yields (Tayea, 2011).

Conservation Tillage

Conservation tillage is any tillage or planting technique that preserves at least 30% of the soil surface with plant residue following planting, hence reducing wind and water erosion. It is believed that conservation tillage is a helpful method for reducing soil erosion and runoff while also improving water penetration (Boincean & Dent, 2019). The kind of conservation tillage employed as well as additional environmental elements like plant cover, slope, and climate, conservation tillage can decrease runoff by roughly 50% to 70% and soil loss by roughly 70% to 95% (Busari et al., 2015).

Use of Soil Amendments

The application of biochar on soil showed that the soil loss was remarkably reduced by approximately 50 % and 64 % at 2.5 % and 5 % of the application of biochar, respectively. In addition, the soil conditions including water holding capacity, soil pH, cation exchange capacity, and microbial count carbon have also been enhanced through the application of biochar (Li et al., 2019). A study conducted in Kuwait shows that one of the ways of reducing wind erosion is by the application of soil amendments (Imran et al.). Their finding indicated that wind erosion was also substantially minimized by the addition of animal dung and biochar to the top-soils. As a result, it may be introduced as a long-term education plan on the decrease of soil erosion in the desert in the form of soil erosion (Madouh & Davidson, 2024).



CONCLUSION

Soil erosion is a deep-rooted menace to the stability of agricultural production and the ecosystem of the world. Its negative effects go further than the physical destruction of farmland to include low soil fertility, low harvesting, and high sedimentation of water bodies, hence compromising the quality of water and biodiversity. In addition, soil erosion increases climate change by depleting soil organic carbon into a feedback loop that amplifies environmental degradation. This is a complex issue that needs a multidisciplinary solution whereby technological innovation, socio-economic knowledge, and ecological values are put into consideration. Optimal monitoring accuracy can be achieved by the use of superior remote sensing and geospatial modeling and the capability to make decisions based on the data. Simultaneously, the socio-economic and policy systems are expected to support the application of the sustainable land management practices, such as conservation tillage, vegetative buffer strips, and agro forestry systems. Preventing erosion involves concerted efforts of scientists and policy makers, farmers, and local people to ensure that scientifically oriented solutions are applied in practice. This distance between the capability of the technology and social acceptability and economic feasibility is significant to achieve long-term soil protection and agricultural stability.

Future Prospective

Future research in the application of mitigation in soil erosion should entail the integration of the high-resolution limits of remote sensing information with the very advanced quantitative models coupled to climatic, topographical and land-use perceptions in a manner that effective prediction and assessment of the identical can be implemented. Maximizing socio-economic analysis that might be implemented by measuring cost of adopting, incentives and policy mechanism will assist willingness of control measures into the workable environment. The other type of biotechnological solution that can be sustained is the intensification of research on microbial soil stabilization methods, such as calcium precipitation mediated by microorganisms (MICP) or fungal mycelial networks. Finally, the construction of harmonized transboundary policy structures according to Sustainable Development Goal 15 and climate adaptation strategies will establish harmonized theories of resilient land management in the globe.

Author Contributions

All authors contributed equally to this review.

Competing of Interest

The authors declare no competing interests.

Declaration of Interest

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

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