International Journal of Science and Research (IJSR)
ISSN: 2319-7064
Impact Factor 2024: 7.101

Climate Variability and Its Implications for Soil Health Systems in India

Pancham Kumar

Department of Chemistry, BSA College Mathura (Dr BR Ambedkar University, Agra)
Email: *beingsachinsir[at]gmail.com*

Abstract: ***Climate change threatens soil health globally by disrupting the delicate balance of its physical structure, chemical makeup, and biological life that sustain farming and natural ecosystems. Hotter temperatures, unpredictable rains, higher CO_2 in the air, and more intense storms are worsening problems like soil erosion, hardening, nutrient loss, and harm to soil microbes. These changes cut crop yields while creating cycles that boost greenhouse gas releases, making degraded soils both victims of and contributors to warming. This review explores how these climate pressures damage soil functions and assesses practical fixes to rebuild soil strength. Approaches like no-till farming, adding organic waste, planting trees alongside crops, boosting carbon storage, and using smart soil sensors can build tougher soils and support lasting food production. Strong policies, farmer involvement, and teamwork across fields are vital to make these work. Combining modern tech with time-tested farming wisdom positions soil as a key weapon against climate threats.***

Keywords: Climate change, soil degradation, carbon sequestration, conservation

1. Introduction

Soil is a crucial and finite natural resource that underpins agricultural productivity, supports biodiversity, and drives essential global biogeochemical cycles. Serving as a buffer and reservoir, soil forms a living matrix that sustains terrestrial ecosystems. However, this indispensable resource faces growing threats from climate change, which manifests through rising temperatures, unpredictable rainfall patterns, extended drought periods, intensified flooding, and elevated atmospheric carbon dioxide concentrations. These environmental changes are transforming the structure, functions, and long-term viability of soil systems worldwide. The effects vary widely, influenced by soil type, agro-ecological conditions, and land management strategies, thus presenting a complex challenge.

With the acceleration of climate change, soils are degrading at unprecedented rates. Common issues include loss of organic matter, soil compaction, acidification, salinization, erosion, and reductions in biodiversity, affecting soils across both developed and developing regions. These alterations not only threaten food production and security but also compromise the soil’s natural capacity to store carbon and regulate greenhouse gases. Paradoxically, soil degradation contributes to increased emissions, forming a negative feedback loop that exacerbates climate change.

In response to the scale and urgency of these challenges, this review critically examines the impacts of climate stressors on soil health and investigates viable mitigation strategies to preserve and enhance soil functionality and resilience. By addressing changes across physical, chemical, and biological soil properties and incorporating insights from scientific research as well as community-based initiatives, the study highlights the importance of integrated approaches. These approaches must blend technological advancements, policy support, and traditional knowledge systems to reposition soil from a vulnerable resource to a vital tool for climate change mitigation and adaptation.

Effect of Climate Change on Soil System in India

Climate change significantly impacts the soil systems in India, posing serious challenges to agricultural productivity and ecosystem sustainability [1]. Rising temperatures, altered rainfall patterns, and increasing climate variability are intensifying soil degradation processes such as loss of soil organic carbon (SOC), erosion, nutrient imbalances, and microbial disruptions [2]. A comprehensive ICAR-coordinated study from 2017 to 2023 reveals a widespread decline in SOC, which is crucial for soil fertility, moisture retention, and nutrient cycling across large parts of India's agricultural landscape [3,4]. The imbalance in fertilizer use, notably the overuse of nitrogen-based fertilizers without adequate organic amendments, exacerbates these effects by disrupting soil microbial activity and accelerating organic matter decomposition [5,6]. Droughts and extreme weather events further stress soils by reducing water availability and increasing erosion risks, which compromise the topsoil—the most fertile layer. This degradation not only reduces soil productivity but also diminishes the soil's role as a carbon sink, turning it into a net source of greenhouse gases, thereby contributing to global warming [7,8]. Various Studies emphasize that sustainable soil management practices, including conservation tillage, integrated nutrient management, use of organic amendments, diverse cropping systems, and erosion control, are essential to restore soil health [9]. India's climate goals rely heavily on reversing soil carbon losses through region-specific policies and farmer education that promote balanced fertilization and soil conservation [10]. The preservation and enhancement of soil health under changing climatic conditions are critical for ensuring long-term food security and environmental sustainability in India [11].

Climate Change and Soil Physical Health

Soil physical health encompasses the soil’s structural integrity and its capacity to function effectively by facilitating water infiltration, aeration, root growth, and resisting erosion [12]. Climate change exerts complex pressures on these physical properties, affecting both natural ecosystems and agricultural lands. One major impact is the disruption of soil structure due to alternating dry spells and intense rainfall events [13]. These cause soil to shrink and swell cyclically, breaking apart soil aggregates and forming surface crusts [14]. This process reduces the pore space, limits gas exchange, and restricts root growth, resulting in plants experiencing water stress despite the presence of moisture.

More frequent droughts decrease soil moisture levels, weakening particle cohesion and increasing vulnerability to wind erosion [15,16]. In contrast, intense rainfall events exacerbate water erosion, washing away nutrient-rich topsoil and causing sedimentation in nearby water bodies, which harms soil horizons and diminishes long-term land productivity. Moreover, heavy rains coupled with mechanized farming lead to soil compaction, raising bulk density, which reduces porosity and restricts water retention and movement. This increase in bulk density further limits root penetration and mobility of soil microbes, slowing down critical nutrient and carbon cycling processes.

Climate-induced loss of vegetation- driven by prolonged heatwaves or pest outbreaks- exposes soil surfaces to raindrop impact and wind erosion, weakening the protective cover that mitigates soil degradation[17]. Collectively, these changes undermine soil resilience and heighten its susceptibility to degradation under ongoing climate stress. Tackling these physical changes through sustainable land management is essential for safeguarding agriculture and ecosystem sustainability in a changing climate. [18].

Climate Change and Soil Chemical Properties

Climate change profoundly affects the chemical characteristics and functioning of soil ecosystems, with significant consequences for plant nutrient dynamics, contaminant behavior, and crucial biogeochemical cycles [19,20]. Soil chemistry, including factors such as pH, nutrient availability, cation exchange capacity, and redox conditions, is highly sensitive to disruptions in temperature, moisture, and atmospheric composition caused by ongoing climate variability [21].

One prominent impact is the alteration of soil pH [22,23]. Increased acid deposition, enhanced breakdown of organic matter, and shifts in vegetation can lead to changes in soil acidity [24]. In wetter climates, intense rainfall and higher temperatures promote leaching of basic nutrients like calcium and magnesium, causing acidification [25]. Conversely, in drier and poorly drained areas, evaporation intensifies salt accumulation, leading to soil alkalinity.

Climate fluctuations also influence the availability of key nutrients. Waterlogging from intense or erratic rainfall creates oxygen-poor conditions that affect the redox state, altering the solubility and mobility of nutrients such as iron, manganese, and phosphorus. Nitrogen cycles are disrupted as heat stress increases ammonia volatilization and denitrification, releasing nitrous oxide, a potent greenhouse gas.

Furthermore, changes in soil moisture accelerate the leaching of essential nutrients like nitrates and potassium, reducing fertility and posing risks to water quality. Drought conditions inhibit microbial activity, slowing nutrient mineralization and reducing plant uptake, which may increase dependence on fertilizers, potentially worsening pollution [26].

Redox and pH changes also mobilize toxic metals such as aluminum and cadmium, increasing bioavailability and causing toxicity that harms root systems and microbial communities. These chemical stresses in soils challenge not only agricultural productivity but also long-term environmental and human health [27].

To address these challenges, it is critical to monitor soil chemistry comprehensively and adapt nutrient management practices proactively in alignment with shifting climate baselines.

Climate Change and Soil Biological Health

Soil biological health reflects the richness, abundance, and functionality of living organisms in soil, including microbes like bacteria, fungi, archaea, protozoa, nematodes, and larger fauna such as earthworms and insects. These organisms are essential for decomposing organic matter, cycling nutrients, controlling diseases, and maintaining soil structure. Climate change is destabilizing these biological communities, reducing soil vitality and impairing ecosystem services. Shifts in temperature, rainfall patterns, and elevated CO_2 directly and indirectly impact soil biota. Extended droughts and heat stress diminish microbial biomass and diversity, especially moisture-dependent groups like mycorrhizal fungi and nitrogen-fixing bacteria, disrupting critical processes such as nitrification and phosphorus mobilization vital for plant growth. Conversely, warming in colder regions may temporarily increase microbial activity, accelerating organic matter turnover but risking long-term soil carbon losses. Vegetation changes driven by climate affect root exudates, altering microbial community composition and function. While elevated CO_2 can enhance initial plant growth and microbial biomass by boosting carbon inputs below ground, nutrient constraints and water limitations often limit sustained productivity [28].

Extreme events like flooding and wildfires further disrupt soil microbial habitats. Floods cause oxygen depletion, fostering bacteria that emit greenhouse gases, while wildfires sterilize soils and hamper microbial recovery, weakening soil resilience [29]. Soil macrofauna, such as earthworms and termites, sensitive to moisture and temperature changes, also decline, reducing soil aeration and organic matter incorporation, further harming soil structure and fertility [30]. Protecting soil biological communities through climate-conscious management- restoring microbial diversity, maintaining organic inputs, and minimizing disturbances—is vital to sustaining soil functions critical for ecosystem health [31,32].

Feedback Loops - Soil as a Source and Sink of Greenhouse Gases

Soils have a complex and dual role in climate change, acting as both sources and sinks of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). This creates feedback loops that can either amplify or mitigate climate change impacts. Understanding and managing these soil-related feedbacks is crucial for effective climate mitigation efforts [33].

Globally, soils contain more carbon than both the atmosphere and terrestrial vegetation combined, primarily as soil organic carbon (SOC). However, climate change-related disruptions such as soil erosion, vegetation loss, and accelerated microbial decomposition can transform soils from carbon reservoirs into net carbon emitters [34]. Rising temperatures, especially in temperate and boreal ecosystems, cause faster decomposition rates in peatlands and permafrost, releasing large amounts of CO_2 and reinforcing global warming via a positive feedback loop [35].

Changes in precipitation modify soil moisture and oxygen availability, affecting microbial processes that produce CH_4 and N_2O. Anaerobic conditions in flooded soils, common in wetlands and rice paddies, foster methanogenesis, whereas dry, compacted soils promote denitrification, increasing N_2O emissions, which have a much stronger greenhouse effect than CO_2 over a century [36].

Land management and use influence whether soils release or sequester greenhouse gases. Practices such as intensive tillage, monoculture, and excessive nitrogen fertilization increase emissions. Conversely, soils managed with organic inputs and cover crops improve carbon sequestration by stabilizing carbon in soil aggregates and humic substances [37].

Soil carbon sequestration capacity depends on factors like clay content, mineralogy, microbial communities, and land-use history, affecting both the amount and stability of stored carbon. Thus, effective soil management must focus on maintaining long-term carbon stocks to maximize climate benefits.

In summary, soils can either buffer or exacerbate climate change depending on how they are managed. Enhancing their role as greenhouse gas sinks requires comprehensive understanding and stewardship of these dynamic feedbacks to minimize emissions and promote sustained carbon storage

Mitigation strategies for soil health in India

Mitigation strategies for soil health in India under climate change stress focus on restoring soil organic matter, improving water use efficiency, and enhancing biodiversity in soil ecosystems through sustainable practices [38]. Conservation agriculture practices such as minimum tillage, crop rotation, and agroforestry reduce soil erosion and improve soil structure and fertility [39]. Incorporating organic amendments like crop residues and compost enhances soil organic carbon stocks, which is critical since Indian soils have experienced significant depletion of soil organic carbon due to unsustainable field management [40,41].

Afforestation on degraded lands and agroforestry systems increase biomass production and soil cover, contributing to carbon sequestration and climate resilience [42]. Precision agriculture and smart technologies enable context-specific interventions that optimize fertilizer use and irrigation efficiency, limiting nutrient losses and environmental pollution [43]. Promoting legumes and cover crops enriches soil nitrogen content naturally and helps maintain soil fertility [44]. Additionally, strengthening community involvement through capacity building, participatory governance, and incentives encourages adoption of healthy soil management practices [45].

India's national initiatives such as the Soil Health Card Scheme, Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), and Rashtriya Krishi Vikas Yojana (RKVY) provide frameworks to upscale these practices, aiming to achieve a regenerative soil landscape by 2047. Integrating indigenous knowledge with scientific approaches further reinforces sustainable outcomes.

Overall, a multidimensional approach- combining conservation, technological innovation, policy support, and community engagement- is key to reversing soil degradation, enhancing resilience, and securing agricultural sustainability in the face of climate change pressures [46].

Future Perspectives and Research Needs

As the climate crisis intensifies and its effects on soil health become more apparent, it is crucial to establish a forward-thinking research and innovation agenda that links scientific knowledge, technological advancements, and practical applications. The ever-changing nature of soil systems amid evolving climatic conditions requires a comprehensive approach that combines physical, chemical, biological, and socio-economic factors across spatial and temporal scales.

A key priority is developing region-specific soil-climate models that can predict how localized climate stressors influence soil health [47]. These models should incorporate detailed data on soil types, land use, cropping patterns, and weather variability to guide adaptive management strategies. Complementing this, establishing long-term experimental sites and observatories is essential for tracking the cumulative effects of climate variability on soil characteristics, microbial communities, carbon cycling, and nutrient dynamics [48].

Another important area involves merging traditional ecological knowledge with advanced technologies like artificial intelligence, remote sensing, and metagenomics. Indigenous land management practices, often sidelined by conventional science, demonstrate effective soil and water conservation techniques suited to extreme climates. Integrating these with modern tools can create hybrid solutions that are ecologically sustainable and culturally acceptable [49].

Scaling up nature-based solutions such as agroforestry, regenerative agriculture, and organic amendments requires thorough investigation of their long-term viability across diverse agro-climatic zones. Research must also evaluate potential trade-offs, including competition for water in tree-crop systems or nutrient imbalances from excessive organic inputs when these practices are widely adopted.

Further, growing attention on soil biodiversity and microbiomes is warranted, as advances in molecular biology and systems ecology reveal their critical roles in climate resilience. This opens pathways for engineering resilient soil ecosystems or developing microbial inoculants to boost stress tolerance and carbon sequestration.

Finally, interdisciplinary collaboration is essential. Soil science must intersect with climate science, economics, social sciences, and policy to develop integrated frameworks supporting sustainable soil management at local and global scales. Emphasizing capacity building and youth engagement will prepare future generations to steward soil resources in a rapidly changing climate [50].

2. Conclusion

Soil health occupies a pivotal role in the broader climate change context, acting both as a vulnerable entity and a key factor shaping global environmental outcomes. With climate change intensifying through increased temperatures, erratic rainfall patterns, and more frequent extreme weather, soils- the bedrock of terrestrial ecosystems- are undergoing substantial shifts. These transformations affect the physical structure, chemical composition, and biological diversity and activity within soils, thereby disrupting fertility, biodiversity, and essential ecosystem services. Without prompt intervention, the degradation of soil under climate pressures threatens food security, water regulation, carbon capture, and the capacity of ecosystems to withstand environmental stressors.

Nonetheless, this challenge presents significant opportunities. Thoughtful soil management can fortify soils against climate impacts and enhance their role in climate mitigation. Practices such as conservation agriculture, agroforestry, organic amendments, and advanced monitoring technologies provide viable solutions to restore and sustain soil health. Complementary to these technical strategies, well-informed policy measures, collaborative governance, and respect for indigenous land stewardship further ensure that innovations translate into impactful, large-scale change.

The future resilience of soils amid warming climates rests on a combination of cutting-edge scientific advances and collective societal commitment. Recognizing soil as a dynamic, living resource—and actively investing in its care- will safeguard ecosystem functions, stabilize climate trajectories, and secure human well-being for generations to come.

References

[1] Jha, N., et al. (2021). Changing climate and land use influences on soil erosion in India. *Science of The Total Environment*, 754.

[2] Singh, J. S., & Kushwaha, C. P. (2014). Impact of climate change on soil health. *Agricultural Research*, 3(2), 107-116.

[3] Kumar, A., et al. (2024). Climate change impact on soil health and crop production. *Agronomy Journal*, 116(7).

[4] Raj, R., & Saharia, M. (2023). Soil carbon sequestration and resilience strategies for Indian agroecosystems. *Soil Biology & Biochemistry*, 158.

[5] Murthy, R. K. (2024). Impact of climate change on soil properties and functions. *Journal of Soil Science*.

[6] Dutta, S., & Rakshit, A. (2016). Soil temperature and moisture changes due to climate variability. *Environmental Science*.

[7] Mondal, N. (2021). Soil degradation under climate change in India. *Agricultural Sciences Review*.

[8] Pareek, A. (2017). Nutrient cycling disruption in Indian soils under climate change. *Soil Biology Journal*.

[9] D'Silva, J., & Patil, S. (2023). Fertilizer imbalance effects on Indian soils. *Journal of Agricultural Chemistry*.

[10] Caubel, V., et al. (2014). Soil organic matter pools under changing climate. *Global Soil Journal*.

[11] Murthy, R. K. (2024). Impact of Climate Change on Soil Properties and Functions. *Journal of Soil Science*, 72(2), 145-156.

[12] Oishy, M. N. (2025). Unravelling the Effects of Climate Change on the Soil-Plant-Atmosphere Nexus. *Agronomy Research*, 15(3), 301-320.

[13] Ramakrishna Parama, V. R. (2017). Effect of Climate Changes on Soil Properties and Crop Production. *Indian Journal of Soil Science*, 65(1), 45-53.

[14] Lalthakimi, C., Singh, N. S., & Upadhyay, K. K. (2023). Land Use Change Effects on Soil Physical and Biochemical Properties in Northeast India. *Environment and Ecology*, 41(2), 345-356.

[15] Patel, R., & Meena, M. C. (2023). Soil Compaction Effects under Climate Change Conditions. *Soil and Tillage Research*, 208, 104698.

[16] Mondal, N. (2021). Soil Degradation in India under Climate Variability. *Agricultural Sciences Review*, 9(3), 200-215.

[17] Water Resources and Soil Studies. (2024). Impact of Extreme Precipitation on Soil Compaction. *Journal of Soil Science and Water Conservation*.

[18] D'Silva, J., & Patil, S. (2023). Fertilizer Imbalance Effects on Indian Soils. *Journal of Agricultural Chemistry*, 29(3), 123-137.

[19] Sharma, P., et al. (2022). Vegetation and Soil Interaction under Climate Stress. *Ecological Indicators*, 132, 108339.

[20] Anjali, M. C., & Dhananjaya, B. C. (2019). Effect of Climate Change on Soil Chemical and Biological Properties. *International Journal of Current Microbiology and Applied Sciences, 8*(2), 4153-4165.

[21] Murthy, R. K. (2024). Impact of Climate Change on Soil Properties and Functions. *Journal of Soil Science*, 72(2), 145-156.

[22] Oishy, M. N. (2025). Unravelling the Effects of Climate Change on the Soil-Plant-Atmosphere Nexus. *Agronomy Research*, 15(3), 301-320.

[23] Kumar, A., et al. (2024). Climate Change Impact on Soil Health and Crop Production. *Agronomy Journal*, 116(7), 2345-2358.

[24] Djodjic, F., et al. (2020). Effect of Climate Change on Soil Environmental Quality and Nutrient Dynamics. *Frontiers in Environmental Science*, 8, 535397.

[25] Ramakrishna Parama, V. R. (2017). Effect of Climate Changes on Soil Properties and Crop Production. *Indian Journal of Soil Science*, 65(1), 45-53.

[26] Singh, J. S., & Kushwaha, C. P. (2014). Impact of Climate Change on Soil Health. *Agricultural Research*, 3(2), 107-116.

[27] Mondal, N. (2021). Soil Degradation in India Under Climate Variability. *Agricultural Sciences Review*, 9(3), 200-215.
[28] Caubel, V., et al. (2014). Climate Change Consequences on Soil Organic Matter Pools. *Global Soil Journal*, 6(1), 15-29.
[29] Gupta, R., & Singh, M. (2022). Soil Erosion Risks and Climate Change in India. *Journal of Soil Conservation*, 35(1), 55-70.
[30] Sharma, P., et al. (2022). Vegetation and Soil Interaction under Climate Stress. *Ecological Indicators*, 132, 108339.
[31] D'Silva, J., & Patil, S. (2023). Fertilizer Imbalance Effects on Indian Soils. *Journal of Agricultural Chemistry*, 29(3), 123-137.
[32] El-Ramady, H., et al. (2024). Soil Degradation Under a Changing Climate. *Egyptian Journal of Soil Science*, 64(2), 123-144.
[33] Science Publishing Group. (2024). The Effect of Climate Change on Soil Health: A Review. *International Journal of Environmental and Ecological Studies*, 9(3).
[34] Pareek, A. (2017). Climate change impact on soil health and crop production. *Agronomy Journal*, 7(4), 835.
[35] Hamidov, A., et al. (2018). Impacts of climate change adaptation options on soil functions. *Land Degradation & Development*, 29(4), 1157-1167.
[36] Oishy, M. N. (2025). Unravelling the effects of climate change on the soil-plant relationship. *Agronomy Research*, 15(3), 301-320.
[37] Murthy, R. K. (2024). Impact of Climate Change on Soil Properties and Functions. *Journal of Soil Science*, 72(2), 145-156.
[38] Blum, W. E. H. (1993). Linking soil functions to environmental and social services. *Soil Use and Management*, 9(3), 105-111.
[39] D'Silva, J., & Patil, S. (2023). Fertilizer imbalance effects on Indian soils. *Journal of Agricultural Chemistry*, 29(3), 123-137.
[40] Singh, J. S., & Kushwaha, C. P. (2014). Impact of climate change on soil health. *Agricultural Research*, 3(2), 107-116.
[41] Mondal, N. (2021). Soil degradation in India under climate variability. *Agricultural Sciences Review*, 9(3), 200-215.
[42] Caubel, V., et al. (2014). Climate change consequences on soil organic matter pools. *Global Soil Journal*, 6(1), 15-29.
[43] Li, D., et al. (2020). Effects of elevated CO2 on soil microbial communities. *Soil Biology and Biochemistry*, 143, 107729.
[44] Beaury, S., et al. (2025, February 17). Land-based climate mitigation strategies for achieving net zero emissions in India. *Frontiers in Climate*.
[45] Jat, M. L., et al. (2023). Conservation agriculture for regenerating soil health and supporting climate adaptation. *Advances in Agronomy*.
[46] Asia Pathways. (2025, January 27). Securing Asia's future through soil health: Why it matters and what must be done.
[47] Pradhan Mantri Krishi Sinchayee Yojana (PMKSY). Government of India—irrigation efficiency program.
[48] Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, 304(5677), 1623-1627.
[49] Minasny, B., et al. (2017). Soil carbon sequestration potential. *Nature Communications*, 8, 15601.
[50] Swarup, A., et al. (1999). Changes in soil organic carbon stocks in agricultural systems. *Geoderma*, 87(3-4), 269-282.