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Review Article

Soil Microbial Responses to Climate Change: From Mechanisms to Mitigation Strategies

Fahim Al Islam [1] , Amena Akter [2] , Sadia Islam Konica [3] , Md Shakil Uddin [4] , Arpan Das [5] , Munira Begum [6] , Sabrina Najnin [6] , Srishti Chauhan [7, 8] , Prodipto Bishnu Angon [3, 9, ✉] , Md Arif Sakil [10]

1. *Department of Environmental Science, Bangladesh Agricultural University, Mymensingh, BGD*
2. *Department of Entomology, Bangladesh Agricultural University, Mymensingh, BGD*
3. *Faculty of Agriculture, Bangladesh Agricultural University, Mymensingh, BGD*
4. *Everglades Research and Education Center, University of Florida, Belle Glade, Florida, USA*
5. *Department of Soil & Crop Sciences, Texas A&M University, College Station, Texas, USA*
6. *Department of Soil Science, Bangladesh Agricultural University, Mymensingh, BGD*
7. *Department of Agricultural Science, Sardar Vallabhbhai Patel University of Agriculture and Technology, Modipuram, Meerut, IND*
8. *Institute of Agronomy, Hungarian University of Agriculture and Life Sciences, Gödöllő, HUN*
9. *Crop Production Engineering, Hungarian University of Agriculture and Life Sciences, Gödöllő, HUN*
10. *Department of Biochemistry and Molecular Biology, Bangladesh Agricultural University, Mymensingh, BGD*

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Abstract

The equilibrium of the soil microbiome is essential for maintaining soil health, as climatic changes in the ecosystem directly or indirectly impact agricultural productivity. These climate change factors, such as rising temperature, altering precipitation trends, elevated CO_2 levels, and high salinity in soil, interfere with the ecological system, affecting soil health, fertility, and microbial diversity. These factors substantially impact the growth, distribution, and reproduction of microbial communities. A wide range of studies investigating the effects of climate change on soil microbial populations has been systematically synthesized, with this review providing a critical analysis and summary of their principal findings. This literature evaluation included an analysis and summary of key findings from each of these investigations. This study examines the impacts of climate change on soil microbial diversity, with particular emphasis on the underlying ecological and biochemical processes. It further explores contemporary technological approaches aimed at enhancing soil microbiota and outlines key directions for future research. Additionally, the study reviews recent advancements in the field, including the application of genetically modified microorganisms, seed microbiome engineering, synthetic microbial communities (SynComs), and next-generation sequencing technologies. Additionally, it identified the research gaps, which have generated new opportunities to enhance plant health and their potential to resist biotic and abiotic stresses. This review aims to highlight microbial-based strategies to mitigate climate-induced stress and support sustainable land management. Sustainable management of soil microbes is crucial for establishing an adaptable agroecosystem. Future studies should be focused on integrative studies combining microbial ecology, advanced sequencing, and management strategies to predict ecosystem stability and microbial community dynamics.

Categories: Soil microbiology, Soil nutrition, Sustainable climate smart agriculture

Keywords: soil science, climate change, microorganisms, plant growth, agroecosystem

Introduction And Background

Human actions are the main causes of climate change, which mainly include industrial processes, deforestation, and the combustion of fossil fuels, which, over time, trigger substantial and irreversible changes in the patterns of the world's climate. Rising temperatures, rising sea levels, greater frequency and severity of storms, altered precipitation patterns, increasing greenhouse gas emissions, and declining water resources are just a few of the consequences of environmental change [1]. These factors have led to significant consequences of anthropogenic activities [2]. This refers to a chain reaction of environmental and socio-ecological damage caused by human activities, including alterations in microbial diversity, impairment of nutrient cycling, weakening of symbiotic relationships, and increased soil toxicity [3]. The impact of climate change on soil microbial communities and plant health is of great interest today. The soil microbial community has played a critical role in maintaining a steady food supply due to the rising need for food production.

Soil is a highly complex and dynamic ecosystem that contains bacteria, fungi, archaea, protozoa, and viruses, collectively forming the soil microbiome, one of the most diverse biological systems on Earth [4]. Its heterogeneous structure supports close plant-microbe interactions through the exchange of carbon and nutrients, which are essential for plant growth and sustainable agriculture [5,6]. Because soil conditions are strongly shaped by temperature, moisture, and redox variability, climate change can disrupt these interactions and alter soil function [7-9]. In addition, microbial responses to environmental stress vary according to physiological and genetic traits, making community resilience highly context-dependent [10].

Microbial respiration acclimation under warming appears to involve shifts in carbon pools, community composition, and respiration rates. Long-term heating can alter microbial growth and favor oligotrophic communities, while drought and heat jointly shape microbial resilience [11-13]. Under drier conditions, less soil organic carbon is decomposed and respired to CO_2 because reduced soil moisture limits substrate movement [14]. Beneficial plant growth-promoting fungi and bacteria in the rhizosphere may help buffer these climate impacts by supporting plant growth and nutrient acquisition under stress [15,16].

The inability of certain pathogens to infect in the absence of adequate surface moisture (e.g., dew or raindrops) or the inability of other pathogens or vectors to overwinter when temperatures fall below a critical level are examples of clear-cut relationships between climate and plant health. Other impacts of climatic shifts may be more subtle, such as the fact that a particular pathogen may only be able to infect its hosts when the plants are in specific developmental stages. This is also one of the indicators of gradual environmental change impacts, which states that the life cycle of pathogen populations must be in sync with host development to maximize their chances of infection. Climate change may affect the onset and severity of plant diseases by altering the rate at which infections and hosts evolve [17].

This review investigates the relationship between environmental change consequences and soil microbial populations. Lastly, it aims to inspect how this affects plant health. This review examines the mechanistic links between climate-induced environmental changes, soil microbial dynamics, and plant health outcomes. Previous works have shown only the relation between soil microbial community and climate change or plant health and climate change. However, this review explores the dynamic relationship between soil microbes and plant health when climate change impacts alter soil microbial communities' regular life cycle.

Review

Microbial communities react to changes in climate

Soil microbial communities are highly sensitive to changes in temperature, water availability, atmospheric CO_2, salinity, and drought. Because these organisms regulate decomposition, nutrient cycling, and plant symbioses, climate-driven shifts in microbial composition and function can have broad consequences for ecosystem functioning [18-20]. The following sections summarize the major climatic stressors and their effects on soil microbes.

Impact of Rising Temperatures

The impacts of climate change on microbial composition and function have been extensively studied. For instance, a 5°C temperature increase in a temperate forest significantly altered the relative abundances of soil bacteria and increased the bacterial-to-fungal ratio within the microbial community [21]. Changes in the relative abundance of organisms regulating key processes - such as nitrogen fixation, nitrification, denitrification, and methanogenesis - can directly alter the rates of these biogeochemical processes [22].

Rising temperatures directly impact microbial soil respiration, as soil microorganisms and their associated processes are highly sensitive to temperature variations. Increasing temperature promotes the decomposition of soil organic matter, enhances soil respiration, and supports microbial biomass growth [23]. Moderate warming enhances microbial enzymatic activity, increasing microbial diversity and population growth [24]. Again, elevated temperatures can heat the soil and alter the structure of rhizosphere microbiomes formed through plant interactions. For instance, increased temperatures significantly enhanced the relative abundances of methanotrophs, such as *Methylosinus* and *Methylocystis* [25]. On the contrary, elevated temperatures also affect symbiotic relationships, such as those between host plants and rhizobia. High temperatures disrupt early molecular signal exchanges between host plants and rhizobia and can impair established nodules [26].

Rising temperatures can stimulate plant growth, resulting in greater nutrient allocation to belowground ecosystems. This redistribution of nutrients influences plant-microbe interactions, particularly the populations of plant growth-promoting rhizobacteria that depend on rhizodeposition. Significant increases in the populations of plant growth-promoting rhizobacteria were observed in the rhizosphere of the groundnut variety B-95 under elevated temperature conditions, likely due to enhanced release of organic carbon-rich root exudates [27].

Microbial communities respond to these changes through trade-offs, such as adapting to new conditions, altering their composition, or limiting their biomass, which are influenced by environmental changes and substrate availability [28]. Arbuscular mycorrhizal fungi, beneficial microbes, adapt to heat stress by accumulating trehalose, a reserve carbohydrate. Enzymes involved in trehalose synthesis and breakdown are activated under heat and other stresses. This process, known as trehalose cycling, was first identified in *Saccharomyces cerevisiae* during heat stress [29]. Trehalose cycling is critical in maintaining cellular stability, making it an essential adaptation mechanism for microbes exposed to elevated temperatures.

Impact of Changing Precipitation Patterns

Alterations in precipitation driven by global climate change can significantly impact below-ground microbial communities. These changes affect the composition and abundance of microbes both directly, through variations in soil water availability, and indirectly, by influencing plant community structure, productivity, and resource distribution [30]. A notable decrease in bacterial abundance has been associated with increased water availability [31]. This decline may result from competitive interactions between soil fungi and bacteria or predator-prey dynamics involving soil microorganisms and protozoa or arthropods. For example, as soil fungi thrive under higher water availability, they may outcompete and suppress soil bacteria, reducing their populations [32]. Additionally, the abundance of protozoa or arthropods that prey on bacteria may increase when water is no longer a limiting factor, further contributing to the reduction in soil bacterial populations [33].

Water plays a crucial role in microbial movement and substrate distribution. Increased precipitation in desert steppe ecosystems elevates soil moisture, stimulating microbial activity [34]. This enhanced activity boosts soil respiration, accelerates carbon dioxide release, and facilitates the cycling and renewal of soil organic carbon, ultimately increasing its input [35].

Microbial biomass generally increases under higher precipitation levels, and microbial respiration intensifies in response to changing precipitation patterns across various ecosystems, including semi-arid grasslands [36]. Rainfall events increase soil moisture, which stimulates microbial enzyme activity by providing easily accessible substrates [2]. Microbes that have adapted to arid conditions can exhibit significant physiological and respiratory responses to increased precipitation in dry environments. When dry soils are rewetted, microbial activity may lead to carbon mineralization and respiratory carbon loss. These processes occur through mechanisms such as microbial cell lysis, the release of intracellular solutes, and the exposure of previously protected organic matter [37]. Such effects may be amplified under substantial rewetting caused by increased precipitation.

Reduced soil moisture limits substrate diffusion and thereby constrains microbial growth and reproduction through resource limitation [38]. However, microbial responses to precipitation change are not always reflected in broad shifts in community composition. In a two-year precipitation manipulation experiment, altered precipitation had no significant effect on soil microbial community composition [39]. Similarly, Wang et al. [40] reported no significant change in overall microbial diversity, although the relative abundances of specific taxa, including *Spirochaetes* and *Treponema*, were affected by precipitation variation.

In ecosystems where microbial communities are adapted to highly variable climatic conditions, changes in temperature and precipitation can nonetheless influence microbial growth, alter soil carbon dynamics, and increase carbon losses through respiration [41]. Together, these findings highlight the complex links among climate variability, microbial community structure, and ecosystem processes, and underscore the need for further study of microbial responses to changing environmental conditions.

Impact of Elevated Carbon Dioxide Levels

In recent decades, atmospheric CO_2 concentrations have increased substantially, primarily as a result of anthropogenic activities such as deforestation, fossil fuel combustion, and industrial processes. While the effects of elevated CO_2 on climate are well established, its impacts on belowground ecosystems, particularly soil microbial communities and plant-microbe interactions, have received growing attention. Because soil microbiota regulate plant growth, nutrient cycling, and organic matter decomposition, their responses to elevated CO_2 are central to predicting plant-soil feedbacks under future climate scenarios.

One of the most consistent responses to elevated CO_2 is an increase in microbial biomass and activity. Meta-analytical evidence indicates that microbial biomass carbon and respiration can rise by approximately 15% under elevated CO_2, accompanied by upregulation of genes involved in carbon and nitrogen metabolism [42]. This response is commonly attributed to increased rhizodeposition and root exudation, which provide additional carbon substrates for microbial growth [43,44]. However, these effects are not universal; prolonged exposure to high CO_2 concentrations can produce neutral or even negative responses in microbial biomass [45]. Zou et al. [46] reported pronounced biomass increases at moderate CO_2 enrichment levels (≤200 ppm), but only modest gains at higher concentrations (>200 ppm).

Elevated CO_2 also alters microbial community structure and diversity. High-throughput sequencing and functional gene array studies show that eCO_2 can reduce taxonomic richness and shift the relative abundance of key microbial groups, including decreases in Crenarchaeota and Chloroflexi and increases in fungal relative abundance compared with bacteria [47,48]. These changes appear to reflect broader shifts in microbial life-history strategy, with communities moving from resource-efficient K-strategists toward faster-growing r-strategists under eCO_2 [49]. Elevated CO_2 also increases beta diversity, resulting in greater spatial turnover and stronger differences in community composition among sites [50].

These structural changes have functional consequences. Elevated CO_2 increases the activity of carbon-acquiring enzymes such as beta-glucosidase, cellobiohydrolase, phenol oxidase, and peroxidase, which can accelerate soil organic matter turnover and carbon cycling [51]. At the same time, meta-analyses suggest a trade-off between carbon and nitrogen acquisition, with increases of about 14% in carbon-acquiring enzymes and declines of about 5% in nitrogen-acquiring enzymes [42]. These responses are also depth dependent, with functional genes involved in carbon, nitrogen, and phosphorus cycling showing stronger responses in topsoil than in deeper soil layers [52].

Elevated CO_2 elicits complex microbial responses, including shifts in community composition, metabolic trade-offs, and depth-specific functional changes. Because these effects are highly context dependent, their consequences for soil nutrient balance and ecosystem resilience remain an important area for further study.

Impact of Increasing Salinity in Soil

Soil salinization, intensified by climate change, is a major environmental stressor that alters microbial community composition worldwide. Elevated salinity imposes osmotic stress on microbial cells, reducing physiological fitness and limiting growth and activity. In agricultural systems, salinity can reduce plant water uptake, impair growth and yield, and, under severe conditions, cause crop loss. In addition, salt toxicity and reduced water availability decrease the energy substrates accessible to microbes and can disrupt plant nutrient balance, depending on soil pH and ionic composition [53,54]. Soil salinization also affects soil permeability, aggregate stability, and the cation exchange complex, and sodic soils are often characterized by structural degradation and reduced permeability. These processes contribute to soil erosion, land abandonment, and desertification [55].

Soil microbial communities play a central role in biogeochemical cycling, and changes in soil structure and physicochemical properties can directly influence microbial activity. Halophilic and halotolerant bacteria have evolved mechanisms that maintain intracellular homeostasis and allow efficient growth under high-salinity conditions [56]. By contrast, many fungi lack comparable adaptations, and increasing NaCl concentrations can inhibit mycelial growth through ionic toxicity and osmotic stress [57]. However, whether fungi or bacteria are more sensitive to salinity remains unresolved [58].

Increasing salinity has also been associated with reduced soil organic matter, altered extracellular enzyme activity, and shifts in bacterial abundance and community composition [59]. In particular, higher salinity has been linked to declines in microbial functional genes involved in carbon degradation. In arid soils, salinity typically suppresses microbial activity and organic carbon decomposition, in part by reducing water availability and potentially limiting oxygen diffusion. Consequently, freshwater habitats often exhibit greater soil CO_2 flux than salt-affected wetlands [60].

Salinity stress constrains crop productivity and alters microbial ecosystem processes. Although many studies report negative effects of salinity on microbial community structure and activity in naturally saline soils [60,61], responses remain context dependent. Elevated salt concentrations and associated ion toxicity likely induce nutrient imbalance and impair microbial growth and enzyme synthesis [62].

Impact of Drought Stress on Soil Microbes

Drought stress is a major environmental factor that affects soil microorganisms both directly and indirectly, altering microbial community composition, enzymatic activity, and metabolite production [63]. Its effects depend on drought frequency and duration [64], as well as soil type and the microbial taxa present. In general, bacterial communities are more sensitive to drought than fungal communities. As soil moisture declines, the carbon:nitrogen ratio often increases, which can favor fungal populations [65], whereas bacteria are more dependent on water for nutrient transport and access within the soil matrix [66]. Gram-positive bacteria are typically more drought tolerant than Gram-negative bacteria, largely because of differences in cell wall structure [67].

In a drought experiment on *Populus* seedlings, the rhizosphere bacterial community shifted toward higher abundances of Actinobacteria, Proteobacteria, Firmicutes, and Verrucomicrobia, with Actinobacteria being the most abundant group [68]. However, Actinobacteria and Firmicutes declined rapidly after re-watering [64]. Drought can also reduce the size of soil nematodes [69].

Microorganisms respond to water limitation by producing compounds such as proline, indoleacetic acid, proteins, deaminases, and osmolytes, which may improve soil water retention, structure, and water movement through fungal hyphae. Under drought, sensitive microbes may lyse and release these compounds into the environment, where they can be taken up by drought-tolerant microorganisms [3]. Under more severe stress, some microbes overproduce protective compounds, including trehalose in *Lactobacillus paracasei* [70], pyrimidines and amino acids in *Rhodococcus jostii* RHA1

[71], and amino acids in *Pseudomonas putida* [72]. Some bacteria also produce siderophores to scavenge iron; for example, siderophore-producing *Azospirillum* sp. strain B2 is more drought resistant than other strains [73]. In addition, *Escherichia coli* can produce extracellular polymeric substances that promote biofilm formation and reduce cellular water loss [74].

Drought also suppresses microbial metabolic and enzymatic activity, leading to reduced carbon mineralization and disruption of nitrogen and phosphorus cycling [75]. In one experiment, drought reduced dehydrogenase and phosphatase activity, consistent with lower microbial abundance under prolonged water stress. Long-term drought also inhibited nitrification, indicating broader disruption of the soil nitrogen cycle [76]. Some microbes respond by entering dormant, spore-forming states; for example, *Bacillus* species form resistant spores that become active when moisture returns [77]. Others may migrate to microsites where water remains available [78].

Advancement of modern technology to enhance microbiota in soil

Soil microbial populations are both directly and indirectly impacted by climate change-related factors, including warming, altered temperature patterns, and elevated atmospheric CO_2. Indeed, the simultaneous changes in several factors brought on by climate induce major changes in the terrestrial microbial community [79].

As awareness grows of how climate change affects soil microbiomes, strategies are needed to harness microbial capabilities for mitigating environmental stress, such as carbon sequestration through biochar and the application of beneficial plant growth-promoting bacteria and fungi [10]. The use of monoculture, combined with heavy synthetic fertilizer and pesticide applications, particularly fumigants, disrupts the function of the microbiome. Applying organic amendments over an extended period successfully increased soil fertility and encouraged the growth of a helpful soil microbiota [80]. In addition to organic inputs, the rhizospheric and endospheric microbial diversification is shaped by agricultural methods such as rotation, cover crops, intercropping, tillage, and multi-cropping [81].

More precipitation improves plant production, soil water availability, and soil organic carbon accumulation and encourages microbial growth, which in turn increases soil microbial diversity. Increases in organic matter breakdown brought on by warming improve the availability of nutrients for microbial growth, ultimately fostering microbial diversity [82].

Soil microbiomes represent a promising resource for mitigating the adverse impacts of environmental change; however, advancing this potential requires a deeper mechanistic understanding of how microbial communities resist, adapt to, and recover from climate extremes [83]. Adapting microbial consortia to particular crops and environmental circumstances has significant potential for resolving present challenges. Intercropping and organic farming are two methods that can be used to improve plant health and encourage advantageous microbial interactions. Novel strategies, including seed microbiome modification and encapsulation technology, hold promise for improving microbial colonization and persistence [84].

In agricultural ecosystems, the preservation of function depends on the soil microbiome community resistance, which is improved by core phylotypes. Core phylotypes should therefore be seen as a crucial component in improving crop yield and agricultural sustainability in the context of global change [85]. However, recent investigations have revealed the possibility of microbial treatments in soil regeneration or ensuring increased crop resilience. Utilizing the natural ability of soil microbes to sequester carbon, photostimulation, biofertilization, rhizome-mediation, enzyme-mediated breakdown, antibiotics, triggering an antioxidant defense mechanism, releasing volatile organic compounds, and inducing an induced systemic resistance response in the host plant are some of the tactics used there [86]. Crop resilience under climate stress can be enhanced by socio-ecological extension systems and engineered synthetic microbial communities (SynComs). Socio-ecological extension system facilitates adoption of microbial technologies by farmers, while SynComs - designed using microbial ecology, genetics, and computational modeling - provide tailored support to crop growth and stress resistance [87].

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Discovering the complexities of the interactions between plants and microbiomes, along with the numerous opportunities to modify them in stressful situations, has revealed important elements pertinent to sustainable agriculture. Therefore, improving plants' health, growth, and functionalities through microbiome engineering is a fundamental strategy. The development of omics tools, gene-editing methods, and sequencing technology has recently made it possible to decipher the complex networks of the interactions between microbes and plants, improving plant fitness and resistance to biotic and abiotic stresses. Genomics is also a useful tool for researching and forecasting how microbes and plants will interact [88]. Also, a new technology known as next-generation sequencing has gained popularity due to its many benefits over the traditional Sanger sequencing technique [89]. As compared with other approaches, using genetically modified microorganisms, produced by genetic engineering or biotechnology to introduce stress-tolerance genes, enhanced enzymatic pathways, or other functional genes into bacteria, is safer and more economical [90].

Future research directions

Soil chemical transformations are governed largely by processes occurring at the micro- to nanoscale [91]. Changes in microbial populations may take decades to emerge fully, yet they can have lasting consequences for ecosystem function. Despite extensive work on mycorrhizal colonization, the effects of broader shifts in microbial community composition on ecosystem function and stress resilience remain poorly understood [92]. Spatial heterogeneity and seasonal variation in microbial traits add further complexity to efforts to understand soil ecosystem dynamics.

Frameworks for evaluating resilience, resistance, and abrupt ecological change are increasingly relevant to soil microbial populations under climatic extremes, particularly drought [93]. Because microorganisms contribute to carbon sequestration across ecosystems, future research should examine how extreme events such as floods and drought affect microbial populations and functional diversity. It should also assess the potential of genetically engineered microorganisms for bioremediation and biofertilization [94].

The relationships between soil microorganisms and physicochemical properties indicate that microbial community structure and composition across soil horizons respond differentially to climate-driven warming and cooling [95]. Many microorganisms can generate new variation rapidly, a capability that distinguishes them from larger eukaryotic organisms. Studying microbial community dynamics may therefore offer new insights into predicting future carbon stability [96].

Several lines of evidence also point to the importance of microbial function across management regimes. Analyses of community composition, abiotic properties, enzyme activity, and biomass across aggregate size classes under no-till and full-till systems have linked bacterial and fungal communities to carbon use efficiency, substrate-induced respiration, and enzyme activity [96].

Grazing exclosures offer a promising approach for restoring degraded grasslands by increasing soil microbial diversity without compromising network stability [97]. Climate change may alter these benefits, however, because warming can increase nitrate levels, which in turn reduce bacterial diversity and network complexity [98]. Under future warming scenarios, grazing exclosures may therefore not rapidly restore soil microbial communities in degraded grasslands. Such delays could affect herders' incomes and, in turn, regional and national economies [99].

Climate change is also expected to alter global precipitation patterns and increase the frequency of both severe droughts and wet spells [100]. In alpine ecosystems, warming-induced shifts in microbial biomass carbon:nitrogen ratios appear to reflect plant-microbe competition for nitrogen [101]. Future studies should therefore examine microbial biomass stoichiometry, including phosphorus constraints, to clarify how nutrient limitation shapes microbial responses to climate change in alpine soils.

Finally, carbon sequestration is supported by diverse soil bacteria, with some taxa potentially contributing more rapidly because of higher metabolic activity [102]. Microbial formulations and biochar can enrich soils by enhancing carbon capture and reshaping microbial diversity through changes in soil properties [103]. Biochar porosity promotes aerobic microbial growth, while porosity, nitrate nitrogen, moisture content, and potassium availability all influence bacterial phyla [104].

Conclusions

The escalating volatility of global climatic patterns represents a formidable threat to the stability of soil-plant-microbe ecosystems, with glycophytic crops (particularly those inhabiting marginal, sandy, and saline environments) demonstrating acute vulnerability. While the multifaceted nature of plant health makes isolating climatic variables challenging, this synthesis underscores that anthropogenic environmental shifts act as a primary catalyst for soil degradation and the disruption of symbiotic microbial networks. These indirect pressures, compounded by the intensification of phytopathogen virulence and pest cycles, significantly compromise agricultural resilience and global food security.

To mitigate these risks, a transition toward regenerative agronomic frameworks is essential. The strategic integration of conservation tillage, optimized soil organic matter sequestration, and the application of microbial biofertilizers provides a robust defense against abiotic stressors. Furthermore, the deployment of advanced precision technologies, including Geographic Information Systems and Machine Learning algorithms, offers a sophisticated means of quantifying complex soil-plant interactions. By leveraging these computational tools, stakeholders can implement site-specific interventions that preserve microbial biodiversity and enhance the adaptive capacity of crops in an increasingly uncertain climate. Future research must continue to refine these predictive models to ensure the long-term sustainability of terrestrial ecosystems.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Prodipto Bishnu Angon

Drafting of the manuscript: Prodipto Bishnu Angon, Fahim Al Islam, Amena Akter , Sadia Islam Konica , Md Shakil Uddin, Arpan Das, Munira Begum, Sabrina Najnin, Srishti Chauhan

Critical review of the manuscript for important intellectual content: Prodipto Bishnu Angon, Md Arif Sakil

Supervision: Prodipto Bishnu Angon, Md Arif Sakil

Acquisition, analysis, or interpretation of data: Fahim Al Islam, Amena Akter , Sadia Islam Konica , Md Shakil Uddin, Arpan Das, Munira Begum, Sabrina Najnin, Srishti Chauhan, Md Arif Sakil

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Data Availability Statements

The datasets (and/or code) supporting this study are available from the corresponding author upon reasonable request.

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