Chapter 9
Impact of Climate Change on Soil Activity (Nitrifying, Denitrifying) and Other Interactions

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Abstract Though the soil is our motherland, it directly influences quantitative and qualitative crop traits, which determine food security and human health. Unfortunately, it is a complicated environment for microbes, and the anatomy and physiology of microorganisms in soil are immensely complicated. These ambiguities make it difficult to forecast the consequences of climate change on the behavior of soil microorganisms. Drought stress is currently the most severe Impact of climate change and significant, concerning, and dangerous abiotic stresses that cause changes in the soil environment that influence soil organisms such as microbes and plants. It alters the functionality and activity of soil microorganisms in charge of essential ecosystem services and processes. Due to the decrease in microbial activity and production of enzymes (such as oxidoreductases, hydrolases, dehydrogenases, catalase, urease, phosphatases, and glucosidase) and disruption of microbial structure caused by these stress conditions, soil fertility declines, plant productivity falls, and economic loss occurs. To identify more effective strategies for reducing the effects of drought and managing agricultural activities under challenging conditions profitably, a thorough understanding of many factors is needed to address potential approaches like genome editing and molecular analysis (metagenomics, transcriptomics, and metabolomics).

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Introduction

The most significant threat to human health in the twenty-first century, according to the WHO, is climate change. Modern climate change includes both human-caused global warming and its impact on the Earth's atmospheric circulation. Human activity has caused a 30% increase in the atmospheric concentration of carbon dioxide (CO_2), the main greenhouse gas. In addition, plant species' interactions with soil microorganisms are likely to be significantly affected by changes in temperature, ozone, nitrogen deposition, and rainfall patterns [1].

Plant and soil health is essential for all lifestyles on this planet. vegetation displays ecological areas, and flowers reply to climatic variables, including temperature and precipitation. It is likewise nicely understood that plant energy depends on soil traits and fitness and that robust interaction among biota above and below ground govern each domain's functioning [2].

Soil is a wonderful source of medium for plant development and microbial community. Interaction between plants and microbes can be beneficial or harmful based on the climate [3]. Symbiotic or non-symbiotic bacteria and a highly specialized group of fungi are responsible for favourable plant–microbe interactions (mycorrhizal fungi). Beneficial plant-associated bacteria, including those from the genus Azospirillum, the genus Bacillus, the genus Pseudomonas, the genus Rhizobium, the genus Serratia, the genus Stenotrophomonas, and the genus Streptomyces, have been shown to promote plant development and resilience to pathological conditions and abiotic stresses. However, global warming and extreme weather conditions increased CO_2 levels and warmth in the atmosphere, hampered microorganism's ability to improve plant development and resistance to infections. It also accelerated the spread and severity of many plant diseases, resulting in the appearance of new lethal mutants and significantly impacting the agricultural system and crop production [4]. Agriculture is regarded as the most sensitive sector to climate change. In the current climate change scenario, utilizing plant–microbe interaction is crucial to increase food production for the population explosion. As individuals, societal action leaders, and researchers with domain expertise, we may work to reverse the current trend.

Climate Change—A Global Issue

The global development agenda will be influenced and defined by climate resilience attempts to address climate change. However, a climate warming system affects many people's access to necessities, including freshwater, nutrition security, and energy. Climate change and sustainable development are closely related in many ways. Particularly those nations that are least developed and undeveloped will be among those that are most badly impacted and least prepared to handle the anticipated shocks to their social, economic, and environmental systems [5].

The UN Protocol on Climate Change was implemented as part of the "Rio Convention," which was adopted during the Rio Earth Summit in 1992. The political response to climate change on a global scale officially began with this (UNFCCC). The objective of this convention was to prevent "dangerous human interference with the climate system" by outlining a plan for controlling atmospheric greenhouse gas (GHG) concentrations. The COP21/CMP1 Conference of the Parties, which met in Paris, France, in December 2015, adopted the Paris Agreement. This international agreement aims to keep the rise in global temperatures for this century well below 2 degrees Celsius and to support efforts to limit the temperature rise to 1.5 °C above pre-industrial levels.

The Member States reiterate in the 2030 Agenda for Sustainable Development their commitment to halting environmental deterioration and tackling climate change as soon as practicable. The Agenda states that one of the main issues of our day is climate change and claims that it is challenging for all countries to achieve sustainable development due to worries about its negative repercussions. Increasing global temperatures, increasing sea levels, the acidity of the ocean, and other effects of climate change significantly negatively impact coastal regions and low-lying coastal countries, especially those least developed countries and Small Island Developing States. Numerous societies, as well as the planet's biological systems, are in danger of extinction [6].

The World summit on sustainable development Conference's final report, The Future We Want, places a strong emphasis on the immediacy of the global issue of climate change and how it would ultimately influence each nation's capacity to sustain its growth. The study captures the concern of the Member States on the rapidly rising greenhouse gas emissions and the vulnerability of all countries, particularly emerging nations, to the adverse effects of climate change. To execute an acceptable and successful global response to climate change, Member States have asked for the highest level of engagement and cooperation from all nations [7].

Impact of Climate Change on Plants

The altering environmental conditions affect all living beings within the civilization [8]. Ecological changes impact the terrestrial and worldwide distribution of numerous crops and their yields. Changing climatic circumstances have improved the productivity of plants cultivated in higher latitudes like maize, wheat, and sugar beets while decreasing the productivity of plants grown in numerous lower latitudes like maize and wheat [9]. Numerous studies show that between 1980 and 2008, global wheat and maize yields declined by 5.5% and 3.8%, respectively, compared to their yield forecasts assuming steady climatic circumstances [10].

Numerous climatic conditions are known to impact the growth and productivity of plant systems. Physical characteristics are typically incorporated, such as temperature, rainfall patterns, CO_2 levels, changes in agricultural environments, and the adaptability of humanoid groups. Temperature is the most critical aspect of changing environmental conditions because of its apparent nature. Its impacts on the growth of the plant system are only fully comprehended up to the best levels for crop development. Some crops may benefit from the increase in warmth and carbon dioxide levels, but only to a limited extent. For example, crops like wheat and soybeans might benefit from greater CO_2 levels when cultivated at appropriate temperatures [11].

Consequently, changing climatic conditions might be advantageous for plant systems, yet, abrupt shifts in environmental factors endanger plant systems. However, the favourable impacts of shifting climatic conditions on plant yields have been predicted to exceed the negative ones until 2030, after which any additional amplification of climatic change will mostly have a negative effect. Consequently, maize, wheat, and rice yields will all suffer in the second half of the twenty-first century, with tropical countries suffering more than temperate ones [12].

Global Agricultural Ecosystem and Extreme Climate Events

One of the main factors contributing to climate change and the greenhouse effect is the large number of greenhouse gases released by the agricultural sector. Contrarily, climate change considerably impacts agricultural production and risks food security. According to the World Food Programme, people should always have access to an adequate supply of safe and wholesome food to satisfy their dietary demands and food choices. Currently, a food shortage poses the most significant risk to food security. More than 10% of the world's population is underweight even though there is enough food to feed everyone [13]. Climate change is predicted to exacerbate food poverty by increasing food prices and lowering output. The fight against climate change may result in higher food prices. The scarce water supply for food production is strained by drought and increased agricultural water demand. There may be more land competition in areas where the climate is unfavorable for agriculture. Price increases for crops may result from extreme weather phenomena linked to climate change [14].

Agriculture is the industry most at risk from climate change because of its size and susceptibility to weather changes. Changes in temperature and rainfall significantly impact the amount of food that can be cultivated. Temperature, precipitation, and CO_2 fertilization affect various crops, locations, and changing things. Warmer temperatures reduce yield, but more rain will likely alleviate this issue [15].

Climate change affects agricultural productivity depending on where you reside and your irrigation type. Extra irrigations may harm the environment, yet they may also increase agricultural productivity [16]. Temperature increases are pretty likely to shorten crop length, reducing agricultural production. Wheat, rice, and maize production are anticipated to fall as it is predicted that temperature will rise by 2 °C in temperate and tropical regions over the next few decades. This indicates that tropical crops are more vulnerable to climate change since they are closer to their high-temperature optimums, making them more susceptible to stress from high temperatures [17].

Insect pests and diseases thrive in warm, moist environments. They all impact how much food we can grow due to factors such as temperature, rainfall, wind speed, and humidity, and their absence could have resulted in an overestimation of the costs of climate change [18]. Due to climate change, droughts are anticipated to worsen in most parts of the world. Drought-affected areas are expected to increase from 15.4 to 44% by 2100. Africa is regarded to be the most vulnerable continent. Because of the dry weather, arid areas are anticipated to lose more than half of their food output by 2050 and more than 90% by 2100 [19].

This year, many people in India may experience temperature surges ranging from 2.33 to 4.78 °C. Climate change would lower food production in many Sub-Saharan African communities by 6–24% during the next few decades. Solomon Islanders are expected to consume more seafood than they produce by 2050 [20]. This is because they are expected to consume more fish than they produce. CO_2 levels in the atmosphere should increase agricultural output. During heat waves, CO_2 levels will double and stay higher for longer. This could be detrimental to the farming industry. The intensity of climate change's effects on tropical areas of impoverished countries will be dictated by where they are and how hot it is. According to agricultural estimates based on resource and environmental research, wheat and rice yields in northwest India could grow by 28% and 15%, respectively, if CO_2 levels rose twice as much as they do currently. Non-leguminous C_3 crops grown in high CO_2 circumstances have reduced N, Fe, Zn, and S levels, all of which are found in proteins [21]. Weather changes have increased the number of bacteria and enzymes in the soil. There were many more bacteria in the temperature gradient tunnel when the temperature was 4–5 °C higher than in the field, but not as many in the area. This happens when there is a lot of CO_2 in the atmosphere. When temperatures hit 29 °C, rice crops develop more quickly, vegetatively and reproductively, and produce more seeds. However, as the temperature rose, the seeds did not set as well as they had previously [22].

Plants and Microbe Interaction in Response to Climate Change

Plants and a range of taxonomically organized microbial communities are closely related. The microbiome (microbiota and their genomes), composed of bacteria, fungus, protists, nematodes, and viruses, colonizes all exposed plant tissues. The host plant interacts intricately and dynamically with the microbiome in the soil, rhizosphere, roots, and other plant tissues. The environment substantially impacts these interactions, which can improve a plant's resistance to environmental dangers. Despite advances in our consideration of the role of the microbiome in plant development and health, there are still many obstacles to overcome before we can harness microbial connections and features to increase plant flexibility to climate change. External factors, including temperature, moisture content, and nutrient status, can impact the interactions between symbiotic and pathogenic plant microbes. Therefore, it is crucial to understand how climatic conditions affect plant–microbe interactions to anticipate disease outbreaks, develop effective symbioses and biocontrol agents, and create agricultural systems more resilient to climate change [23].

Pathogen-Plant Interaction

Three-way interactions between the environment, the host, and the pathogen, which operate on a scale from resistance to sickness, affect plant health and productivity. The quantity and behavior of pathogens, host–pathogen interplay, and the formation of novel diseases could all be affected by climate change [24]. As global temperatures rise, many plant infections are predicted to spread proportionately more widely [25]. To make matters worse, several commonly employed treatments for diseases don't work well in hot climates [26]. Dryness and high temperatures can weaken ETI (Effector Triggered Immunity) and cause disease in various plant pathobiology [27]. Most research on how climate change affects host-disease interactions has relied on overly simplistic models that only account for one host plant and one pathogen.

In contrast, the interaction and rivalry of the pathobiota and other members of the plant microbiome influence the development of pathogens. In contrast, plants interact in their natural habitat with various potentially harmful microbes [28]. We still don't know how the pathobiota and plant microflora will interact in response to ongoing abiotic stressors.

Positive Plant–Microbe Interactions

Climate change will impact beneficial plant–microbe interactions in a variety of ways. For example, warming might decrease the amount of available photosynthate below ground, restricting the size and diameter of roots [29]. Therefore, it is preferable to use arbuscular mycorrhizal fungus (AMF) species with reduced needs for carbon (C) as they are less prone to colonize roots [30]. Abiotic stresses can have adverse effects on plants. However, some plant microbiome inhabitants have characteristics that mitigate those effects. Extracellular polymeric substances (EPS), which can form hydrophobic biofilms that protect plants from desiccation, are a few examples. Another is the production of 1-aminocyclopropane-1-carboxylate (ACC) deaminase, which enhances stress tolerance by controlling ethylene levels in plants. For instance, a novel mechanism for how heat shock factor A2 (HSFA2) induces thermotolerance in plants methylates heat stress memory genes. It enhances thermotolerance in plants when HSFA2 is produced persistently through the ethylene signaling pathway and the transcription factor EIN3 [31]. It's even conceivable that some bacteria that aid in plant growth may also help plants overcome various challenge [32]. It is likely that multiple microbiome pathways that may be active simultaneously improve plant performance under stress. However, our knowledge of the interconnected molecular pathways that start the series of interactions between plants and the microbiota associated with climate change is insufficient (Table 9.1).

Nitrifying and Denitrifying Interactions

The consequences of the global shift on belowground nitrogen (N) cycle activities affect plant populations, productivity, and trace gas effluxes. However, few in vivo studies have looked at how different global change components interact to affect nitrification or denitrification.

Over 4 years, the interplay between the nitrifying and denitrifying enzyme activities (NEA and DEA) in an annual grassland ecosystem in response to various aspects of climate change (rising atmospheric CO_2 concentration, temperature, precipitation) has studied [33]. To shed insight on the mechanisms behind NEA and DEA's response to environmental change, they looked at the correlations between these activities and soil moisture, microbial biomass C and N, and soil extractable N. Elevated CO_2 reduces NEA activity across all examined climate change components and their interactions with other treatments. NEA was unaffected by temperature changes or precipitation. Temperature increase had no discernible impact on DEA.

The duration of climate change affected highland grassland fields, N_2O fluxes and related microbial enzymatic activity, microbial population abundance, and community diversity have been studied [34]. Warming, summer drought, and high CO_2 benefitted N_2O fluxes, nitrification, N_2O release through denitrification, and the population size of N_2O reducers and NH_4 oxidizers. In situ, N_2O changes were more closely related to microbial population increase in warmer environments than in the control site.

Barnard et al. investigated how NEA and DEA, soil microbial N, and soil organic N responded to increased CO_2 in the European grasslands. The study revealed that increasing CO2 had little to no effect on soil extractable [NH_4^+] and [NO_3], NEA, DEA, and microbial biomass N, DEA, and NEA at some sites. However, it was predicted that DEA and soil [NO_3] would decline by 22 and 45% in French grasslands, respectivel [35].

Alteration in Microbial Distribution

It is generally known that plant communities react to climate changes and that these reactions can change how plants are distributed in space. Several studies have made assumptions about possible alterations in the habitats of numerous plant species under extreme climatic condition [36]. However, there aren't many publications that discuss how allied soil bacteria may alter the host distribution to maintain a good or bad relationship with the host plants. It has been found that plants adapt

Table 9.1 Types of microbial interactions that can enhance plant uptake of N and related biological processes

Phylum	Family	N-associated biological process	Specificity	The efficiency of plant N nutrition improves	Intracellular versus extracellular	Specific cellular structure	Bacterial taxa	Plant taxa
Bacteria	Rhizobia	N fixation	High	High	Intracellular	Nodule	Rhizobium (alpha proteobacteria) Gram-negative	*Fabaceae*
		N fixation	High	High	Intracellular	Nodule	Rhizobium (alpha proteobacteria) Gram-negative	*Parasaponia* spp.
		N fixation	High	High	Intracellular	Nodule	*Frankia* spp.	Actinorhizal plants
		N fixation	Wide range	High	Intracellular/Extracellular	Heterocyst	*Nostoc* spp.	Aquatic plants
Fungi	Arbuscular Mycorrhizal Fungi	N uptake stimulation	Wide range	Low/High	Intracellular/Extracellular	Arbuscles	Glomeromycota	Angiosperms

Source Dellagi, A., Quillere, I. & Hirel, B. Beneficial soil-borne bacteria and fungi: A promising way to improve plant nitrogen acquisition. *J. Exp. Bot.* **71**, (2020) to changing climatic circumstances more quickly than soil-native microbes due to their superior dispersion capabilities. At the level of local communities, there is a shortage of knowledge on microbial dispersal, which only helps to increase worry. Few changes have been caused by scattering in essential microbial functions like a breakdown. However, modifications to plant and microbe dispersion capacities can influence plant establishment, production, and communication within a community, for instance, by changing the input predominance of plant litter [37].

Although it is well known that microbiological species also respond to climate changes, it is usually unknown how quickly or frequently isolated microbiological groups may adapt to climatic changes. Therefore, it is still necessary to answer the questions, such as how much microbiological dispersal restraint matters for ecosystem purposes and how rapidly microbial systems will acclimatize to changing environment. By altering their distribution within the soil systems, the microbial communities that live there may respond to the strain brought on by climate changes. For instance, in search of the ideal thermal range, the higher soil surface temperatures may cause soil bacteria to move deep within the soil profile. This type of microbiota reclassification in soil systems can potentially modify plant–microbe process relations. It is yet unknown to what extent interactions between microorganisms and plants due to direct and indirect effects of climate change may still be necessary for ecosystem functioning. Viral, bacterial, and cyanobacterial members will be more prevalent in future sub-Antarctic zone waters due to shallow mixed layers and rising iron levels. As a result of the region's iron restriction, autotrophic and heterotrophic bacterial and viral populations have declined in the waters of the Polar Frontal Zone. An increase in the number of bacteria in heated plots with higher CO_2 proportions has been noticed, but a decrease in bacterial abundance in heated plots with ambient CO_2 levels. The relative richness of Acidobacteria and Proteobacteria was affected by variations in rainfall, with Acidobacteria falling and Proteobacteria increasing in wet treatments compared to dry ones [38].

Plant–Microbe Communication

There is a communication pathway between the bacteria and the host plant. Plants release compounds under stress that attracts microorganisms that can boost plant resistance [39]. For instance, actinobacteria are enriched with the genetic ability to transport and utilize glycerol-3-phosphate (G3P) for growth due to glycerol-3-phosphate (G3P) secretion caused by root dryness [40]. Drought decreases the quantity of iron and phytosiderophores available in the rhizosphere, allowing for Actinobacteria enrichment, which may thrive in low iron settings, improving their fitness advantage and capacity to encourage plant development. The host phenotypic plasticity that the plant microbiome also influences can impact plant phenology in a changing climate [41]. For instance, rhizosphere bacteria can regulate the flowering time by modifying the nitrogen (N) cycle and converting the amino acid tryptophan in root exudates to the phytohormone indoleacetic acid [42].

Furthermore, plants communicate with insects, nematodes, and bacteria using volatile organic compounds (VOC). It is suggested that variations in the plant immune system or the host's stress signalling network may be related to variations in the microbiome's makeup caused by drought and warmth that are mediated by root exudates. VOC emissions are increasing due to climate change. To increase plant resistance to climatic stresses, it is essential to comprehend the molecular interactions that abiotic stresses have with metabolites to change the composition and efficiency of the plant microbiome (Fig. 9.1).

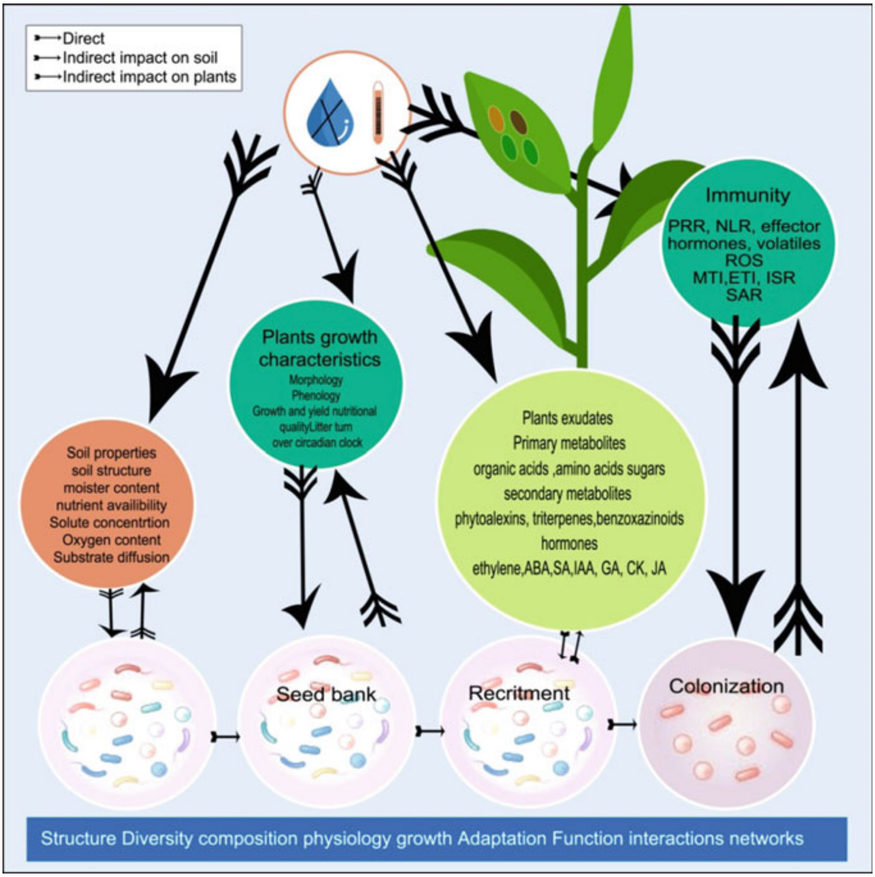

Fig. 9.1 Impact of climate change on the plant-associated microbiome. *Source* P. T. B. D. B. K. E. B. B. K. S. (2022). *Plant-microbiome interactions under a changing world: responses, consequences and perspectives.* Pankaj Trivedi 1, Bruna D Batista 2, Kathryn E Bazany1, Brajesh K Singh 2 3. https://pubmed.ncbi.nlm.nih.gov/35118660/]

Climate Change Mitigation and Adaptation Strategies

Farmers' assessments of the severity and threat of climate change serve as the primary drivers of voluntary mitigation. However, the accessibility of crucial information affects the adaption [43]. The number of people who experience water stress will also decrease due to mitigating measures, but those who do will still need adaptation techniques because of the increased stress [44]. Farmers can apply climate-resilient technology by combining conventional and agro-ecological management strategies, such as biodiversification, soil management, and water harvesting. These management strategies result in resilient soils and cropping systems, which boost carbon sequestration, improve soil quality and health, and reduce soil erosion, all of which help ensure food security in the face of climate change [45].

The most successful educational initiatives for raising awareness of climate change for ecological development focus on regional, practical, and local aspects and may be monitored by individual behaviour [46]. The fact that most farmer's favoured adaptations but a tiny percentage favoured GHG reductions highlights the need to focus on programmes with both adaptation and mitigation components. The three main adaptive mitigation strategies are cropping system technologies, resource-conservation technologies, and socioeconomic or policy interventions. Due to a lack of information, small and marginal farmers are less able to adapt to climate change, making them more vulnerable to losses [47]. A lack of management measures and financial repercussions make farmers in African nations particularly susceptible to climate change. Changes in sowing dates are just one agronomic tactic that can be utilized to lessen the consequences of climate change. Simple strategies to cut GHG emissions include alternate rice drying, mid-season drainage, better feeds for cattle, improved N-use efficiency, and soil carbon. The ability of the agroforestry sector to lower atmospheric GHG concentrations and assist small farmers in Kenya in their adaptation to climate change can be advantageous. The use of alternate rice drying, mid-season drainage, better feeds for cattle, improved N-use efficiency, and soil carbon are a few simple ways to lower GHG emissions. Simple adaptation strategies to mitigate climate change's consequences include modifying planting dates and cultivars. The diffusion of technology will significantly impact farmers' responses to climate change. The primary priorities are capacity building, public research assistance, and market integration.

Technologies that maintain soil structure deliver nutrients or water, or both, are most beneficial in reducing climate change. In semi-arid West Africa, it has been demonstrated that Zai, stone bunds, half-moons, and the application of nutrients are appropriate technologies for preserving food production and safeguarding smallholder farmers [48]. In Punjab, Pakistan, studies on climate-smart agriculture practices showed that cotton yield increased with higher returns and more efficient resource utilization. However, the climate is changing, which severely impacts the ability to grow rice and wheat. The Indo-Gangetic plain is particularly vulnerable [49]. Nevertheless, farmers have indicated that they are receptive to utilizing climate-smart agriculture practices that can substitute more profitable farming techniques for traditional ones. The most popular CSA technologies in the western Indo-Gangetic Plains (IGP) are direct sowing, LLL, zero tillage, crop insurance, and irrigation scheduling [50].

In contrast, weather warning services, crop insurance, and laser land levelling (LLL) are most popular in the eastern Indo-Gangetic Plains (IGP). These mitigating strategies have significant potential for flexibility and mitigation. However, they depend on various elements, such as a technology's relevance to the field, public perception, commercial viability, and technical complexity. These techniques perform best when several interventions are employed in conjunction with one another [51].

Conclusion and Future Perspective

All higher organisms, including those in the plant kingdom, have their origins in the microbial world. Both plants and microbes have developed a few ways to enhance their health. However, plants and microorganisms have developed in specific environments and can only withstand a certain amount of environmental change. In addition to exceeding their tolerance limit, the difference in the climate stresses out microorganisms, reducing both their productivity and the ecological function given to them. Rapid change is constantly testing plants' fitness and operational effectiveness and microbial systems in the world's climatic circumstances. Every conceivable ecological process is recognized to be primarily driven by microbial systems. Extreme weather conditions are known to interfere with these activities, disturbing the functioning of microorganisms. The modification of these processes is also known to interfere with plant productivity, which reducing agricultural output might soon result in a state of food insecurity. Therefore, repairing ecosystem harm brought on by climatic change and further halting these constantly shifting conditions may be practical tools in overcoming this obstacle. Restoration of arable and degraded lands can remove up to 51 gigatons of CO_2 from the atmosphere, which can further help increase food production by 17.6 megatons annually. Reducing water use in the agriculture sector without sacrificing agricultural output would also help attain a milestone toward acclimatizing to shifting climatic conditions since agricultural inputs account for 70% of freshwater extractions. Additionally, reducing human intervention and implementing sustainable techniques like afforestation can help limit the effects of climate change.

To conclude this study, we would like to emphasize that despite our focus on how temperature, circadian rhythm, moisture, and nutrients affect plant–microbe interactions, other environmental factors, most notably atmospheric CO_2 concentration, have attracted increasing consideration. Furthermore, there are innumerable instances of how the environment affects relationships between animals and microbes. These include (1) the Impact of ultraviolet radiation (UV-R) on the skin microbiome; (2) the disruption of the circadian clock by the gut microbiome; (3) the effects of climate change on the frequency and severity of viral diseases affecting marine animals as well as coral reef bleaching; (4) the role of nutrition in animal immunity. There are probably critical cross-kingdom principles that have not yet been discovered. The study of how climate affects host-microbe interactions in both the plant and animal kingdoms has a more significant impact on our comprehension of how current and future host-microbe interactions in both the plant and animal realms may therefore are influenced by global climatic conditions.

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