Chapter 5
Climate Change and Microbes: Mechanisms of Action in Terrestrial and Aquatic Biosystems

Sonal Kalbande, Arun Goud, Vishal Hivare, Mukesh Bhendarkar, and Karankumar Ramteke

Abstract The most crucial issue in the contemporary environmental picture is climate change. Climate change causes changes in a variety of elements at the same time, resulting in complicated alterations in the terrestrial and aquatic microbial population. These issues develop due to rising CO_2 levels, greenhouse gases in the atmosphere, changing temperature trends, and global warming, which directly and indirectly affect soil microbial communities. Microbial interactions play a vital role in the worldwide fluctuations of the significant biogenic greenhouse gases (carbon dioxide (CO_2), nitrous oxide, and methane). They usually respond to climate change immediately. Microbes regulate terrestrial and aquatic greenhouse gas fluxes. Thus, considering microbe's intricate interactions with various biotic and abiotic variables. The promise of lowering greenhouse gas emissions by regulating terrestrial and aquatic microbial processes to combat climate change is a tempting option for the future. This environmental issue is resolved by changing the microbial community structure and composition, a key feedback response mechanism for climate change when microbial communities and their mechanisms are coupled, a good strategy for addressing climate change emerges.

S. Kalbande (✉) · M. Bhendarkar
ICAR-National Institute of Abiotic Stress Management, Baramati 4131151, India
e-mail: sonalkalbande123@gmail.com

A. Goud
College of Fisheries, Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth (Agricultural University), Dapoli 415629, India

V. Hivare
International Crops Research Institute for the Semi-Arid Tropics, Patancheruvu, Telangana, India

K. Ramteke
ICAR-Central Institute of Fisheries Education, Mumbai, India

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Introduction

Currently, climate change is universally acknowledged as the most significant contemporary human threat. Based on a recent study by the Intergovernmental Panel on Climate Change [16], the situation is worsening, with 3,300 million people considered to be highly vulnerable to the effects of climate change and existing unsustainable development models increasing ecosystems and human susceptibility to climate risks. Microbes are the only life forms in specific habitats, such as deep seas and extreme environments. Microbes inhabit all the environments on earth. Microbes have been on Earth for at least 3.8 billion years, and despite any potential extinction events, they seem likely to last a long time [6].

As part of multiple processes, including the carbon and nitrogen cycles, microbes use and produce greenhouse gases such as carbon dioxide and methane. Microbes are essential to climate change models because they can respond positively and negatively to temperature. Numerous studies have demonstrated the importance of microorganisms to climate change.

It is difficult to determine their function in the ecosystem due to their diversity and the wide variety of responses to environmental change. However, microbes are rarely referred in conversations on climate change. Due to a lack of knowledge, most climate change models have not effectively accounted for microbial activity concerning climate change and its effects on the microbial population; this review aims to understand better the role of microorganisms in terrestrial and aquatic environments. The review emphasizes how vital the biosphere's microbial component is as both a "victim" and a "producer" of climate change.

Climate Change

"Climate change" refers to long-term modifications in weather patterns and temperatures. These changes could be natural, like when the sun's cycle changes, but since the 1800s, people have been the main factor in earth's climate change. Most of the time, this is because they use fuels like coal, oil, and natural gas, which are made of carbon [29]. Changes in global temperatures and the frequency of heat waves, droughts, floods, storms, and other extreme weather occurrences are all part of this.

System of Climate

The atmosphere, the oceans, the cryosphere (snow and ice), the land surface, the biosphere, and their interactions make up the very complex global system known as the climate system [12]. These interactions determine both daily weather and long-term climate averages. Natural occurrences like volcanic eruptions, solar radiation, and changes in the composition of the atmosphere by humans impact the internal dynamics of climate systems. The sun is the sole source of energy for the climate system. The equilibrium of radiation on earth can be affected by three primary factors:

1. By modifying the amount of solar energy flowing in.
2. By altering the amount of reflected solar radiation (known as "albedo").
3. By modifying the amount of long wave radiation that earth emits back into space.

Feedback mechanisms both directly and indirectly affect the climate [14].

Factors Leading to Climate Change

Greenhouse gas emissions have increased significantly in recent years due to natural events such as volcanic eruptions and human activities. Carbon dioxide, methane, nitrous oxide, and halocarbons are some gases that fall under this category. Due to the gradual accumulation of these gases in the atmosphere, the concentration of these gases gradually increases over time. During the time of industrialization, all of these gases have seen prominent peaks in their concentrations. Many different factors also contribute to the acceleration of climate change. Some of these elements are beyond our ability to manage because they are naturally occurring and are not affected by human activities. Climate change has also been caused by other natural events such as meteor strikes, which dramatically impact the earth's conditions. The climate is also impacted by variations in the sun and the earth's orbit [8]. When fossil fuels are used for ignition, cooling, transportation, construction, and cement production, carbon dioxide is produced, thereby speeding up climate change.

Additionally, it is released by microbial decomposition, respiration, and deforestation. Because of fossil fuels and biomass burning, aerosols, including organic chemicals, black carbon, and sulfide compounds, have increased. Aerosols are tiny particles that vary in size, concentration, and chemical composition and are present in the atmosphere. Although some aerosols are created using different materials that are immediately discharged into the atmosphere, others are created using factory processes. There exist both naturally occurring and artificially produced materials.

As a direct result of human activities such as open-pit mining and industrial processes, there is more dust in the atmosphere. Natural aerosols are volcanic sulfate and dust aerosols, sea salt aerosols, land- and ocean-based biogenic emissions, and surface-emitted mineral dust. The biggest culprit, however, has been the explosion of CO_2 released into the atmosphere due to human activity, especially when seen over the previous century. Fifty percent of the world's carbon is emitted by just 10 percent of the population, according to a 2015 Oxfam research. Human activities such as fossil fuel production, distribution and combustion, landfills and garbage, animal husbandry, biomass burning, and rice agriculture contribute to methane production. Wetlands and oceans are unique producers of methane emissions due to their natural processes [23].

Microorganisms and Climate Change

The sustained life of all higher trophic living species depends on the presence of microorganisms. Microorganisms are essential to the process of carbon and nutrient cycling, as well as to the maintenance of animal and plant health (including human health), as well as to the functioning of agriculture and global food, even though microorganisms are crucial in minimizing the consequences of climate change.

Role of Aquatic Microbes

According to the Census of Marine Life, microbial biomass makes up 90% of aquatic biomass. Aquatic microbes are abundant, perform essential ecological tasks, and are the backbone of ocean food webs, which in turn support the global carbon and nutrient cycles by fixing carbon and nitrogen and remineralizing organic compounds [3].

The micro, nano, and picoplankton found in the ocean, including bacteria and archaea, are responsible for most of the ocean's carbon cycle's mechanical processes. In aquatic environments, primary microbial production plays a vital role in the sequestration of CO_2. As a result, aquatic bacteria release CO_2 into the atmosphere as they recycle nutrients for use in aquatic food chains. The aquatic ecosystem is also a considerable contributor to methane emissions into the atmosphere. Because methane is constantly escaping from holes in the ocean floor and each of these methane seeps has its unique population of methane-eating bacteria because no species are consistent over the entirety of the deep sea at these places. These microorganisms can remove approximately 75% of the newly produced methane before it is released into the atmosphere. As a result, these species play an essential role in protecting the climate by reducing greenhouse gas emissions [28].

Role of Terrestrial Microbes

Around 1029 microorganisms can be found in all terrestrial ecosystems, which is similar to the number seen in marine habitats [13]. Microorganisms are the principle organic matter decomposers in a spectrum of terrestrial ecosystems, liberating nutrients for plant growth and greenhouse gases such as CO_2 and CH_4 into the soil. Microbes play a crucial role in altering the emission of greenhouse gases. The Interactions between microbes and biotic, abiotic factors lead to these alterations. It's well understood that microbes play an important role in determining the concentrations of greenhouse gases. Microbes react and impact climate change (through greenhouse gas emissions), and climate change affects microbial responses (e.g., increased CO_2, warming, and changes in precipitation) oxygen minimum zone (OMZ), or oxygen most community. Microorganisms in the soil control the amount of organic carbon sequestered there, and the amount returned to the atmosphere. They also indirectly affect the amount of carbon sequestered in plants and soils by providing macronutrients (nitrogen and phosphorus) that regulate plant productivity [4].

Atmospheric permafrost is the most significant terrestrial carbon sink due to the accumulation of carbon from organic matter (the remains of plants, animals, and microorganisms) [18, 21]. Terrestrial ecosystems rely mostly on higher plants for net primary production to remove CO_2 from the atmosphere. However, microbes also play an essential role in net carbon exchange through decomposition and heterotrophic respiration, indirectly through their roles as plant pathogens or symbionts and their influence on soil nutrient availability. The decomposition of organic matter by soil bacteria leads to an annual release of between 50 and 75 Pg. of carbon into the atmosphere; this release is 7.5–8 times more than the total amount of carbon emitted by humans across the globe [9]. This mechanism is vulnerable to the impacts of global warming, which have the potential to exacerbate atmospheric warming by creating carbon cycle-climate feedbacks. These feedbacks can be considered a positive feedback loop in which the carbon cycle influences climate.

Climate Change: Mechanisms of Action

Temperature, precipitation, and the seasons' duration are all climate change indicators [24]. Consequently, the mechanism of action is mostly shown with variations in moisture and temperature.

Aquatic Microorganisms

Climate changes have an impact on the microbial community's structure and capabilities both directly and indirectly. Climate change has speeded global warming by decomposing organic matter, thereby increasing carbon dioxide emissions into the atmosphere [26, 31]. Microbes and enzymes also stimulate warming by decomposing organic matter more efficiently, emitting toxic compounds into the environment, and averting climate change. Nearly the ocean covers 70% of the surface of the planet. has a mean depth of 4,000 m, and is diverse chemically and physically, with over 50 biomes ranging from poles to tropics and from oceanic surface to the dark abyssal zones. Microbes in the ocean account for about 98% of the global biomass; they produce 50% of the planet's oxygen and are the main processors of greenhouse gases. Marine microbes can also alleviate the effects of climate change [30]. With an evolutionary history of nearly 4 billion years, the oceanic microbes have adapted to continuously changing earth's environment and developed resiliency and physiological plasticity, which would offer some protection from artificial climate changes. At present, the rate of climate change is higher in the earth's history due to heat-trapping greenhouse gases, posing a huge threat to marine microbes [27]. An increase in green gases elevates the global temperature, thereby increasing the temperature of the sea surface. In this century, due to global warming, there is expected to be an increase in surface ocean water temperature from 2 to 6 °C [19]. This wide range of temperature fluctuations may directly affect water chemistry, thereby majorly affecting microbes' growth and biological activity.

Increasing temperature affects biological processes and reduces water density of water and thus affecting the stratification and cycling of organismal dispersal and nutrient transport. Enhance in stratification also increases the pace of future warming. Hot upper layers in deeper lakes may reduce air exchange, usually one of the processes of adding oxygen to water. Large anoxic dead zones that cannot support life may result from this. The oxygen minimum zone (OMZ) has increased due to ocean warming over the last five decades, reducing oxygen solubility [20]. Increased carbon dioxide levels could assist changes in composition and competition among algal communities. In the aquatic ecosystem, the abundance of microbes is inversely proportional to temperature. The water's important property, i.e., viscosity, also relies on temperature, and its changes significantly impact the growth rate of consumers, carrying capacity, and the mean density of apex predators. Oceanic phytoplankton multiplication and cell density are higher, and early decaying occurs at a higher temperature. Temperature and other environmental factors determine the global biogeography of phytoplankton and select species based on optimal growth potential [15]. The effects of warming on controlling the phytoplankton dynamics in aquatic systems, such as lakes and the open ocean have been reported.

Survival of phytoplankton at high temperatures depends on phenotypic domestication, mutation, and selection. Microbes can adapt to adverse conditions due to phenotypic acclimation, which results from physiological modifications. A general trend indicates that warming favors smaller phytoplankton's as they have more tolerance to increasing temperature. Nature selection toward small-size primary producers possesses a great effect on biogeochemical cycles. Both marine and freshwater microalgae growth rates are affected by temperature, showing rapid responses to climate changes. Such changes are exhibited by changing algal species in the oceanic environment. These effects on algae are useful in understanding the past and detecting current anomalies. For example, changes in red algae pigmentation indicate an irradiation state and are therefore good signs of climate change. In some micro-algal species, the increase in temperature increases metabolism and growth. And also, competition at the species and community level is altered among other sensitive species. A prominent role is played temperature in the distribution of algal species. In general, microorganisms disperse more than macroscopic organisms [2]. It is mentioned that the algal species Fucus distichus disticus is distributed to the north of 13° isotherms in Britain. A 1–2 °C increase in seawater temperatures in summer could lead to a shift by 13° isotherms northward by this species and their disappearance in Britain [11]. Because of decreasing nutrient contents and shallowing of the surface mixed layer, remote sensing data show that diatom populations dropped globally from 1998 to 2012, mainly in the North Pacific [6].

In marine microbial food webs, the Heterotrophic bacteria occupy the central position. Temperature regulates the metabolic activity of heterotrophic bacteria and their interactions with other compartments in the web. In aquatic systems, the bacterioplankton activity is mainly determined by temperature, and because of their huge numbers and significant turnover, these play an important role in biogeochemical cycles. Important ecosystem processes such as bacterial production, growth efficiency, respiration, and bacterial–grazer trophic interactions may alter in warmer oceanic water. A higher correlation is found between temperature and bacterial activity in estuarine and coastal environments than in the open ocean and freshwater environments. As temperatures increases, the grazer's predation rates are anticipated to surge in proportion to the predator's body mass. Temperature and no substrate availability limit the bacterial productivity in cooler temperate coastal regions. However, the rising ocean temperatures may favour heterotrophic bacterioplankton over phytoplankton, which may lead to substantial heterotrophic yield.

Terrestrial Microbes

Soil microbes play a vital role in maintaining climate by controlling the turnover rate of soil organic matter (SOM), the biggest organic carbon pool in the lithosphere. Microbial communities found in soil carry out Carbon (C) and nutrient cycling in ecosystems. Rising atmospheric carbon dioxide levels, changing weather patterns, and global warming may affect the microbial populations in soil directly or indirectly. We have little understanding of how climate change affects soil microbes and climate. Multiple factors are altered because of climate change that brings complex changes in the soil microbial community. These alterations may have a major impact on the microbes and plants and also on the carbon balance of the soil [7]. Interactions between multiple variables of climate change factors could selectively target specific soil microbes, which could lead to changes in communities that may ultimately determine the state of ecosystems in the future [5].

Biotic and abiotic factors like temperature, litter inputs, and moisture affect microbial activities. And both abiotic and biotic factors are affected by atmospheric and climatic changes. Climate changes induce stress in abiotic factors, which may change the diversity of soil microbes and their processes [22]. Microbe's activity, processing, and turnover ability enhance with increasing temperature, which may cause the microbial community to shift towards representatives adapted to high temperatures and faster growth rates. For instance, climate change in western USA had effect on the arid topsoil cyanobacteria i.e. Microcoleus vaginatus and Microcoleus steenstrupii. As the temperature increased, the thermo-tolerant Microcoleus steenstrupii replaced and outcompeted the Microcoleus vaginatus, which is psychrotolerant. These bacteria maintain the topsoil microbial population as they control soil erosion [10]. The quantity and function of soil microbes are affected by climate change. Microorganisms that control cycles, like denitrification, nitrification, nitrogen fixation, and methanogenesis, are also affected which may affect other ecosystem processes.

Increased microbial activity because of climate change may also elevate soil respiration [32]. Changes in the structure of the microbial community, availability of substrate, quality, and quantity of plant litter, and available carbon abundance brought by an increase in temperature trigger alterations in soil respiration. Soil respiration and temperature are correlated positively and may be inhibited at high or low moisture content. And also, the enzyme production rate is affected by alterations in moisture and temperature because of its effect on the availability of substrate, enzyme, and microbial efficiency. The N-degrading enzymes are less sensitive to temperature than enzymes degrading C [25]. Soil respiration, microbial biomass turnover, and soil organic matter are greater in tropical regions when compared to temperate soils [17].

Plants are prominent biotic factors that change the soil respiration rates by emitting carbon substrates from roots and also alter temperature and soil moisture through evaporation and by giving shade and altering the amount of precipitation. Moisture also plays an important effect in soil respiration patterns in many land ecosystems. The microbial activity could also be suppressed by moisture in many environments like saltwater and soils. Moisture may have severe effects on dynamics and the emission of carbon dioxide [1].

Climate Change Effect on Microorganisms

Climate change affects the speed in direct and indirect ways or slows down the composition of land and aquatic-based microbial groups and their roles. The following are the effects of climate change on microorganisms: biodiversity stimulation, diversity, and composition can lead to extinction or alteration, which can have beneficial or adverse effects on the reduction or effect on its physiology and the production of greenhouse gases. The architecture of the microbial community changes in response to rising temperatures, which also affects the structure of the microbial community changing with increasing temperature, which also affects the accelerating processes such as respiration, fermentation, and methane production. The resulting heat waves, wildfires, intense storms, rising floods, natural disasters, extreme heat, poor air quality, drought, injury caused by spread and emerging diseases, and death risks are all involved in the impact of global warming on biotic and abiotic elements. The effects of bacteria, fungi, algae, and archaea on: first, an acceleration of global climate change is as follows warming caused by the breakdown of the organic component; second, an increase in carbon dioxide flux into the atmosphere.

Climate change impacts terrestrial microbes through altering temperature patterns, changing precipitation, increasing carbon dioxide levels, and altering ecosystems, among other things. Climate change impacts aquatic ecosystems due to increased ocean stratification, a rise in the temperature of coastal waters, the extinction of species, and an increase in the nitrogen-fixing capacity of plants and animals. Due to the warming of the ocean, primary output has been reduced. The melting of ice, the prevalence of storms, the rising amounts of carbon dioxide, variations in particular

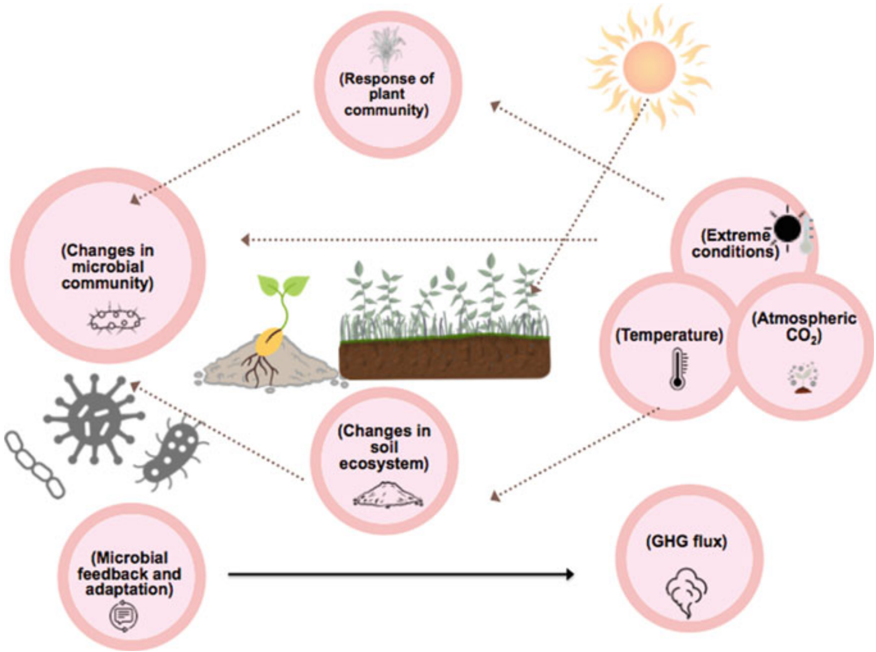

Fig. 5.1 Effect of Climate change on microbial diversity and functioning

ocean bacteria, and increase in toxic algal blooms are all effects of climate change (Fig. 5.1).

Mitigation Strategies

1. A better understanding of microbial interactions might help build climate change remedies.
2. Strategies to reduce emissions in agriculture are provided by an understanding of the ecophysiology of the microorganisms that convert N_2O to N_2.
3. Reduce the usage of synthetic chemical fertilizers in agriculture and replace them with beneficial microorganisms as bio-fertilizers, which eliminate immediately all greenhouse gas emissions.
4. Rumen microbiome manipulation and breeding programs targeting host genetic variables alter microbial community responses. The United Nations' 17 Sustainable Development Goals can be addressed by implementing microbial technologies, which provide practical solutions (chemicals, materials, energy, and remediation) for these issues.
5. It is essential to introduce new species into the ecosystem regularly.
6. Improving the ability of biotic organisms to withstand drought.

7. Implementing afforestation programs on a global scale. The sequestration of carbon is then easily managed.
8. Getting people to support these actions will be much easier if they know more about microorganism's crucial roles in global warming, called "microbiology literacy.
9. Using bio-based chemicals and polymers because they reduce greenhouse gas emissions.
10. Plastic bags can be recycled and reused to reduce the impact of land-based pollution on maritime ecosystems.
11. Increasing the general public's knowledge of microbiology will help them make more environmentally responsible judgments (Fig. 5.2).

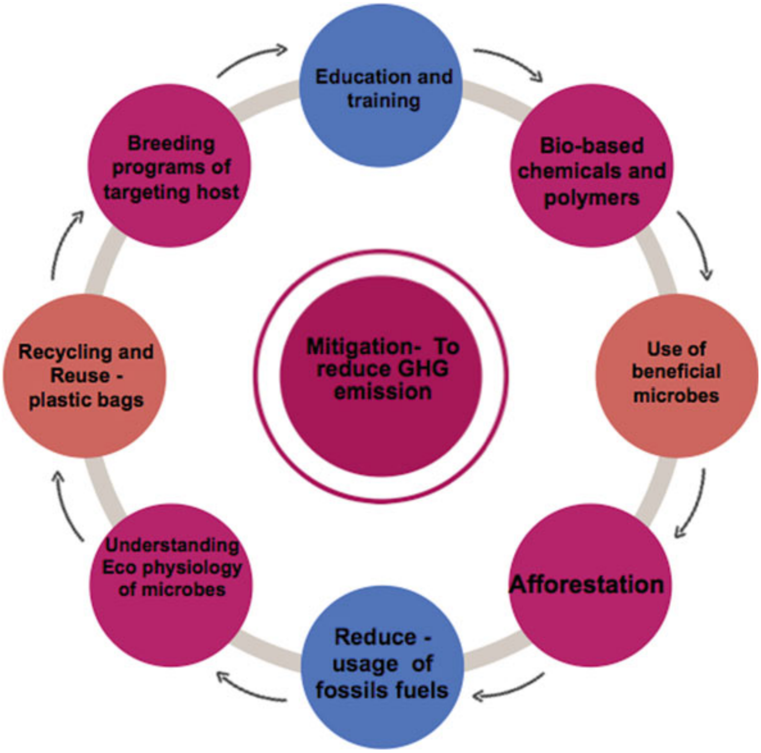

Fig. 5.2 Mitigation strategies for climate change

Conclusion

To the scientific community's admiration, bacteria play a vital role in determining greenhouse gas emissions. Estimates of these bacteria's long- and short-term reactions to changing climate and their direct and indirect effects can be used to determine their potential contributions. We can use microbes as a natural resource to combat global warming if they are appropriately utilized. Consequently, ignoring this could be a significant contribution to the problem's worsening. Investigating this issue, learning more about the underlying mechanisms, and using that knowledge in developing practical solutions are long overdue.

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