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Microorganisms as Eco-Engineers in Mitigating Global Warming: A Short Review from Bangladesh Perspective

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Microorganisms are the unseen architects of our ecosystems. They are the key players in maintaining the ecological balance through nutrient cycling, waste degradation, bioremediation, and even climate regulation. Microbes control the greenhouse gas flux by consuming and producing CO_2, CH_4, and NO_2 during their metabolic processes. They also protect plants from abiotic stress via carbon sequestration. Thus, microbes help safeguard both the atmosphere and life. To better understand and leverage this microbial contribution to combat climate change, biostimulants and other strategic environmental interventions must be improved with a suitable climate model and policy framework. Especially in Bangladesh, where climate vulnerability is high and heatwaves strike more frequently, using microbial resources can significantly enhance resilience. This review outlines the major roles of microorganisms as eco-engineers, examining recent studies and developments that emphasize their importance in ecosystems and in reducing greenhouse gases.

Keywords: Microorganisms, Eco-engineers, Climate change, Bioremediation, Heatwave

INTRODUCTION

The inception of life on Earth, dating back nearly four billion years, was marked by the emergence of microorganisms-the earliest architects of our biosphere. Microscopic organisms like bacteria, viruses, fungi, and archaea exhibit the most diverse life patterns. Their impact on human life and every corner of Earth's surface is undeniable. Their influence extends from regulating atmospheric gases to enhancing soil fertility and maintaining ecological balance. From hydrothermal vents to lithospheric bedrock, the diverse distribution of microbes plays a pivotal role in atmospheric chemistry, enabling adaptation to fluctuating environmental stress (1,2). Microbes can function both as bio-indicators of environmental perturbation and as biotechnological tools for the ecosystem. These ecological engineers influence the climate trajectories (3,4). Earth's average surface temperature has increased uncontrollably over the last 100 years. Anthropogenic activities are the main driving reason disrupting the environmental balance. Greenhouse gases like CO_2, CH_4, CFC (Chlorofluoro carbon), etc., trap the terrestrial emission as heat energy on the earth's surface, subsequently heating the world. This warming causes natural disasters to occur more frequently, diseases have become more incurable, and foods have become more perishable. Politicians, business leaders, and policymakers prioritize the topic to mitigate environmental exploitation. Microorganisms have both positive and negative impacts on climate change as they increase greenhouse gases in their daily life, along with decreasing them. They are both the users and generators of global warming (5).

Microbes can uptake, store, and recycle the atmospheric pollutants through their nutrient cycle. Strategic modification of their genes can lead to significant amplified results. Today, in the era of rapid climate change, microbes are increasingly recognized for their potential to reduce greenhouse gases and promote environmental stability (5). For Bangladesh, utilizing microbial strategies in agriculture and climate resilience could provide crucial benefits. In this review, we examine the multifaceted roles of microorganisms in climate regulation, with a particular focus on their potential contributions within the Bangladeshi context. By examining current research, this paper seeks to establish a foundation for utilizing microbes as a cornerstone of future climate action frameworks.

Climate Change and Global Warming: Atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere are the Earth's climate layers to protect the lives on Earth. The atmospheric gases are involved in a complex interaction to make the world livable. The increased concentration of greenhouse gases in the atmosphere causes a long-term alteration of the global climate system. Natural factors such as volcanic eruptions, solar variability, and oceanic cycles, as well as anthropogenic activities, play a vital role in disrupting the system. In the last decades, the industrial revolution, and human-driven emissions of carbon dioxide (CO_2), methane (CH_4), oxides of nitrogen (NO_x), oxides of sulphur (SOx), and

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other pollutants have risen sharply due to fossil fuel combustion, deforestation, intensive agricultural processes, and urbanization. These gases trap outgoing longwave radiation, increasing global mean surface temperatures and altering precipitation patterns, sea levels, and extreme weather event frequencies (5). Water vapor, the most abundant greenhouse gas, amplifies warming through positive feedback mechanisms, while aerosols exert complex effects, both cooling by reflecting sunlight and warming via black carbon absorption. Observed consequences include glacial retreat, ocean acidification, biodiversity loss, and disruption of ecosystem services. Projections indicate that without significant mitigation, climate change will intensify, posing critical risks to food security, public health, water resources, and socio-economic stability (6). Addressing these challenges requires coordinated global strategies for emission reduction, adaptation, and sustainable resource management. Some greenhouse gases, their sources, and impacts (5, 7-10) are listed below in Table 1. The global temperature has increased alarmingly over the last decade. The annual average temperature was noted as the highest in 2023 (1.54℃), where the threshold value was assumed to be 1.5℃ (6). The trend of temperature is expected to continue upward in the upcoming year as well. The El Niňo event is getting combined with natural and man-made global warming issues, creating a record-breaking warm year. Arctic temperature has risen four times over the last 40 years, melting down the sea ice and snow cover. The increase in greenhouse gas concentrations, specifically carbon dioxide, has reportedly been 1.1% higher than in previous years (12). The overall temperature increasing trend (6) is shown in Figure 1.

Table 1: Greenhouse gases with their sources and effects (5, 7-10).

Greenhouse gas	**Primary Sources**	**Natural Sources**	**Anthropogenic Sources**	**Climate Impact**
Carbon dioxide (CO_2)	Respiration, microbial decomposition, and volcanic activity	Plant decay, respiration, and volcanic eruption	Fossil fuel combustion (transport, industry, power), cement manufacturing, and deforestation	Long-lived greenhouse gas; a major contributor to global warming via the enhanced greenhouse effect
Methane (CH_4)	Anaerobic decomposition in wetlands and oceans	Wetlands, termites, and marine sediments	Fossil fuel extraction/transport, livestock farming, rice cultivation, landfills, biomass burning	High global warming potential, shorter atmospheric lifetime than CO_2
Nitrous oxides (NO_x)	Microbial processes in soils and oceans	Nitrification/denitrification in soils, ocean upwelling	Fertilizer application, fossil fuel combustion, biomass burning	Contributes to both warming and stratospheric ozone depletion
Halocarbons	None (synthetic compounds)	None	Refrigerants (CFCs, HCFCs), industrial solvents, propellants	Extremely high global warming potential, ozone layer depletion
Ozone (O_3)	Photochemical reactions in the atmosphere	Stratospheric formation via UV radiation acting on O_2	Tropospheric formation from NO_x, CO, VOC (Volatile Organic Carbon) emissions; stratospheric depletion from halocarbons	Tropospheric ozone acts as a GHG (Greenhouse Gas); stratospheric ozone loss increases UV radiation reaching the surface
Water vapor (H_2O)	Evaporation from oceans, lakes, and soil; transpiration from plants	Hydrological cycle processes	Indirectly increased by warming (greater moisture capacity), CH_4 oxidation in the stratosphere	Most abundant global warming potential; amplifies warming via positive feedback
Aerosols	Mineral dust, sea salt, volcanic ash, biogenic particles	Desert dust storms, sea spray, volcanic eruptions, and vegetation	Fossil fuel combustion, biomass burning, industrial emissions, mining, and land-use change	Can cool (via scattering sunlight) or warm (via black carbon absorption) the atmosphere; affect clouds

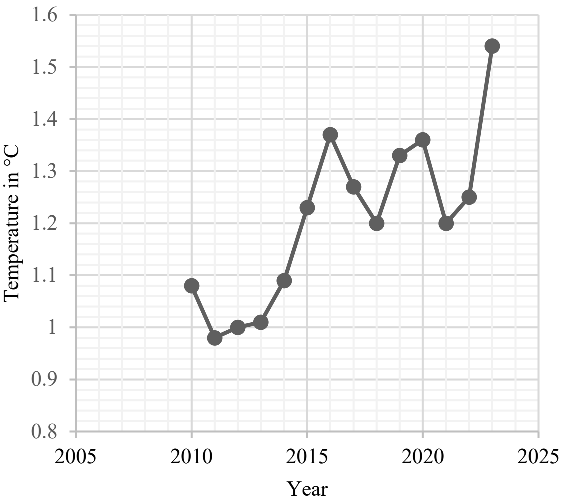

Figure 1: Average temperature change in the last few years shows the global warming (6).

Finding solutions to climate change, increasing global mean temperatures, intensified climatic variability, and extensive biodiversity loss have been major challenges in recent years. These phenomena are primarily attributable to anthropogenic greenhouse gas emissions. Nature-based approaches, such as bioremediation using microorganisms, might be a better option to explore.

Microbial remediation of climate change: Microorganisms are commonly known for their detrimental effects, though they are indispensable allies to ecological sustainability. From medicine to food, microbes can be utilized scientifically to protect our climate. Microorganisms are the engineers of ecology. They can actively protect the environment by decomposing waste, maintaining soil fertility, mitigating pollutants, and converting them into useful or less harmful products. The International Union for Microbiological Societies (IUMS) and the American Society for Microbiology (ASM) jointly convened a Scientific Advisory Group (SAG) comprising global experts in microbiology, technology, and economics to examine how microbiology can be harnessed safely and effectively to mitigate climate change and protect biodiversity (13). Innovation to utilize microbes in mitigating greenhouse gases, along with converting them into useful goods, is the futuristic solution to climate change.

Microorganisms in controlling methane emission: Methane (CH_4) has a higher global warming potential than CO_2, though it has a shorter lifespan in the atmosphere. It traps more heat energy, thereby contributing more strongly to global warming. Methanotrophic and nitrifying bacteria reduce CH_4 and N_2O emissions through oxidoreductase-driven metabolic pathways (14). Microorganisms are both the generator and consumer of methane. Identification, characterization, and manipulation of methanogens using biotechnological approaches are necessary to reduce atmospheric emissions of methane. The major sources of methane are wetlands and atmospheric methane. Aerobic and anaerobic methanotrophs modulate CH_4 fluxes via enzymatic oxidation (15). Around 17% global methane contribution comes from enteric fermentation of ruminants (16). The common rumen methanogenic species include *Methanobacterium formicicum, Methanobacterium bryantii, Methanobrevibacter ruminantium, Methanobrevibacter millerae, Methanobrevibacter olleyae, Methanomicrobium mobile, Methanoculleus olentangyi,* and *Methanosarcina barkeri*. Aerobic methanotrophs oxidize CH_4 at oxygen-methane interfaces, reducing methane escape (*Methylocystis parvus*, *Methylosinus trichosporium)* (17). *In wetlands,* facultative methanotrophs operate in oxic-anoxic soil layers, mitigating methane fluxes in sensitive ecosystems (*Methylobacter tundripaludum*, *Methanomonas methanica)* (18). Research is focused on reducing methane emissions through biotechnological strategies. These techniques include biological control of ruminal methanogens, use of probiotics, removal of protozoa, mitigation through feed additives, feeding management, and genetic manipulations of ruminal microbes for reduced methane production (19).

Soil Microbes in Microbial Remediation of Greenhouse Gas: Soils function as significant global carbon sinks, with microbial activity contributing to the stabilization of soil organic carbon (SOC) pools (20). Autotrophic microbes such as *Thiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans* fix CO_2 via chemoautotrophic pathways, transforming inorganic carbon into stable organic matter (21). Soil microorganisms, including bacteria and fungi such as *Trichoderma harzianum* and *Bacillus megaterium,* secrete exopolysaccharides (EPS), which bind soil particles, forming microaggregates that physically protect organic carbon from decomposition (22). *Sporosarcina pasteurii* facilitates Microbially Induced Carbonate Precipitation (MICP), locking atmospheric CO_2 into stable calcium carbonate minerals (23). Mycorrhizal associations, such as those involving fungi like *Rhizophagus irregularis*, enhance root exudation (rhizodeposition), which feeds soil microbes and further stabilizes carbon in the rhizosphere (24). These processes reduce atmospheric CO_2 while enhancing soil fertility, resilience, and water retention capacity.

Bioconversion: Microorganisms possess diverse metabolic capabilities that enable the conversion of waste into high-value products (biofuels, chemicals, and biofertilizers) while mitigating greenhouse gas emissions. Bioconversion processes include bioenergy production (anaerobic digestion by *Methanobacterium* spp. and *Clostridium* spp., ethanol fermentation by *Saccharomyces cerevisiae*), carbon capture via Ralstonia eutropha, and biomanufacturing. It replaces petrochemical-based products with renewable alternatives. These technologies are adaptable to local resources, supporting decentralized production of fuels, fertilizers, and bioplastics (13,25-32). Sustainable aviation fuel (SAF) and biodiesel from *Yarrowia*

Table 2: Microorganisms in bioconversion to mitigate climate change (27-32).

Microorganism	Bioconversion Process	Value-Added Product	Application	Reference
Methanobacterium spp.	Anaerobic digestion	Biogas (methane)	Renewable energy, waste reduction	Bentsen *et al*. (27)
Clostridium spp.	Anaerobic digestion, solvent fermentation	Biogas, solvents (acetone, butanol)	Biofuel production, chemical feedstocks	Weiland *et al*. (32)
Saccharomyces cerevisiae	Ethanol fermentation	Bioethanol	Transportation fuel, GHG mitigation	Ibrahim *et al.* (28)
Ralstonia eutropha, *Cupriavidus necator*	CO_2 fixation & biosynthesis	Bioplastics (polyhydroxybutyrate - PHB)	Petrochemical replacement, biodegradable plastics	Keasling *et al*. (30)
Azotobacter spp.	Biological nitrogen fixation	Biofertilizers	Sustainable agriculture	Bentsen *et al*. (27)
Rhizobium spp.	Symbiotic nitrogen fixation	Biofertilizers	Crop yield improvement	Bentsen *et al*. (27)
Yarrowia lipolytica	Lipid accumulation	Biodiesel, specialty lipids	Renewable fuels, industrial oils	Baral *et al*. (31)
Chlorella vulgaris	Photosynthetic carbon fixation	Biodiesel, biomass	High carbon capture, non-arable land use	Liu *et al*. (26)
Nannochloropsis spp.	Photosynthetic lipid production	Biodiesel	Sustainable aviation fuel, marine biofuels	Ashour *et al*. (29)

lipolytica and microalgae (*Chlorella vulgaris*, *Nannochloropsis* spp.) can cut greenhouse gas emissions by up to 80%. The emitted CO_2 from biofuels (biodiesel, bioethanol, biohydrogen) can be absorbed by the plants and contribute less to greenhouse gas (20). Table 2 shows the examples of microbes in the bioconversion of greenhouse gases.

Microbiome Engineering and Nanotechnology: Microbiome engineering represents a transformative approach to climate mitigation, involving the deliberate manipulation of microbial consortia to enhance ecosystem services. Environmental microbiome engineering involves the strategic introduction of beneficial microbial consortia into ecological niches to modulate biogeochemical processes (2). Operational framework includes the functional targeting to enhance carbon retention or nutrient cycling, microbial selection of diazotrophs which enhance nitrogen fixation and thus reduce the need for synthetic fertilizers., Methanotrophs regulate methane cycles in soil and waste management. Phosphate solubilizers mobilize insoluble phosphorus, improve plant uptake, and reduce eutrophication risks. and thus, inoculum design using synthetic biology or directed evolution (4); field application in soil, aquatic, or phyllospheric environments using tailored carriers. Biostimulants, enhancing plant physiological performance under environmental stresses (33), can be utilized. *Bacillus subtilis* and *Azotobacter chroococcum p*romote rhizogenesis via phytohormone modulation, like auxins and cytokinins production (34). *Pseudomonas fluorescens* and *Paraburkholderia phytofirmans* induce systemic resistance via jasmonic acid and salicylic acid pathways (35). *Rhizophagus intraradices* and *Claroideoglomus etunicatum* facilitate phosphorus and zinc mobilization through arbuscular mycorrhizal networks (32).

Nanoscale (the dimensions of sizes in the range of one-billionth of a meter) innovation is the futuristic new scope to explore. The development of nanodevices mimicking natural photosynthesis enables artificial photosynthesis. Semiconductor-based biocatalysts are used to absorb light energy. *Sporomusa ovata* and engineered *E. coli* are used as biocatalytic agents (36). The utilization of unassisted solar CO_2 fixation to value-added chemicals and nanowire bacterial hybrids is an effective technology, as it possesses a high reaction rate of CO_2 reduction (37). A single enzyme nanoparticle (SEN)-based biosensor utilizing carbonic anhydrase has also been reported for gaseous CO_2 sequestration (38). Researchers in Israel have engineered *E. coli* to grow entirely on CO_2 by incorporating a non-native Calvin cycle (39). Normally a heterotroph, *E. coli* was reprogrammed through targeted genetic modifications to convert it to a fully autotrophic organism. The key innovation involved reversing the formate hydrogenlyase (FHL) reaction under pressurized CO_2 and H_2. FHL acted as a CO_2 reductase, producing formate ($HCOO^-$), which then powered carbon fixation via the Calvin cycle. This enabled the bacteria to synthesize biomass directly from atmospheric CO_2. The breakthrough offers a promising biological tool for CO_2 sequestration, contributing to novel strategies for mitigating climate change.

Bangladesh: Regional Perspective on Microbial Climate Remediation: The geographical position of Bangladesh makes it more vulnerable to climate change. Every year, people of Bangladesh face frequent heatwaves, cyclones, droughts, and floods. The damaged ecosystem is affecting the livelihood, infrastructure, and food security. It has been reported that temperature might be increased by 0.8°C, and heavier rainfall might increase the river flow by 16% raising the risk of flooding (40). People in coastal areas are affected more due to an increase in sea level during cyclones. Saline water will make their livelihood more difficult. Extreme stress in the recent heatwaves is reducing productivity and costing lives. Hyperthermia, heatstroke, headache, and fatigue have become daily life issues. A rise in temperature by 3°C is decreasing productivity of outside and inside workers by 25% and 19%, respectively (41). Most of the rural people in Bangladesh are directly or indirectly dependent on agriculture. Heat stress affects the overall food wave. Study revealed that around 37% and 22% of the people working in the agricultural and garment sectors are badly affected by the heat stress (42). Even the people working in poorly ventilated areas suffer more in heatwaves.

A forecast in Khatun *et al*., 2021 (43) showed that by the year 2030, around 30,366,230 households will be affected by climate change, including a 5.17% increase in greenhouse gas emissions. 17% of the people will need to be relocated if global warming persists at the present rate, and there will be 3 to 10 million internal migrants in Bangladesh over the next 40 years. Jihan *et al*., 2025 (44) expected the temperature rise from 1°C to 4.4°C, shifting to warmer and drier conditions. A very high temperature with increased humidity is called a heatwave. Generally, the temperature range between 36°C to 38°C is noted as a mild heatwave, 38°C to 40°C as a moderate heatwave, and above 40°C is considered a severe heatwave. These waves are generally meant to occur just before the monsoon season, but in recent years, they have been appearing frequently. In 2024, the Bangladesh Meteorological Department (BMD) mentioned that severe heatwaves (≥40°C) were affecting Rajshahi, Pabna, Chuadanga, Natore, Chapai Nawabganj, Kushtia, Jhenaidah, Jashore, Meherpur, and Bogura, while moderate heatwaves (38-39.9°C) were hitting Bagerhat, Satkhira, Barguna, and Barishal. The most affected areas were Rajshahi, Khulna, Rangpur, Dhaka, and Barisal (45). Figure 2 shows the affected areas. This heatwave lasted for three to seven days. Over these seven days, temperatures in the heatwave-affected places have been consistently 4°C to 5°C higher than in the last 30 years' record. The Directorate General of Health Services (DGHS) reported 10 heatstroke-related deaths across Bangladesh. The Government announced the closure of educational institutions immediately during those days, considering public health. Heat-related illness, like heat stroke and dehydration, has increased alarmingly, where

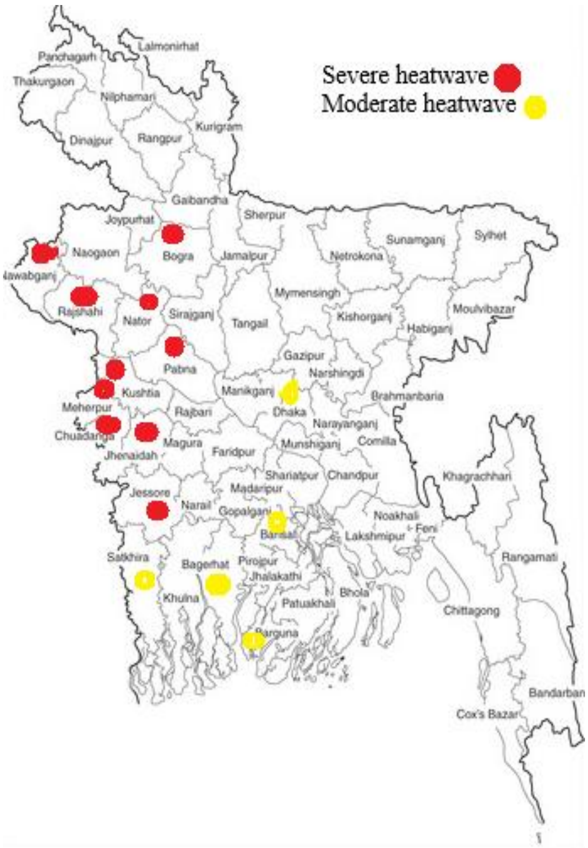

Figure 2: Map of Bangladesh indicating heatwave areas (32).

the elderly, children, and low-income communities were more vulnerable (46).

Several researchers (47-49) concluded that the heatwave areas are a combination of various factors, including the duration of high temperature, air flow, and weather patterns. Miah et. al. 2022 (45) suggested analyzing the heat database and weather forecasting about heatwaves. Monitoring the soil moisture is considered an improvement plan for heatwaves. Unfortunately, microbial remediation is less focused and less utilized.

In response, the country has made noteworthy strides in utilizing indigenous microbial resources to combat climate-induced stress. Native microbial strains, such as *Azospirillum brasilense, Rhizobium leguminosarum,* and *Pseudomonas putida,* have demonstrated multifunctional plant growth-promoting traits, including biological nitrogen fixation, phosphate solubilization, production of phytohormones, and stress-induced gene expression enhancement (50). Institutions like the Bangladesh Agricultural Research Council (BARC) and Bangladesh Institute of Nuclear Agriculture (BINA) spearhead microbial trials for crop resilience enhancement (46). Enhancement of drought resilience through nitrogen fixation (*Azospirillum brasilense)*, pulse crop productivity (*Rhizobium leguminosarum*) provider of phosphate solubilization, and stress resilience (*Pseudomonas putida*) are utilized. Methanotrophic taxa in rice paddies, combined with modified irrigation, show potential to reduce CH_4 emissions (51). Development of microbial bioformulations suitable for deltaic and saline soils positions Bangladesh as a leader in applied microbial climate adaptation (52).

Limitations and Future Aspects: Bangladesh is a climate-vulnerable region where environmental degradation and agricultural dependency exacerbate susceptibility to climate impacts. The strategic application of microbial functions presents a scientifically robust and underexploited mitigation pathway. Consequently, integrating microbial ecology into climate change frameworks is not ancillary but essential to the development of comprehensive, evidence-based mitigation strategies. Several limitations obstruct this pathway. Inoculum formulation often lacks biofilm stability and compatible carriers (3). Ecological compatibility is challenged by niche competition and predation (2). Monitoring frameworks for persistence and efficacy lack standardization (4). Regulatory oversight remains ambiguous with varying biosafety approvals. Lack of harmonized global biosafety standards delays approvals (3).

Advancements in meta-omics, synthetic biology, and AI-driven modeling offer unprecedented precision in microbial consortia design (53). Meta-omics (genomics, transcriptomics, proteomics, and metabolomics) provides deep insights into microbial community structure and function. Synthetic biology constructs designer strains with enhanced resilience, targeted metabolic outputs, and reduced ecological risks. AI-based modeling predicts ecosystem interactions, optimizing microbial formulations for site-specific needs. Field validation, integration with systems ecology, and policy development are prerequisites for translational success (54).

CONCLUSIONS

Microorganisms mitigate greenhouse gases through their natural metabolic pathways. Recently improved technologies, like nanotechnology and genetically modified strains, can amplify the mitigation process. Utilization of these underutilized bioremediation processes can minimize the scorching heatwaves and save the ecosystem on a broader scale. Strategic investment in research, policy, and technology is vital to unlocking their full potential, especially in frontline nations like Bangladesh. Coordinated transdisciplinary efforts are essential to realize these potentials at ecologically and economically relevant scales.

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