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REVIEW

Microbial Biotechnology: A Key Tool for Addressing Climate Change and Food Insecurity

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ABSTRACT

Amidst escalating climate change and food insecurity concerns, exploring the potential of microbes offers a promising and sustainable solution. This review delves into the complex interplay between microbial communities and the dual challenge of environmental crisis and food security. Ubiquitous microorganisms—from bacteria to fungi and archaea—shape our planet's ecosystems, playing a crucial role in soil health, nutrient cycling, and plant-microbe interactions. This review dissects diverse microbial habitats, highlighting their remarkable adaptability to varied environments. It then underscores the reciprocal impacts of human-induced environmental changes on microbes and their habitats. Addressing these challenges, the review presents microbes as powerful allies in mitigating climate change. Their ability to sequester carbon, reduce greenhouse gas emissions, and enhance soil fertility is explored. Innovations like biofertilizers and biopesticides demonstrate the potential of microbial technologies to revolutionize agriculture and ensure global food security. Concluding, the review emphasizes the symbiotic link between microbes and sustainable food production. Microbial technologies can adapt agriculture to changing climate conditions, addressing water scarcity and enhancing soil moisture retention. Their potential to boost productivity in both traditional and precision agriculture under diverse climatic conditions is highlighted. This review calls for the urgent recognition and harnessing of microbial power for a sustainable future. Embracing microbial technologies not only fosters environmental stewardship but also paves the way for a resilient and resource-efficient agricultural future.

Keywords: Biotech for resilience, climate-smart agriculture, sustainable food systems, symbiotic solutions.

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1. Introduction

The world's population is rapidly growing and is expected to reach between 9.4 and 10.2 billion by 2050. This growth, coupled with the expansion of industrialization, has led to widespread environmental pollution. Human activities such as burning fossil fuels, using excessive land, deforestation, and intensive animal farming have all contributed to climate change. This change is having a significant impact on life on Earth (UN-Habitat, 2023). Population growth can lead to resource depletion, causing environmental concerns such as global warming, deforestation, and decreasing biodiversity. As the population increases, the Earth's resources deplete more rapidly, leading to deforestation and loss of biodiversity as humans strip the Earth of resources to accommodate rising population numbers. This growth also results in increased greenhouse gas emissions, mostly from CO_2 emissions. For instance, during the 20th century, CO_2 emissions increased twelvefold as the population grew fourfold (Mayer, 2018).

Climate change poses a significant threat to life on Earth. If greenhouse gas emissions are not limited from the burning of fossil fuels, the consequences of rising global temperatures include massive crop and fishery collapse, the disappearance of hundreds of thousands of species, and entire communities becoming uninhabitable (Lindwall, 2022). Rising temperatures around the globe are increasingly killing humans and trees, forcing half of all species on the planet to relocate, causing more water-borne and respiratory illnesses in people, and threatening food and water security for millions (Isaacs-Thomas, 2022). Addressing these issues requires a concerted global effort to reduce greenhouse gas emissions and promote sustainable practices. It's a complex problem that requires solutions at multiple levels, from individual actions to international policies. It's also important to remember that the impacts of these environmental changes are not evenly distributed, with developing countries and marginalized communities often bearing the brunt of the effects (Mayer, 2018).

Climate change affects the prevalence, invasion, and propagation of invasive species. Changing climate conditions can worsen existing problems, creating new pathways for invasive species to be introduced and allowing existing invasive species to expand their range into habitats that are currently too cool. This can intensify stress on affected ecosystems, disrupting their balance and functionality (USGS, 2023).

In addition, climate change poses a significant threat to biodiversity. Global warming has the potential to cause extinctions in a majority of the world's especially valuable ecosystems. Depending on a species' responses to the warming, especially their ability to migrate to new sites, habitat change in many ecoregions has the potential to result in catastrophic species loss (PANDA, 2023).

Climate change has diverse impacts on food security. It negatively affects all four pillars of food security: availability, access, utilization, and stability (IPCC, 2019).

Rising temperatures and changing weather patterns often result in lower crop yields due to water scarcity caused by drought, heat waves, and flooding. Microbes play key roles in nutrient cycling, biodegradation, climate change, food spoilage, the cause and control of disease, and biotechnology. They are involved in many processes, including the carbon and nitrogen cycles, and are responsible for both using and producing greenhouse gases such as carbon dioxide and methane (EPA, 2023).

Climate change and food security are intricately linked. Climate change disrupts crop yields, reduces the nutritional content of crops, and increases the frequency of extreme weather events. These disruptions threaten food production, availability, and access, particularly in vulnerable regions. Microbes, including bacteria, fungi, and other microorganisms, play a vital role in maintaining soil health, nutrient cycling, and ecosystem resilience. They enhance the availability of essential nutrients for plants, improve soil structure, and suppress harmful pathogens. However, climate change can influence microbial communities, potentially altering their functions and affecting the balance of ecosystems (Myers, 2022; Affoh *et al*., 2022; Lake & Barker, 2012; IMF, 2022).

Transitioning to a low-carbon economy requires a global effort. Mitigation strategies include enhancing energy efficiency, adopting renewable energy sources, electrifying industrial processes, implementing efficient transportation systems, and introducing carbon taxes or emissions markets. Additionally, switching to renewable energy sources like solar and wind power can significantly reduce greenhouse gas emissions. Addressing climate change necessitates a multi-level approach encompassing individual actions and international policies (Ahuja, 2009; Kyriakopoulos, 2023; Marinina *et al*., 2023).

Microbes play a critical role in maintaining soil health, nutrient cycling, and ecosystem resilience. They influence various soil processes, including decomposition of organic matter, nutrient mobilization, and plant growth promotion. However, climate change poses a significant threat to microbial communities, potentially disrupting their functions and altering ecosystem dynamics (Wang *et al*., 2022).

The complex relationship between climate change, food security, and microbes is evident in several aspects. Climate change can alter the physical and chemical properties of soil, affecting the composition and activity of microbial communities. These changes can influence nutrient availability, plant growth, and overall ecosystem resilience. Conversely, certain microbial processes can either exacerbate or mitigate climate change effects. For instance, microbes involved in carbon sequestration can help offset greenhouse gas emissions (Koza *et al*., 2022).

Harnessing the potential of microbes is essential for addressing the challenges posed by climate change to food security. Innovative agricultural practices, such as the use of microbial-based fertilizers and bioremediation techniques, can enhance crop resilience and productivity in the face of changing climate conditions. Additionally, sustainable soil management practices that promote microbial diversity contribute to the overall health and adaptability of agricultural ecosystems (Chen *et al*., 2023).

Understanding and managing the interactions between climate change, food security, and microbes is crucial for developing sustainable and resilient food production systems. By promoting microbial diversity and enhancing microbial functions, we can mitigate the adverse impacts of climate change and ensure a sustainable food supply for future generations (Aguilar-Paredes *et al*., 2023).

The widespread use of agrochemicals in modern agriculture has posed significant challenges to agricultural sustainability. While these chemicals have undoubtedly contributed to increased crop yields, they have also brought about a multitude of adverse consequences. The indiscriminate application of pesticides and fertilizers has detrimental effects on beneficial soil organisms, animals, human health, and the overall nutritional value of crops. Moreover, the overuse of pesticides has led to the development of resistant pests and pathogens, further exacerbating the issue. Additionally, modern agricultural practices have resulted in a substantial decline in crop diversity, making agriculture more vulnerable to pest outbreaks, pathogen infestations, and environmental stresses such as water scarcity, extreme temperatures, and increased salinity. To effectively address these multifaceted challenges, a comprehensive approach is necessary. This approach should encompass the adoption of sustainable agricultural practices, the implementation of soil conservation measures, and the development of climate-resilient strategies. By embracing these principles, we can strive to achieve both food security and the long-term sustainability of our ecosystems (Brzozowski & Mazourek, 2018; Damalas & Eleftherohorinos, 2011; Dhanaraju *et al*., 2022).

Ensuring robust and consistent crop yields requires safeguarding plants from both biological and environmental stresses. Introducing genetic variability within crops can effectively combat diseases, enhance productivity, improve adaptability to environmental factors, and promote biodiversity. To achieve long-term agricultural sustainability, developing crop varieties that exhibit high productivity and resilience to diseases, pests, and adverse environmental conditions like drought, extreme temperatures, and soil salinity is crucial. Traditional methods have primarily focused on identifying well-adapted and high-performing organisms. Environmental stressors, encompassing both biotic factors like parasites, pathogens, and pests, and abiotic factors like chemicals, temperature, light, and other climatic variables, serve as selection pressures, influencing the acclimation, adaptation, and evolutionary processes of species (Bailey-Serres *et al*., 2019; Cheng & Cheng, 2015; Dong & Ronald, 2019; Das *et al*., 2023).

2. Microbial Biotechnology: An Overview

Microbial biotechnology is the application of biotechnology principles and advanced technology to the study and utilization of microorganisms and their products. It involves the use of bacteria, fungi, and other microorganisms to perform various tasks that are beneficial to human health, food, agriculture, industry, and the environment (licón-Hernández *et al*., 2022). Microbial biotechnology plays a vital role in addressing global challenges related to health, food security, environmental sustainability, and industrial production via using advancements in genetic engineering, synthetic biology, protein omics, and high-throughput screening technologies (De Sousa *et al*., 2018; Poblete-Castro *et al*., 2020). For example, Microorganisms are used to produce a wide range of industrial products through fermentation, such as antibiotics, enzymes, organic acids, biofuels, and pharmaceuticals (Raveendran *et al*., 2018; Mosunova *et al*., 2021; Yafetto, 2020).

Microorganisms play a crucial role in various ecological processes, contributing significantly to the functioning of ecosystems. Their impact extends beyond ecological dynamics, as their potential applications in addressing climate change and food insecurity have gained increasing attention. Microorganisms are central to nutrient cycling, breaking down organic matter into essential nutrients that can be utilized by plants and other organisms. This process, known as decomposition, is vital for sustaining life in ecosystems (Raza *et al*., 2023). For example, Certain bacteria, like nitrogen-fixing bacteria in the root nodules of leguminous plants, convert atmospheric nitrogen into a form usable by plants, enhancing soil fertility (Chakraborty & Kundu, 2023). In addition, microorganisms are key players in the biodegradation of pollutants (Fig. 1), helping to mitigate the impact of environmental contaminants on ecosystems (Dave & Das, 2021; Hussein *et al*., 2012). Many plants form symbiotic relationships with mycorrhizal fungi, aiding in nutrient uptake, while certain bacteria form symbiotic associations with the roots of plants, providing benefits such as improved tolerance to environmental stress (Hussein *et al*., 2012).

Microorganisms have great potential in addressing climate change, they contribute to carbon sequestration through processes like photosynthesis and the formation of organic matter. Strategies involving microbial-enhanced carbon sequestration were explored to mitigate climate change (Jiao *et al*., 2020). Microbial communities in soil influence its health and resilience. In addition, sustainable agricultural practices that enhance microbial diversity and activity contribute to climate change adaptation and mitigation.

Certain microorganisms promote plant growth by increasing nutrient availability and enhancing stress tolerance. Utilizing these beneficial microbes offers a sustainable approach to improving crop yields (Mohammad *et al*., 2003). Nitrogen-fixing bacteria and other microbial biofertilizers enhance soil fertility, promoting sustainable agriculture and addressing nutrient deficiencies (Bhardwaj *et al*., 2014).

3. Microbial Biotechnology for Climate Change Mitigation

Climate change is generally defined as a significant variation of average weather conditions, becoming warmer, wetter, or drier—over several decades or more. Microbial biotechnology stands at the forefront of innovative strategies to mitigate climate change, offering solutions ranging from carbon sequestration and methane mitigation to bioenergy production and circular economy practices (Fig. 2). Several research studies and technological developments in microbial biotechnology indicated the potential for sustainable and environmentally friendly approaches to combat climate change, as indicated below.

Microbial biotechnology offers promising avenues for mitigating climate change by leveraging the unique capabilities of various environmental processes, which include enhancing Carbon sequestration, particularly by microbes residing in soil, through organic matter decomposition. This involves manipulating microbial communities to enhance carbon storage in soils (Onyeaka & Ekwebelem, 2023).

Methane is a potent greenhouse gas, and methanotrophic bacteria play a crucial role in its oxidation. Research explores the potential of these bacteria for mitigating methane emissions from natural and anthropogenic sources (Nazaries *et al*., 2021).

Another important aspect is the potential of microorganisms in harnessing the production of biofuels, providing a sustainable alternative to fossil fuels. Advances in metabolic engineering and synthetic biology enhance the efficiency of microbial biofuel production (Lopes & da Silva, 2021).

Microbial processes, such as anaerobic digestion, convert organic waste into biogas, a renewable energy source. This contributes to waste management while providing an alternative to fossil fuels (Kougias *et al*., 2021).

Compant *et al*. (2021) indicated that endophytic microorganisms residing within plant tissues are explored for their potential in improving plant health, nutrient uptake, and resistance to diseases and environmental stress. Enhancing microbial diversity in soil contributes to improved soil health and resilience. This, in turn, affects carbon and nitrogen cycling, influencing greenhouse gas dynamics (Zhang *et al*., 2020).

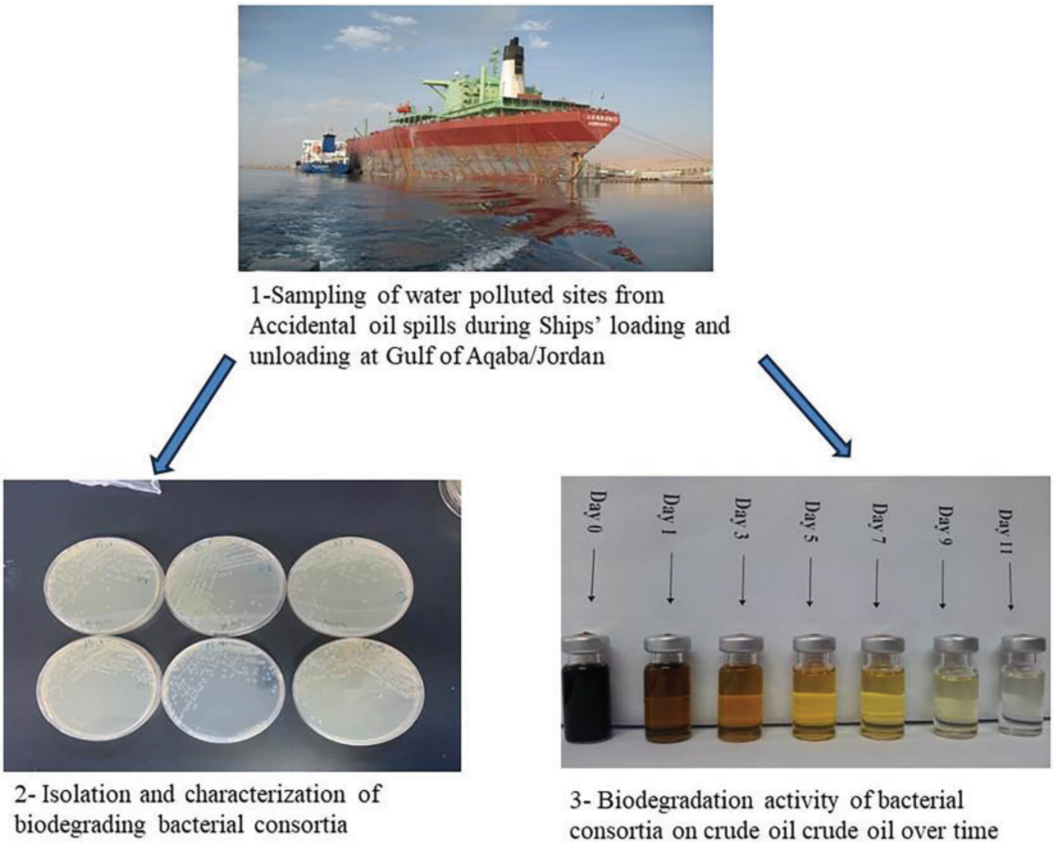

Fig. 1. Bacterial biodegradation of petroleum hydrocarbons in oil polluted sites in the Gulf of Aqaba-Jordan (Hussein *et al*., 2012).

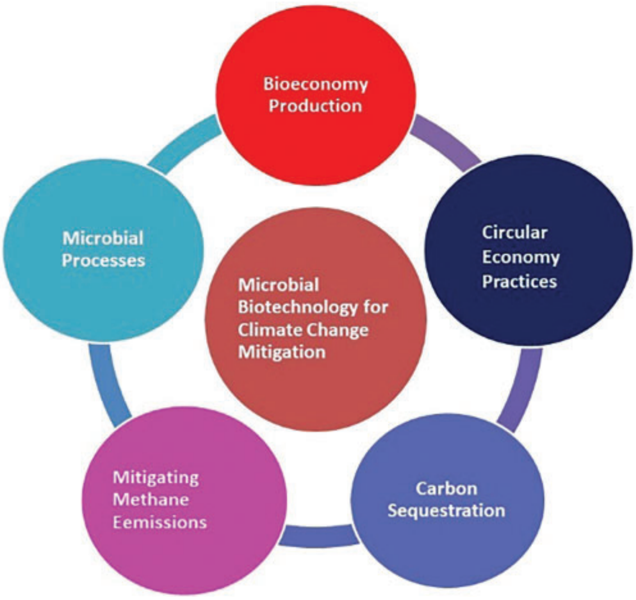

Fig. 2. Innovative strategies of microbial biotechnology to mitigate climate change.

4. Microbial Biotechnology for Enhancing Food Security

Microbial biotechnology plays a pivotal role in enhancing food security by offering innovative solutions to challenges in agriculture, crop production, and food preservation, promoting sustainable agriculture, improving crop yield, and mitigating food-related issues. Microbial biotechnology presents a multifaceted approach to address food security challenges by improving crop yield, enhancing nutrient cycling, maintaining soil health, and providing sustainable pest management strategies (Fig. 3). These microbial-based approaches offer environmentally friendly solutions, contributing to the development of resilient and sustainable agricultural systems. Bhattacharyya *et al*. (2020) showed that microbial biofertilizers, such as nitrogen-fixing bacteria and mycorrhizal fungi, enhance nutrient availability for plants, promoting sustainable and eco-friendly agricultural practices.

Microorganisms, including entomopathogenic fungi and bacteria, were explored for their role in biological pest control, providing alternatives to chemical pesticides and contributing to sustainable pest management (Kumar *et al*., 2021).

Beneficial microorganisms that promote plant growth and enhance stress tolerance were also employed to improve crop resilience in challenging environmental conditions, contributing to increased yields (Nadeem *et al*., 2021).

Microbial biotechnology contributes to food security through microbial biopreservation techniques involving the use of beneficial microorganisms, which contribute to extending the shelf life of food products by inhibiting the growth of spoilage and pathogenic microbes (Gänzle, 2015).

Some studies have demonstrated the potential of microbial-based strategies to improve crop yield, nutrient cycling, soil health, and pest management, offering sustainable solutions for global food challenges. Bashan *et al*.

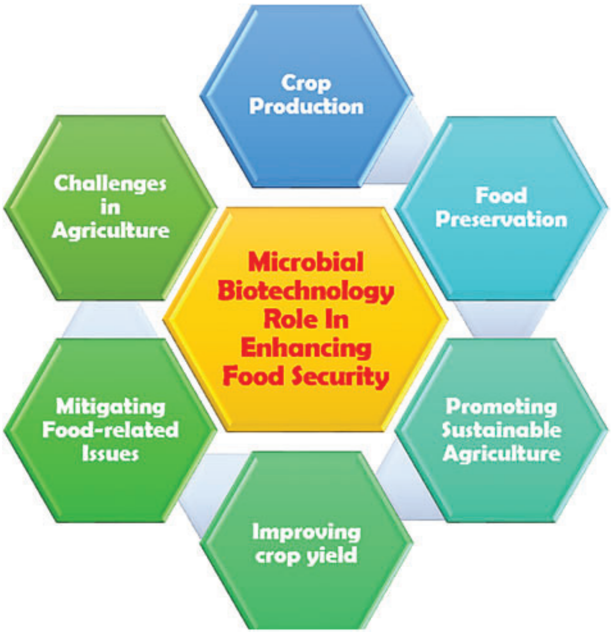

Fig. 3. Revolutionary approaches in microbial biotechnology to enhance food security.

(2016) indicated that Plant Growth-Promoting Rhizobacteria (PGPR) enhanced plant growth by promoting nutrient uptake, producing growth-promoting substances, and protecting against pathogens. A research study that was conducted by Smith and Read (2010) revealed that arbuscular mycorrhizal fungi (AMF) form symbiotic associations with plant roots, improving nutrient uptake and water absorption, thus enhancing crop productivity, especially in nutrient-deficient soils.

Also, as indicated by Bhattacharyya *et al*. (2020), the nitrogen-fixing bacteria and other microbial biofertilizers contributed to nutrient cycling, enriching the soil with essential nutrients, accordingly enhancing soil fertility and supporting sustainable agriculture. Other success research studies were mentioned in the review article by (Reisoglu & Aydin, 2023) about how microalgae were cultivated for bioenergy production, where algae could be used to capture carbon dioxide and produce biofuels, providing a renewable energy source while mitigating climate change.

5. Microbial Biodiversity and Adaptability

Microbial biodiversity is intricately linked with several ecological concepts, encompassing the collective presence of all organisms and abiotic elements within a specific environment, known as an ecosystem, and the specific portion of an ecosystem where a community of organisms can thrive, referred to as habitat. Microbes, comprising a diverse array of microorganisms such as fungi, bacteria, and viruses, are fundamental to life on Earth, playing critical roles in sustaining ecosystem functions and services.

Some research studies underscore the significance of microbial communities in functions crucial for global well-being. Nutrient cycling and food security, litter decomposition, primary production, and the influence on the structure of oceans and atmospheres are among the pivotal roles played by microbial communities, contributing significantly to climate change dynamics (Delgado-Baquerizo *et al*., 2018; Louca *et al*., 2016).

Worldwide, the diversity of microorganisms is astonishing, encompassing an estimated 5–30 million species. Only around 2 million of these have been officially documented, leaving the majority undiscovered or unnamed. In just one gram of soil, there are over 1 billion bacteria, and less than 5% of them have been identified. The extensive fungal variety, comprising at least 1.5 million species, further emphasizes the abundance of microbial life (Tedersoo *et al*., 2014). This microbial diversity surpasses that of arthropods and seed plants combined, emphasizing its ecological significance (Onen *et al*., 2020). Despite the remarkable biodiversity within microbial communities, knowledge tends to be biased toward larger animals, temperate ecosystems, and species relevant to human use.

Astonishingly, between 55% and 98% of Earth's total biodiversity resides in the soil, predominantly due to the presence of thousands of microbial species and genotypes (Anthony *et al*., 2023). Agricultural soil alone contains around 3,000 kg (fresh weight) of microorganisms per hectare, showcasing their pervasive influence (Fierer, 2017). Microorganisms exhibit an unparalleled capacity to adapt to diverse environments rooted in their genetic and reproductive mechanisms. This adaptability results in substantial variability, while the specificity of selection provides them with a unique advantage.

Various factors regulate microbial growth in nature, including essential resources such as carbon, nitrogen, macronutrients, micronutrients, oxygen, and other electron acceptors. Environmental conditions such as temperature, water potential, pH, oxygen availability, light, and osmotic conditions also play crucial roles in influencing microbial growth (Thakur *et al*., 2022). Also, microorganisms have the potential to adapt to thrive and live in extreme harsh environments. These extreme niches encompass hot springs (Fig. 4), (Malkawi & Al-Omari, 2010), saline lakes, arid deserts, deep ocean depths, acidic and alkaline locations, polar frigidity, contaminated areas, and regions with restricted energy and nutrient resources. Within these harsh domains, microorganisms adapt to shifting conditions, devising cellular, biochemical, and molecular strategies. They produce enzymes, molecules, and metabolites to safeguard against extremes in salinity, pH, pressure, temperature, solar radiation, nutrient availability, oxygen levels, osmotic pressures, and gravitational variations (Thakur *et al*., 2022). Diverse microorganisms interact with environmental stressors in distinctive ways, honing mechanisms for survival.

Understanding and appreciating the complexity of microbial biodiversity is essential for unlocking the full potential of these microscopic life forms in sustaining ecosystem health and addressing global challenges.

6. Microbial Growth Environments and Habitats

6.1. *Terrestrial Environments*

Soil, a dynamic ecosystem, encompasses various components, including inorganic mineral matter (constituting approximately 40% of soil volume), organic matter

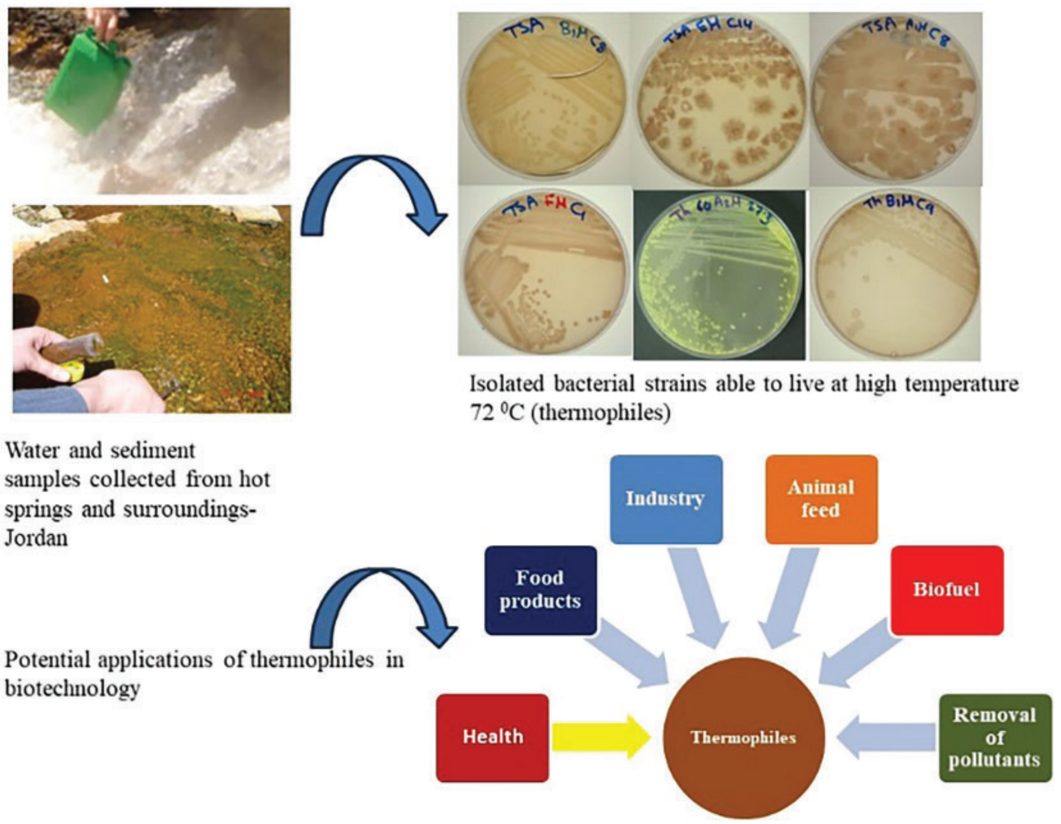

Fig. 4. Bacterial communities adapted to live in hot springs environments and their potential biotechnological applications (Malkawi & Al-Omari, 2010).

(around 5%), air and water (comprising about 50%), and living organisms (approximately 5%). The soil is stratified into distinct layers, including the O horizon, A horizon (the primary site for microbial growth), B horizon, and C horizon (Sposito, 2023).

Free-living microorganisms have a pivotal role in soil creation and fertility. Approximately 40% of soil organic matter is influenced by microbial activity, significantly impacting nutrient cycling and availability (Javed *et al.*, 2022). Microorganisms contribute to soil structure, play a key role in mitigating greenhouse gas emissions, and are integral to the recycling and acquisition of nutrients by plants. Their functions encompass crucial aspects of soil formation, carbon fixation and cycling, nutrient cycling, and water regulation, serving as reliable indicators of soil health.

6.2. *Marine Environments*

More than 70% of the Earth is covered by ocean. Microbes account for about 70% of the marine biomass and constitute a hidden majority of life that flourishes in the sea. Marine microbes play many important roles in the Earth's system: they influence the climate, are the major primary producers in the ocean, dictate much of the flow of marine energy and nutrients, and provide a source of medicines and natural products (Bolhuis & Cretoiu, 2016). Microbes (which include Bacteria, Archaea, microbial eukaryotes and their associated viruses) are as varied as the marine environments they come from.

The oceans wield a profound influence on life and Earth's climate, with marine microorganisms emerging as critical players (Glöckner *et al.*, 2012). The diversity and number of microbes in the ocean far exceeds that of macroscopic life, and many employ unique life strategies not seen anywhere else on Earth. Without them, life on Earth almost certainly would not be possible.

Ocean microbes also play an important role in Earth's biogeochemical cycles, particularly the carbon, nitrogen, phosphorus, iron, and sulfur cycles. They form the very base of the marine food chain, recycle nutrients and organic matter, and produce vitamins and cofactors needed by higher organisms to grow and survive (Arrigo, 2005; Glöckner *et al.*, 2012).

A report published by the Food and Agriculture Organization of the United Nations-FAO (2017) highlighted the pivotal support provided by marine microorganisms, sustaining fisheries and benefiting around 820 million people globally in terms of food security and income. The intricate interplay of marine microbial communities underscores their significance in maintaining ecological balance and supporting human well-being on a global scale.

7. Microbial Contributions to Nutrient Cycling, Food Production and Food Security

Microorganisms are often underestimated in their significance, even though they play a pivotal role in the functioning of ecosystems, forming the foundation for agriculture and food production. Several studies highlighted the intricate web of microbial activities that influence elemental cycles such as carbon, nitrogen, sulfur, and iron, showcasing the vital role these microorganisms play in sustaining ecosystems, as indicated below:

7.1. Microbial Impact on Elemental Cycles

The carbon cycle, nitrogen cycle, sulfur cycle, and iron cycle stand out as elemental processes significantly shaped by microorganisms (Kuypers, 2018; Luo *et al*., 2020). Bacteria, yeast, and fungi, including well-known species such as Saccharomyces cerevisiae, play transformative roles in these cycles.

7.2. Microbial Contributions to Agriculture

Microbial contributions to agriculture are pivotal for sustainable and productive crop production. The interactions between plants and various microorganisms, including bacteria, fungi, and archaea, play a crucial role in nutrient cycling, disease suppression, and overall soil health. Also, microbial activities contribute to the formation and stabilization of soil structure. This is crucial for water retention, aeration, and overall soil health (Six *et al*., 2004). Chen *et al.* (2023) indicated in their study that phytomicrobiome plays a crucial role in soil and ecosystem health, encompassing both beneficial members providing critical ecosystem goods and services and pathogens threatening food safety and security. They also indicated that mitigating plant diseases can be achieved through in situ manipulations of resident microorganisms using various agronomic practices, including but not limited to minimum tillage, crop rotation, cover cropping, and organic mulching. Additionally, the application of microbial inoculants has shown promise in disease control. Advances in DNA sequencing technologies have facilitated the study of the plant microbiome, providing insights into the complex interactions between plants and their associated microbial communities (Pucker *et al*., 2022).

8. Factors Contributing to Climate Change

There are several key factors contributing to climate change, among which are the following:

- ***Global warming***: The long-term warming of the planet's overall temperature. The decade from 2011 to 2020 witnessed record warmth, registering a global average temperature 1.1 °C above pre-industrial levels in 2019 (WMO, 2022). Human-induced global warming is accelerating at a rate of 0.2 °C per decade. The world will most likely reach 1.5 °C (2.7 °F) global warming in the period 2021–2040.
- ***Greenhouse gases***: Anthropogenic emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are key components responsible for climate change since the pre-industrial period, and the use of fossil carbon sources in the energy, industry, transport, waste and product use sectors and land use, land use change and forestry, has led to increased atmospheric concentrations of CO_2, CH_4 and N_2O and driven Earth's surface energy balance into surplus (Jones *et al*., 2023). While greenhouse gases play a role in maintaining a habitable global temperature, human activity has increased these gases' atmospheric concentrations, causing too much heat to become trapped in our atmosphere. The atmospheric extra heat leads to increased temperatures around the globe and climate change.
- ***Generating power***: Emissions from electricity and heat generation, largely fueled by burning fossil fuels, contribute significantly to climate change, and coal, oil, and gas remain primary sources for electricity generation, releasing carbon dioxide and nitrous oxide, potent greenhouse gases (IPCC, 2022).
- ***Manufacturing goods***: Industrial processes, encompassing cement, iron, steel, electronics, plastics, and clothing production, emit greenhouse gases through fossil fuel combustion, as well as Mining activities and construction further exacerbate the impact on climate (IPCC, 2022).
- ***Deforestation***: Approximately 12 million hectares of forest are lost annually, hindering the Earth's capacity to absorb carbon dioxide, and deforestation, coupled with changes in land use, contributes to about a quarter of global greenhouse gas emissions (IPCC, 2022).
- ***Transportation***: The predominant reliance on fossil fuels in vehicles and transportation modes is a significant source of greenhouse gas emissions, particularly carbon dioxide; for example, the total Emissions in the USA in 2021 was about 6,340 million Metric Tons of CO_2 equivalent. (IEA, 2021).
- ***Food production***: Missions from food production result from various activities, including deforestation, land clearing, livestock digestion, fertilizer and manure use, and energy consumption in farming and fishing activities (IPCC, 2022).
- ***Powering buildings***: Increasing energy demands in buildings, driven by heating, cooling, and heightened air-conditioner usage, contribute to a surge in energy-related carbon dioxide emissions. This includes augmented electricity consumption for lighting, appliances, and electronic devices in residential and commercial structures (IEA, 2021).

9. The Impact of Climate Change on Microorganisms

Climate changes exert diverse influences on microorganisms, impacting various aspects of ecological systems. The following points elaborate on the multidimensional relationship between climate change and microorganisms:

- ***Impact on the cropping agriculture system***: Climate changes can lead to shifts in cropping agriculture systems, allowing for expansions into inhospitable regions while restricting others due to drought. The introduction of microorganisms may become necessary in response to these shifts, with potential applications in supporting drought tolerance (Kumar *et al*., 2020).
- ***Effect on microorganisms' communities and structures***: Climate changes significantly impact microorganism communities due to their short generation times, allowing rapid responses to new environmental conditions. Under extreme

conditions, both beneficial and detrimental microorganisms may respond swiftly (Ondik *et al*., 2023). Climate change also can lead to alterations in microbial community structures, impacting processes like respiration, fermentation, and methanogenesis.

- ***Effects on functional groups of microorganisms***: Climate-related factors such as temperature, humidity, and nutrient availability directly influence soil microorganisms, affecting the sustainability of life in the soil. Changes in these physical factors due to climate change will affect the composition and diversity of microorganisms (Ibáñez *et al*., 2023).
- ***Impact on distribution and plant pathogens***: Plants are infected by a diverse range of pathogens, including bacteria, fungi, oomycetes, viruses, and nematodes, that differ in their lifestyles. Climate change increases outbreak risks by altering pathogen evolution and plant–pathogen interactions and facilitating the emergence of new pathogenic strains. The pathogen range can shift, increasing the spread of plant diseases in new areas (Singh *et al*., 2023).
- ***Impacts on biotic and abiotic components***: Climate change poses risks such as injury, illness, and death from heatwaves, wildfires, storms, floods, and natural disasters (Watts *et al*., 2021). Biotic components like bacteria, fungi, algae, and archaea contribute to climate change by accelerating global warming through organic matter decomposition, increasing CO_2 flux in the atmosphere.

10. The Contributions of Microorganisms in Mitigating the Effects of Climate Change

The role of microorganisms in mitigating the effects of climate change is substantial, with active involvement in the production and consumption of key greenhouse gases, namely carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Anthropogenic alterations have provided microbes with increased access to carbon and nitrogen, contributing to heightened levels of these gases. Microbes participating in the generation and consumption of these gases inhabit diverse habitats, impacting greenhouse gas dynamics (Bardgett & van der Putten, 2014). Additionally, certain pathogenic microbes respond to climate change by expanding their ranges through factors like insect vectors, flooding, or severe storms, potentially affecting hosts vulnerable to heat or drought stress.

Microorganisms could contribute to mitigating the effects of climate change in several ways including:

- ***Soil ecosystems and greenhouse gas dynamics***: Microorganisms, particularly in soil ecosystems, actively break down soil organic matter, making it available to crops and influencing the production and consumption rates of key greenhouse gases (Bardgett & van der Putten, 2014). Microbes fix an estimated 70–140 million tons of nitrogen annually globally, providing an alternative to synthetic fertilizers and contributing to ecosystem resilience.
- ***Adaptation to climate change***: Plant-associated microorganisms, with traits like drought tolerance, influence plant responses to abiotic stressors, aiding in the adaptation of agricultural practices to changing climate conditions (Bardgett & van der Putten, 2014).
- ***Global fluxes of greenhouse gases***: Microbial processes significantly influence global fluxes of biogenic greenhouse gases, and their rapid response to climate change is observable.
- ***Terrestrial microbial processes***: Managing terrestrial microbial processes holds promise for mitigating climate change by reducing greenhouse gas emissions.
- ***Microbial communities and feedback responses***: Microbial communities play a crucial role in feedback responses to climate change by altering their structure and composition, contributing to environmental problem-solving through nutrient cycling and functional genetic material stimulation (Bardgett & van der Putten, 2014).
- ***Biogeochemical cycles***: The linkage of microbial communities and biogeochemical cycles serves as an effective mechanism for climate change mitigation, as microorganisms utilize greenhouse gases as an energy source and incorporate them into their cellular structures (Falkowski *et al*., 2008).
- ***Oxygen absorption***: Microorganisms contribute to mitigating climate change by absorbing oxygen, a critical aspect given the significance of carbon dioxide in the atmosphere (Cavicchioli *et al*., 2019).
- ***Nitrous oxide emission reduction***: Efforts to reduce nitrous oxide emissions involve microbiological methods through manipulation of microbiomes in diverse environments and integrating microbiome-based knowledge of nitrous oxide sources and sinks. These include also using bacteria-based systems for directly removing nitrous oxide from sources like car exhausts and power stations (Hu *et al*., 2017).
- ***Smart agriculture applications and innovative technologies***: With an understanding of microbial ecology and plant-microbe interactions, smart agriculture applications are integral to climate-smart agriculture, aiming to minimize the long-term impact of the agricultural industry on the climate (Das *et al*., 2019). Also, Innovative technologies, such as "living concrete" utilizing photosynthetic cyanobacteria, offer environmentally friendly solutions by absorbing CO_2 from the atmosphere. Cyanobacteria can induce carbonate precipitation in aquatic and terrestrial environments, therefore, the utilization of cyanobacteria for the biomineralization process in cementitious structures has attracted researchers (Sidhu *et al*., 2022).

11. Role of Microorganisms in Food Security

The role of microorganisms is pivotal in ensuring global food security, particularly in the context of addressing water scarcity, a critical factor influencing agricultural productivity. Microorganisms play diverse and indispensable roles in contributing to sustainable and resilient food production systems, as elucidated below:

- ***Nutrient cycling and soil health***: Microorganisms are fundamental to nutrient cycling in the soil, breaking down organic matter and releasing essential nutrients, thereby ensuring soil quality and enhancing soil fertility and ensuring crops have access to vital elements for growth (Schröder *et al*., 2016). Healthy soils with robust microbial communities significantly contribute to increased agricultural productivity.
- ***Biofertilizers and nitrogen fixation***: Certain microorganisms, such as nitrogen-fixing bacteria and mycorrhizal fungi, form symbiotic relationships with plants, aiding in nutrient acquisition. These biofertilizers enhance nutrient utilization efficiency, reducing the dependency on synthetic fertilizers, which is crucial in water-scarce regions (Sánchez-Navarro *et al*., 2020).
- ***Water use efficiency***: Microorganisms play a role in improving water use efficiency in plants, with certain microbial inoculants enhancing the ability of plants to absorb and utilize water more effectively, mitigating the impact of water scarcity on crop yields (Bardgett & van der Putten, 2014).
- ***Disease resistance***: Beneficial microorganisms contribute to plant health and disease resistance, acting as biopesticides to protect crops from harmful pathogens and reduce the need for chemical interventions (El-Saadony *et al*., 2022). This ensures a healthier food supply while minimizing the environmental impact associated with conventional pest control methods.
- ***Biological control of pests***: Microorganisms, including certain bacteria and fungi, serve as biological control agents against pests, reducing reliance on water-intensive chemical pesticides and promoting sustainable pest management practices (Bonaterra *et al*., 2022).
- ***Efficient waste decomposition***: Microorganisms are integral to the decomposition of organic matter, including agricultural residues. Efficient decomposition enriches the soil with organic content and contributes to water conservation by preventing the accumulation of biomass that can interfere with water availability (Raza *et al*., 2023).
- ***Improved crop resilience***: Microbial inoculants, such as plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi, enhance crop resilience to environmental stressors, including water scarcity, by stimulating root development and improving overall plant tolerance to water stress (El-Saadony *et al*., 2022).
- ***Bioremediation of contaminated water and soil***: Microorganisms play a crucial role in bioremediation, utilizing microbial activity to clean and purify water and soil contaminated with pollutants (Dave & Das, 2021). This process is essential for ensuring the safety and quality of water and soil resources in agriculture.

12. Leveraging Microbial Biotechnology for Sustainable Agriculture and Climate Mitigation

Microbial biotechnology provides a promising approach for addressing persistent social and environmental issues, promoting sustainable agriculture, and mitigating climate change. Microbial biotechnology holds significant potential as a tool for sustainable agriculture and climate mitigation. The following are some key points:

- ***Sustainable agriculture***: Microbial biotechnology can enhance sustainable agriculture by improving plant-microbe interactions, smart crop farming, and biodiversity. Microbes can augment disease resistance and yield, allowing crops to be grown without chemicals by harnessing microbes that live in/on plants and soil1 (Tan *et al*., 2022). They can also enhance nutrient cycling, disease control, soil health, and plant resilience (Kumar *et al*., 2023).
- ***Climate mitigation***: Soil microbes play a crucial role in mitigating the impact of climate change. They have the potential to sequester carbon dioxide (CO_2) from the atmosphere through processes like carbon fixation and storage in organic matter. This microbial-driven carbon storage could revolutionize climate-smart agricultural practices, leading to sustainable productivity and environmental conservation (Kumar *et al*., 2023).
- ***Biofertilizers, bioprotectants, and biostimulants***: Beneficial microbial communities can provide biofertilizers, bioprotectants, and biostimulants, in addition to mitigating various types of abiotic stress in plants (Abdul *et al*., 2022; Yadav *et al*., 2021).

13. Climate Change and Food Insecurity: A Global Challenge

Climate change and food insecurity are two of the most pressing global challenges we face today. Climate change is disrupting food production systems around the world, making it more difficult to grow crops and raise livestock. This is leading to food shortages, price spikes, and increased hunger. Moreover, addressing the challenges of climate change and food insecurity requires a multifaceted approach that includes understanding the interconnections between climate change and food production, and implementing innovative solutions to mitigate their effects.

13.1. Current Challenges Posed by Climate Change and Food Insecurity

Climate change and food insecurity are two interconnected global challenges that are intensifying. The number of people suffering acute food insecurity increased from 135 million in 2019 to 345 million in 82 countries by June 2022. This rise is due to various factors, including wars, supply chain disruptions, and the continued economic fallout of the COVID-19 pandemic, which pushed food prices to all-time highs (World Bank, 2022; Kirubanandan, 2023).

Global warming is influencing weather patterns, causing heat waves, heavy rainfall, and droughts. These phenomena are affecting food production and contributing to rising food commodity prices, pushing approximately 30 million additional people in low-income countries toward food insecurity (World Bank, 2022).

About 80% of the global population most at risk from crop failures and hunger from climate change are in Sub-Saharan Africa, South Asia, and Southeast Asia, where farming families are disproportionally poor and vulnerable. A severe drought caused by an El Nino weather pattern or climate change can push millions more people into poverty insecurity (World Bank, 2022).

13.2. Interconnections Between Climate Change and Food Production

The global food system is both impacted by climate change and a major contributor to it (IFPRI, 2022). It was estimated that the global food system is responsible for about a third of greenhouse gas emissions, second only to the energy sector. It is also the number one source of methane and biodiversity loss (World Bank, 2022).

Climate change worsens unsustainable food systems by directly impacting soil fertility, rain patterns, crop yields, food production, food-nutrient and anti-nutrient composition, and nutrient bioavailability. These changes decrease macro- and micronutrients available in the global food supply (Victor *et al*., 2022).

13.3. Need for Innovative Solutions

Innovative solutions are needed to mitigate the effects of climate change on food security and production. These efforts should include investment in agricultural infrastructure, diversification of crops and food sources, food storage systems designed for long-term preservation, and training for local farmers on sustainable agriculture techniques (Swinnen *et al*., 2022).

Numerous contemporary technological advancements, such as solar-powered irrigation pumps, cold storage, genome-editing technologies, and value chain digitization, hold promise for simultaneously reducing emissions and increasing productivity. These innovations offer mutually beneficial opportunities to address both hunger and climate change. Furthermore, inclusive innovation has the potential to revolutionize food systems and contribute to eradicating global hunger. A funding gap of $15.2 billion exists for food system innovation, crucial for ending hunger, maintaining emissions within a 2 °C limit, and reducing water usage by 10%. The World Economic Forum and the UN Food and Agriculture Organization have collaborated to publish a roadmap aimed at assisting countries in expediting inclusive food systems innovation (Whiting, 2022).

14. Challenges and Limitations

Microbial biotechnology holds great promise in addressing critical global challenges such as climate change mitigation and food security; however, its implementation is not without challenges and limitations. The following discussion will delve into these challenges and providing insights into potential solutions to such limitations:

14.1. Challenges in Microbial Biotechnology for Climate Change Mitigation

- ***Scale-up challenges***: Scaling up microbial processes for large-scale climate change mitigation is a significant challenge. A potential solution for such a challenge may be achieved via integrated approaches that combine microbial biotechnology with engineering solutions that need to be developed (Smith *et al*., 2020).
- ***Complexity of microbial community and interaction***: Understanding and manipulating complex microbial communities for targeted climate interventions is challenging. In addition, the intricate interactions among different microbial species and their responses to changing environmental conditions make it challenging to predict and control microbial processes effectively. A proposed solution for this challenge would be to use advanced omics technologies and systems biology approaches that can enhance a better understanding of microbial community dynamics (Banerjee *et al*., 2021).

14.2. Limitations of Microbial Biotechnology for Food Security

- ***Resource intensity***: Some microbial processes can be resource-intensive, limiting their practicality for widespread use in agriculture. A potential solution to overcome such limitations could be via research efforts that focus on developing resource-efficient microbial technologies (Hartman *et al*., 2017).
- ***Ethical and regulatory concerns***: Stringent regulations and public skepticism may impede the widespread adoption of genetically modified microbes in agriculture, though a transparent and inclusive regulatory framework, coupled with public engagement, could facilitate acceptance of GMOs.

Moreover, implementing the following general recommendations may prove beneficial in addressing the challenges indicated above:

- ***Interdisciplinary collaborations***: Collaborations between scientists with different specialties, including microbiologists, engineers, biochemists, agriculturists, and environmental scientists, can facilitate the development of holistic solutions for scaling up microbial processes.
- ***Education and outreach***: Increased efforts in public engagement and education can address concerns and enhance the acceptance of microbial biotechnologies for different useful applications. In climate change and food security.
- ***Innovation and research fundings***: Governments and private sectors should invest in innovative research funding models that support long-term, high-risk projects in microbial biotechnology for climate change and food security.

While microbial biotechnology presents exciting opportunities for addressing climate change and food security, addressing the associated challenges requires collaborative, multidisciplinary efforts, innovative funding mechanisms, and transparent communication with the public. Ongoing research and technological advancements will be pivotal in overcoming these challenges and realizing the full potential of microbial biotechnology in sustainable agriculture and climate change mitigation.

Microbial biotechnology continues to be a dynamic field with promising avenues for future research and development. Recent advancements underscore the potential in diverse areas, including synthetic biology, environmental applications, and therapeutic interventions. Exploration of engineered microbial systems using synthetic biology tools for sustainable bio-manufacturing (Rojo *et al*., 2023), harnessing microbial consortia for environmental remediation, and innovative CRISPR-based tools for precision genome editing in microbes (Wei & Li, 2023) represent just a few focal points. These recent advancements underscore the diverse and multifaceted opportunities that lie ahead in the dynamic landscape of microbial biotechnology.

15. Policy Implications and Societal Impact

The policy implications of harnessing microbial biotechnology for addressing climate change and food insecurity are critical for shaping sustainable and effective strategies. Policymakers play a pivotal role in facilitating the integration of microbial biotechnological solutions into broader frameworks for climate mitigation and food security. The exploration of the importance of these policy implications is indicated below:

Harnessing microbial biotechnology for climate change mitigation requires strategic policy interventions (Tan *et al*., 2022). Policies promoting research funding for projects related to microbial biotechnology are also essential.

Policies supporting the integration of microbial technologies into agriculture are paramount for achieving food security goals. Initiatives like those discussed by Smith *et al*. (2022) highlight the importance of microbial soil amendments, which can help by informing agricultural policies aimed at enhancing soil fertility and crop resilience.

Given the potential risks associated with the release of genetically engineered microbes, robust regulatory frameworks are essential. Trump *et al*. (2023) discussed that the success of any advanced genetic development and usage requires that the creators establish technical soundness, ensure safety and security, and transparently represent the product's ethical, legal, and social implications.

There are many task forces that were established globally and are concerned with policy and ethical issues regarding biotechnology, microbial biotechnology, synthetic biology, and other advanced technologies.

Policymakers must also address ethical considerations associated with microbial biotechnology. The article published by The White House-USA (2022) entitled "*Executive Order on Advancing Biotechnology and Biomanufacturing Innovation for a Sustainable, Safe, and Secure American Bioeconomy*" stated clearly about the policy of the administration to coordinate a whole-of-government approach to advance biotechnology and biomanufacturing towards innovative solutions in health, climate change, energy, food security, agriculture, supply chain resilience, and national and economic security. Also stated, the outcomes of this policy are principles of equity, ethics, safety, and security that enable access to technologies, processes, and products in a manner that benefits the entire global community.

The realm of microbial biotechnology has given rise to an extensive array of materials and products that are swiftly making their way into the commercial sphere. Despite the revolutionary potential offered by numerous advancements, certain innovations carry uncertain or largely unexplored risks. This has the potential to spark debates, cause consternation, and trigger outrage among individuals and groups who could be impacted by the development and utilization of these technologies. While the advancements in microbial biotechnology are praised for their potential societal benefits, it is crucial to exercise great care in prioritizing safety and security. Additionally, careful consideration must be given to the Ethical, Legal, and Social Implications (ELSI) concerning the production, dissemination, utilization, disposal, and governance of these innovations (Trump *et al*., 2023).

The potential of adopting microbial-based solutions on a global scale extends beyond technological advancement, influencing various societal aspects. Incorporating these solutions into diverse sectors can yield profound societal benefits, ranging from environmental sustainability to public health improvements. Recent studies emphasized the significance of microbial technologies in shaping the global societal landscape, impacting environmental sustainability, agriculture, public health, and socio-economic development (Trump *et al*., 2023), as discussed in the following points:

- Microbial-based solutions play a crucial role in addressing environmental challenges. By enhancing soil health, promoting sustainable agriculture practices, and facilitating efficient waste management, these solutions contribute to overall environmental conservation efforts,
- The adoption of microbial-based solutions in agriculture has the potential to revolutionize food production. Such solutions can improve soil fertility, enhance crop resilience, and reduce the reliance on traditional chemical inputs, thereby promoting sustainable and resilient farming practices,
- Microbial technologies also offer innovative solutions in the healthcare sector. From the development of novel antibiotics to the exploration of microbial therapies, these advancements hold promise for addressing global health challenges, including antibiotic resistance and infectious diseases.

The societal impact extends to socio-economic aspects, with the potential to create new economic opportunities and industries centered around microbial-based technologies. This can contribute to job creation and economic development on a global scale.

As society embraces microbial-based solutions, ethical considerations become paramount. Comprehensive governance frameworks are essential to address potential risks and ensure responsible deployment. Ethical scrutiny and public engagement are crucial components of navigating the societal implications of these technologies. While microbial biotechnology holds the potential to yield diverse and abundant food products with enhanced characteristics, its contribution alone is insufficient for ensuring human well-being. Addressing critical challenges such as poverty reduction, social inclusion, equity enhancement, education improvement, healthcare accessibility, biodiversity conservation, sustainable energy, water security, and climate change adaptation and mitigation is imperative. These interconnected challenges are encapsulated within the framework of the 17 Sustainable Development Goals (SDGs) (Herrero *et al*., 2021)

16. Future Perspectives

Microbial biotechnology holds great promise in addressing both climate change and food insecurity, offering innovative solutions that leverage the power of microorganisms to tackle these global challenges. The interplay between microbial processes and the environment provides a fertile ground for research and development, with potential applications ranging from sustainable agriculture to bioenergy production.

The following future research areas are promising in microbial biotechnology in addressing climate change and food security:

- ***Synthetic microbial communities***: investigating the assembly and functioning of synthetic microbial communities could optimize their performance in agriculture and environmental applications.
- ***Omics technologies***: advancements in metagenomics, meta-transcriptomics, and metabolomics will enable a deeper understanding of microbial communities and their interactions.
- ***Microbial-plant signalling***: Exploring the potential of extremophile microorganisms in harsh climates could open new avenues for sustainable agriculture in challenging regions.
- ***Microbial engineering for extreme environments***: Exploring the potential of extremophile microorganisms in harsh climates could open new avenues for sustainable agriculture in challenging regions.

17. Conclusion

This review reveals the remarkable adaptability and influence of microorganisms in shaping environmental health. Their pivotal role in soil health, nutrient cycling, and plant interactions forms the foundation for climate resilience. Further, innovative microbial technologies like biofertilizers and biopesticides offer a sustainable alternative to traditional agricultural practices, paving the way for reduced greenhouse gas emissions and enhanced food production.

We must forge a symbiotic relationship with microbes. By integrating advanced microbial solutions into agriculture, we can adapt to changing climatic conditions, address water scarcity, and boost yield in both traditional and precision farming systems. This review underscores the urgency of embracing microbial power. Doing so promises a future where we coexist with these tiny allies, nurturing a resilient and resource-efficient agricultural landscape that secures food for generations to come.

Further research should delve deeper into unlocking the full potential of yet-undiscovered microbial strains for climate mitigation and soil improvement, optimizing the application of microbial technologies for diverse agricultural ecosystems and environmental conditions, and addressing potential social and economic challenges associated with the widespread adoption of microbial solutions.

As we continue to unlock the secrets of the microbial world, we stand on the cusp of a revolution in agriculture and environmental sustainability. The future lies in fostering this symbiotic partnership, and the rewards—a thriving planet and secure food for all—are well worth the investment.

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