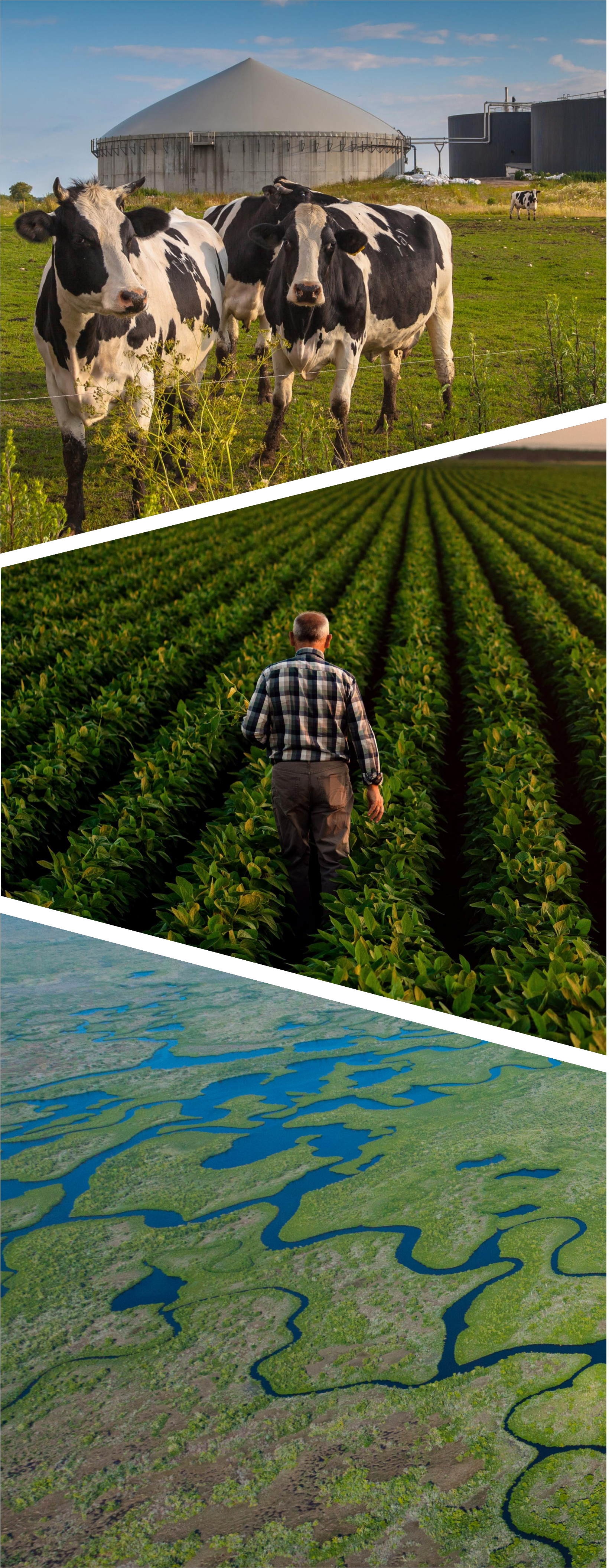

Microbial Solutions for Climate Change

Toward an Economically Resilient Future

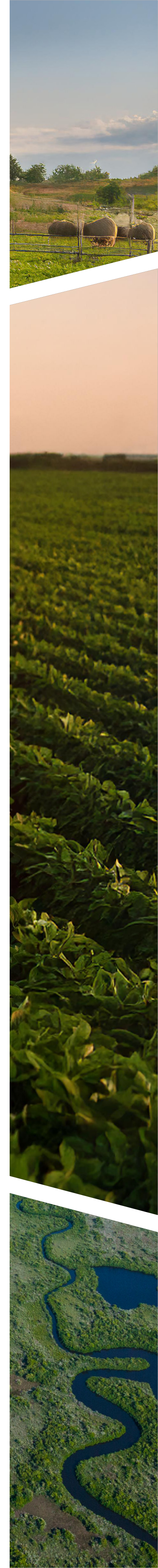

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Table of Contents

Preamble....2

Scientific Advisory Group Members....3

Executive Summary....4

Introduction....5

Applying an Economic Lens to Microbe-based Innovations for Climate Change....7

Microbes for a Non-fossil Carbon Economy....8

Microbes for Food Security and Ecosystem Resilience....11

Microbes for Urgent Methane Mitigation....14

Market Readiness – Considerations for Microbial Products to Deliver Social Impacts....17

Considerations for Policymakers to Support Bio-based Solutions for Climate Change....19

Conclusions....20

Acknowledgements....21

References....22

Preamble

Despite significant progress in addressing climate change, its impacts continue to leave devasting effects worldwide. From extreme weather events to the emergence of new infectious diseases and the extinction of millions of species, these effects cost human lives and billions of dollars to help society recover from these disasters. More than ever, the need for more effective and affordable climate solutions is more pressing and requires the scientific community to work together to find such solutions.

As the most abundant organisms on Earth, microbes touch every aspect of human life and the environment. With the effect of climate change, microbes become our friends and foes. The spotlight has been predominantly put on microbes as infectious agents that harm human health and well-being. However, there has not been enough focus on the potential of microbes as solutions for climate change.

In recent years, several scientific societies have made efforts to build awareness of the many roles of microbes in climate change. As the microbiology community develops effective actions to deliver societal impacts, the American Society of Microbiology and the International Union of Microbiological Societies have partnered to convene a global scientific advisory group (SAG) with a clear focus: T*o study and identify the top 3 microbial solutions for climate change*.

The Scientific Advisory Group (SAG) comprises experts from various areas of microbiology, health, environmental sciences, policy, biosecurity and economy around the world. The group met several times in 2024 to develop criteria to select the solutions and examine different microbial innovations, their science and their applications. The SAG deliberated on these innovations and examined them using the set criteria before narrowing down to the top 3 solutions in this report.

The report aims to provide concrete microbial solutions for climate change. We want to move the dialogs of the microbial science community from a high level, i.e., *microbes can help,* to very specific, i.e., *we need new investment to support this microbial solution to reduce methane emission*. This report does not endorse any specific company or product, and the SAG also does not disavow other solutions. Following our methodology and the publicly available information, we recognize and encourage further advancement of the 3 microbial solutions. Through this effort, our organizations want to set a step forward to promote a global partnership and establish a scientific foundation to help inform the public, policymakers, the global scientific community and future programmatic activities.

Finally, we would like to thank the American Academy of Microbiology for coordinating the project; the members of the Scientific Advisory Group for providing scientific expertise, writing and reviewing the report, and the many ASM staff, especially Dr. Nguyen Nguyen, Director of the American Academy of Microbiology, and Dr. Rachel Burckhardt, Program Officer, Scientific Analysis, for their leadership, contributions and support in bringing the project and report to fruition. Without them, this report would have not been possible.

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Executive Summary

Mitigating the impact of climate change is a challenge that needs innovative multi-faceted solutions. The world must address the causes, manifestations and consequences of climate change to slow or reverse its pace and to prevent continued damage or undo past damage to human health and wellbeing. Though currently underrepresented in discussions, microbial technologies provide powerful tools in climate science. Microorganisms have unique and diverse properties relevant to all of these domains. These properties encompass the ability of microorganisms to address—or be designed to address—fundamental aspects of climate change and the threats it poses. The International Union for Microbiological Societies (IUMS) and American Society for Microbiology (ASM) formed a scientific advisory group composed of global experts in diverse areas of microbiology, technology, policy and economics to showcase the potential of microbe-driven solutions to the challenge of climate change.

This report highlights 3 microbe-based innovations to help humans adapt to and sustainably mitigate climate change in terms of its pace and deleterious consequences.

- Microbes for a non-fossil carbon economy.
- Microbes for food security and ecosystem resilience.
- Microbes for urgent methane mitigation.

The scientific advisory group finds these solutions scientifically sound, economically sustainable, safe and scalable in a 5-to-15-year period. It is also confident that these solutions will promote social equity and societal well-being more generally and that they can be tailored to the needs and capacities of local communities, countries and regions.

Introduction

Microbial solutions provide powerful tools in mitigating the impacts of climate change. Climate change negatively impacts society's physical, financial and emotional health. More extreme weather events, increased disease burden and reduced food and water security are all attributed to rising greenhouse gas emissions. Without major changes to curb greenhouse gas emissions, these negative effects are expected to continue to accelerate.

Climate change alters the way in which humans interact with each other and nature, with vulnerable communities disproportionately negatively affected by climate change because of long-standing social and economic inequities (AR6 Synthesis Report). Humans are not alone in experiencing these changes: all of nature is impacted by climate change. As the most abundant organisms on Earth, microorganisms are greatly influenced by climate change; however, unlike humans, microbes have acclimated more rapidly in response to environmental change. Microbes have numerous unique and diverse mechanisms to adapt to climate change, mechanisms that humans can learn from and use to combat climate change's negative impacts.

Microbes and Climate Change

Microbes and climate change are intricately linked. Microbes are major drivers of global geochemical cycling, such as carbon and nitrogen, and important producers and consumers of greenhouse gases. How microbes react to environmental change will therefore have a major impact on global greenhouse gas budgets. For example, thawing permafrost releases carbon that microbes can use to produce methane and carbon dioxide, which increases greenhouse gas levels in the atmosphere. Realizing their importance, modelers and microbiologists have made recent efforts to better incorporate microbial activity into Earth system models for more accurate climate predictions (Lennon et al. 2024).

Human, animal and plant health are also greatly impacted by microbes. Microbes support a healthy immune system and provide essential nutrients; however, pathogenic microbes cause disease and illness. Infectious diseases are a leading cause of mortality (WHO 2020). Climate change alters pathogens and vector species spatial range, resulting in increased incidents of water-borne and vector-borne illnesses associated with climate change. One Health pathogen surveillance systems can aid public health responses to disease outbreaks, which are expected to increase with more extreme weather events helping to spread pathogens.

Microorganisms greatly impact food and water safety as well. Soil and root microbes promote plant health and resilience. Increased temperatures and altered precipitation levels resulting from climate change are projected to favor bacteria and fungi that lead to food spoilage and harmful algal blooms that contaminate water systems. Environmental stress because of climate change can impact the microbial community (known as a microbiome) of the plant and may affect overall crop production (Li et al. 2018).

Microbes as Climate Change Solutions

There is a great need for novel innovations to combat the current climate crisis. Mitigation and adaptation solutions have expanded in recent years, but there remains a gap in innovation to keep on track for the Paris Agreement standards.

Though famous—or infamous—for causing sickness, microbes' unique abilities provide numerous benefits for society. With regard to health, many microbes are critical to human's digestive and immune systems, and microbial research has resulted in numerous medicines and vaccines. Microbes are used industrially to produce various products, enrich agricultural production and clean contaminated water or soils. The opportunities for microbes to benefit society are as diverse as they are. However, these processes are generally underemphasized in plans to mitigate climate change, certainly relative to increased reliance on sources of clean energy such as wind, hydroelectric and solar power.

To bring the potential of microbe-driven solutions to the attention of scientists and policy makers, the International Union for Microbiological Societies (IUMS) and American Society for Microbiology (ASM) joined forces and formed a scientific advisory group (SAG) composed of global experts in diverse aspects of microbiology, technology and economics and asked them to discuss how microbiology can positively and safely address climate change and preserve biodiversity. The group assessed both the technical and economic feasibility of microbial innovations, emphasizing solutions that prioritize human health and safety, reduce social inequities and promote economic well-being for the global population.

Microbe-based solutions are another pillar in a comprehensive and integrated climate change strategy

In this report, we highlight major scientifically sound microbe-based innovations that have the possibility to help humans adapt to and lessen the negative consequences of climate change. We do not regard these solutions as substitutes for other promising strategies for tackling the challenge of climate change, such as reduced demand for energy-intensive goods and services, increasing the energy efficiency of different production processes and forest protection/reforestation. Rather, microbe-based solutions are another pillar in a comprehensive and integrated climate change strategy.

Applying an Economic Lens to Microbe-based Innovations for Climate Change

Besides their technical feasibility, the viability and desirability of microbe-based approaches also require the demonstration of their economic feasibility. The goal is to provide technologies that also boost the economy. Microbe-based innovations may be judged economically feasible in 1 or 2 ways: commercially or societally. Commercial feasibility requires that the discounted value of expected revenues derived from 1 or more microbe-based solutions be at least as large as the discounted costs of implementing the solution(s) after adjusting for financial risks. Societal feasibility requires that the *fully monetized benefits* created by a microbe-based approach be at least as large as the full cost of implementing that approach, also on a discounted and risk-adjusted basis. Discounting facilitates meaningful comparisons of benefits and costs that occur at different points in time. Fully monetized benefits encompass a wide range of individual and collective gains stemming from improved climate conditions, ranging from lifetime income, health and satisfaction to social, economic and intergenerational equity to food and energy security. Insofar as the benefits of climate interventions can extend beyond the borders of the jurisdiction implementing them, net benefits are naturally calculated and assessed at global, national and subnational levels. A comprehensive assessment must also consider the inherent risks, both financial and those related to safety or other unintended consequences. The failure to properly account for benefits and costs can bias assessments of economic feasibility and lead to ill-founded policy decisions.

This report highlights 3 microbe-based innovations to help humans adapt to and sustainably mitigate climate change in terms of its pace and deleterious consequences.

- Microbes for a non-fossil carbon economy.
- Microbes for food security and ecosystem resilience.
- Microbes for urgent methane mitigation.

The scientific advisory group finds these solutions scientifically sound, economically sustainable, safe and scalable in a 5-to-15-year period. It is also confident that these solutions will promote social equity and societal well-being more generally and that they can be tailored to the needs and capacities of local communities, countries and regions.

Microbes for a Non-fossil Carbon Economy

Microbes have unique and expansive metabolic capabilities that can be utilized to produce a variety of value-added products, such as medicines, chemicals and energy. Microbial processes provide a vast repertoire of carbon catabolism and biosynthetic pathways to transform waste feedstocks to bioproducts that are tailored to the needs of local communities. These microbial processes reduce greenhouse gas emissions by directly converting greenhouse gases into a value-added product and replacing a technology that emits substantial greenhouse gases.

Mitigation	Adaptation
Reduces greenhouse gas emissions and reliance on fossil fuels.	Reduces waste, frees up land and water resources and produces value-added products with a lower carbon output.

All microbial bioconversion processes use microbes to transform a feedstock into a value-added product. However, these processes may take on a variety of formats and with a diversity of microorganisms. Below are 2 main categories of microbial bioproduction processes.

Bioenergy: This involves generating energy from organic matter rather than fossil fuels. Bioenergy production from microbial bioconversion of a variety of feedstocks, coupled with carbon capture and storage, is modeled to be able to deliver nearly 245 exajoules of energy per year by 2050. Anaerobic digestion, which uses consortia of bacteria to break down organic matter in the absence of oxygen to produce biogas, can convert up to 60%-80% of the organic matter in feedstocks to biogas (Weiland 2010). Microbial fermentation can convert feedstock sugars into ethanol or other biofuels. The United States alone generated over 15 billion gallons of ethanol through primary fermentation of corn in 2022 (eia.gov).

Microbial bioconversion is an essentially modular and widely implementable technology

Biomanufacturing: Renewable and sustainable carbon sources are used as feedstocks for microbially converted value-added products. The goal is to offset the use of petrochemicals, and thus greenhouse gas emissions, and create a robust supply route to the commodity market. Over 70% of CO_2 emissions are attributed to transportation and the chemical industry (Net Zero America 2021). Microbial production of fuels not only can substantially reduce greenhouse gas emissions but also can be used to produce new advanced fuels with higher energy density and fuel blend properties (e.g. 1,4-dimethylcyclooctane) (Baral et al. 2021). It is estimated that over 60 billion gallons of renewal carbon liquid fuels could be manufactured from currently available biomass (BETO Billon-Ton Report 2023).

Microbial bioconversion is an essentially modular and widely implementable technology that can be tailored to a geographic location, market or community. This can be a source of equity and opportunity worldwide and to a range of communities. Thus, each region can develop a system that is tailored to their starting materials as well as desired products based on the local need and availability of resources. Bioproduction of fertilizers, foods and even therapeutics can also indirectly ameliorate problems in food shortage, ecological preservation and disease spread that are all exacerbated by global warming and climate change (Fig. 1).

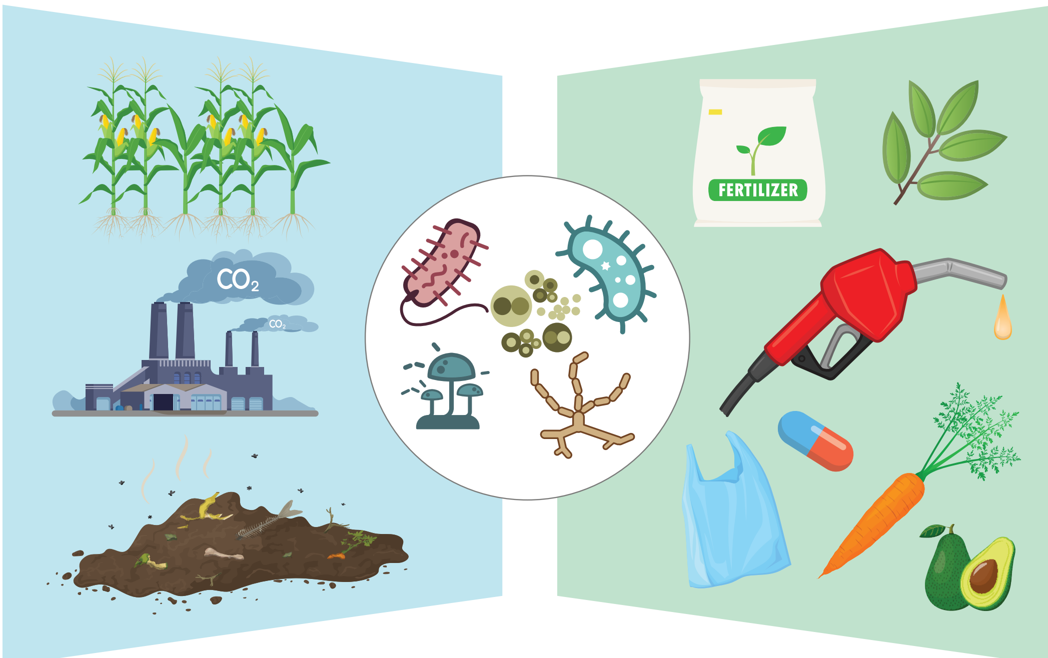


Figure 1: Microbes transform waste feedstocks into value-added products such as fuel, food or medicine. Figure source: López et al. 2021.

The overall net benefits of microbial conversion of waste products are dependent on the efficiency of the conversion, the sustainability of the feedstock and the offset of the product. Agricultural residues, energy crops, wood processing and municipal waste are all common types of waste feedstocks. For example, agricultural residues, such as corn stover, wheat straw and rice husks, could provide up to 5.2 billion tons of biomass annually for bioenergy production (Bentsen et al. 2014) while municipal solid waste, such as food scraps and yard trimmings, is projected to reach 3.4 billion tons by mid-century (Kaza et al. 2018). Large markets represented by fuels, materials and platform chemicals provide the obvious bioproduction targets that stand to have an immediate effect on greenhouse gas reduction.

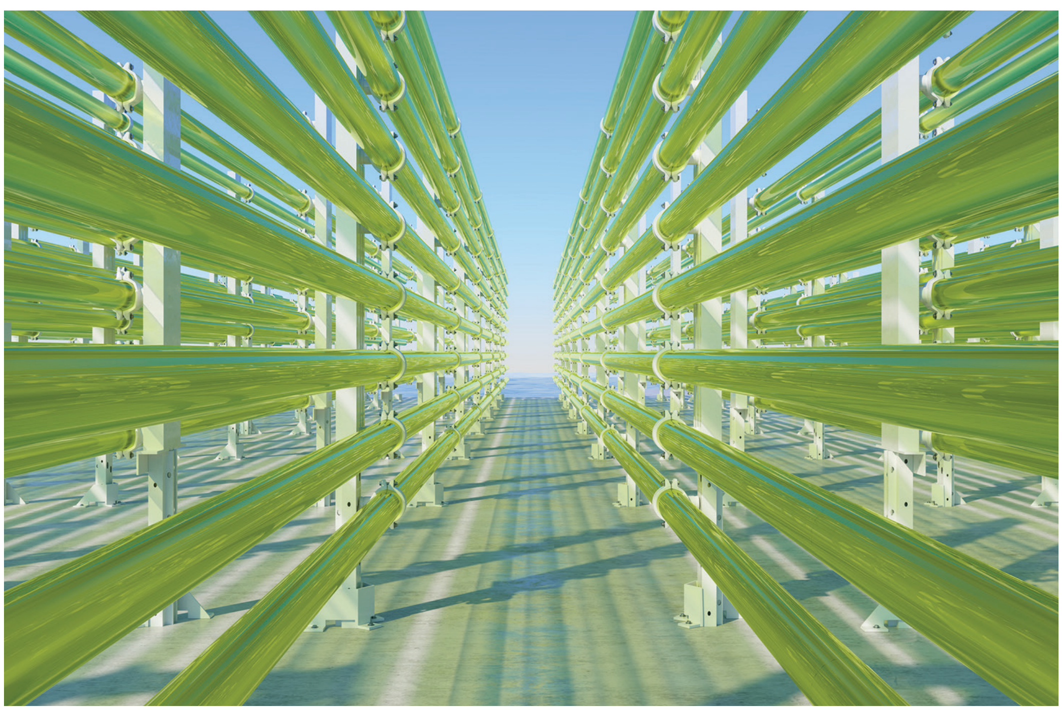
Economic Feasibility of Microbial Biofuels

The high cost of traditional petroleum-based aviation fuel and the desire by airlines to reduce greenhouse gas emissions are critical drivers in the expansion of bio-based and sustainable aviation fuel (SAF) (Market Research Future 2024). Innovative companies demonstrate the potential for microbe-based technologies to disrupt traditional energy markets and create new opportunities for cost-effective SAF.

The global SAF market is projected to grow from 0.6 billion USD in 2023 to 18.3 billion USD by 2032, representing a compound annual growth rate of approximately 53% (Market Research Future 2024). Financial analyses indicate substantial cost savings from a projected shift to SAF and up to 80% reductions in greenhouse gas emissions, thereby pointing to both the commercial and societal feasibility of SAF technologies (Kalnes et al. 2009). The economic feasibility of microbe-based approaches for producing energy, chemicals and fuels largely depends on their ability to lower costs and compete with fossil fuel alternatives. Although the current cost of SAF is 3 times higher than that of traditional jet fuel, increased scale is expected to lower prices and make SAF prices competitive with traditional jet fuel (Azarova et al. 2024).

Additionally, microalgae-based biofuels represent a compelling alternative for sustainable energy production, owing to the unique ability of microalgae to thrive on non-arable land and use wastewater, minimizing resource competition and reducing production costs. Microalgae possess remarkable carbon fixation capacities, capturing CO_2 at rates **10 to 50 times greater** than terrestrial plants, which positions them as one of the most promising biological platforms for addressing greenhouse gas emissions (Ashour et al. 2024). A comprehensive techno-economic analysis of microalgae biofuel production suggests that with optimized production methods, microalgae biofuels could achieve greenhouse gas emission reductions of 50% compared with fossil fuel-based diesel (Liu et al. 2013). While estimates project that algae-based biofuels could accommodate the total energy needs of the global transportation sector, the economic viability of algae-based biodiesel production depends heavily on scaling efficiencies (Adeniyi et al. 2018). Government incentives, such as subsidies, can also play a critical catalytic role by reducing financial costs and risks and thereby accelerating the adoption of algae-based biodiesel fuels.

Advancements in synthetic biology and metabolic engineering are enhancing the capabilities of microorganisms to produce a wider range of biofuels and biochemicals more efficiently (Keasling et al. 2021). Integrated research and development programs focused on improving conversion efficiencies of a broader range of waste feedstocks, sustainable feedstock production and sourcing, and producing a larger variety of valuable end products are all critical to realizing the full potential of microbial bioproduction.



Microbes for Food Security and Ecosystem Resilience

Living organisms and ecosystems depend on their associated microbial communities, called microbiomes, for essential benefits, including nutrient cycling, pathogen control and removal of harmful compounds. Climate change leads to widespread environmental changes that compromise microbiome integrity, resulting in the loss of critical microbial functions and an increased prevalence of disease-causing organisms (Berg and Cernava 2022). This is especially challenging for a growing human population that needs reliable food production. Climate change poses significant challenges to crop production through increased temperature extremes, water stress, pest and disease pressures, nutrient deficiencies, soil salinity and reduced yield stability (Zhuang et al. 2021; Rodell and Li 2023). Microbes offer a sustainable solution to meet the nutritional needs of an expanding global population.

Mitigation	Adaptation
Supports rehabilitated ecosystems that reduce greenhouse gas emissions and increase carbon sequestration of agricultural soils.	Prevents biodiversity loss and promotes enhanced ecosystem resilience and increased crop yields.

Microbiome stewardship, defined as the targeted management of microbiomes through interventions such as microbial probiotics or environmental manipulations, aims to prevent biodiversity loss and enhance ecosystem services. This approach leverages the understanding that microbiomes play pivotal roles in the health and resilience of ecosystems by influencing nutrient cycling, disease resistance and stress tolerance of host organisms and their environments (Peixoto et al. 2022). Strategically enhancing or restoring microbiomes supports ecosystem services that are vital to human health and well-being.

Microbial communities may be able to reduce greenhouse gas emissions from agricultural soils, with soil microbes reducing N_2O emissions by up to 50%

Introducing beneficial microbes in agriculture improves soil health, boosts crop yields, reduces reliance on chemical fertilizers and promotes carbon sequestration that contributes to sustainable practices (Berg et al. 2013; Berg et al. 2021; Cavicchioli et al. 2019; Allard et al. 2020) (Fig. 2). Production and use of synthetic nitrogen fertilizers in agriculture accounts for over 10% of agricultural greenhouse gas emissions and 2.1% of global greenhouse gas emissions (Menegat et al. 2022). Application of plant growth-promoting microorganisms, known as biofertilizers, reduces the amount of chemical fertilizer used and increases overall crop production (Shah et al. 2021). The use of biofertilizers in Brazil's soybean crop is estimated to have reduced carbon emissions by 430 million tons of CO_2 equivalent in Brazil each year (Olmo et al. 2022). Additionally, microbial communities may be able to reduce greenhouse gas emissions from agricultural soils, with soil microbes reducing N_2O emissions by up to 50% (Kamadia et al. 2020; Wu et al. 2018; Hils et al. 2024). Biochar, a carbon-rich material produced by heating organic biomass in the absence of oxygen, is recognized as a valuable tool for

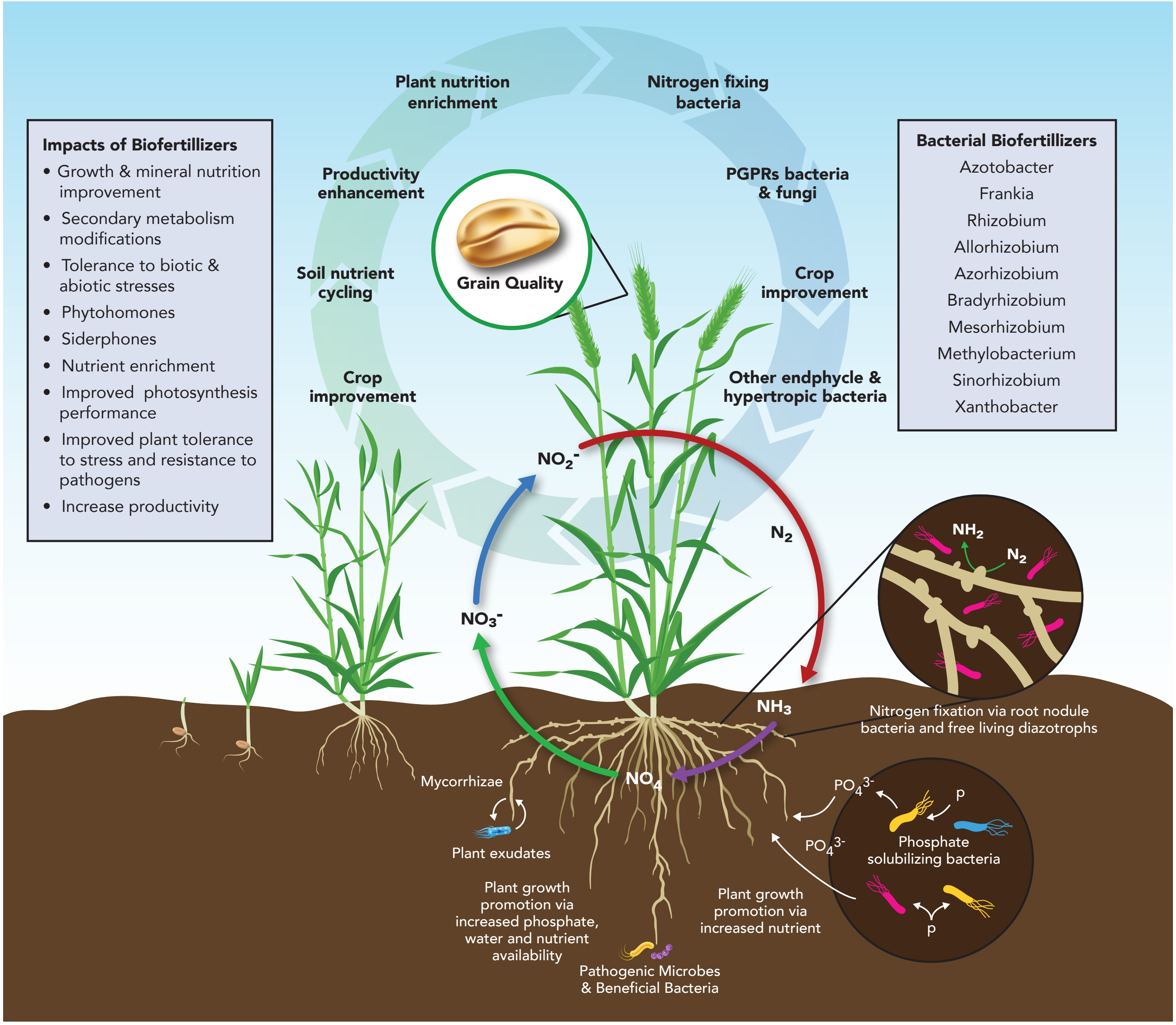


Figure 2. Microbial biofertilizers improve agricultural yield, promote soil health and increase soil carbon sequestration. Figure source: Al-Zubade et al. 2021.

carbon storage and provides a long-term carbon sink due to its resistance to decomposition. The combined application of biochar with microbial inoculants plays a crucial role in climate change adapation by enhancing soil fertility, promoting plant growth, suppressing soil-borne diseases and reducing greenhouse gas emissions (Bolan et al. 2023; Zhu et al. 2024).

Economic Feasibility of Biofertilizers

The use of microbe-laced biofertilizers is expanding worldwide, with growth spurred by the global promotion of sustainable agricultural practices and increased demand for organic produce. The global biofertilizer market is estimated to grow from 2.5 billion USD in 2024 to 6.3 billion USD by 2032, with an anticipated annual growth of 12.2% (Fortune Business Insights 2024).

By improving nutrient uptake efficiency, microbial treatments allow farmers to cut down on expensive chemical inputs, which can account for a large portion of operational costs (Paravar et al. 2023; Upadhayay et al. 2023; Chojnacka et al. 2020). Microbial inoculants can reduce the need for nitrogen-based fertilizers, one of modern agriculture's most energy-intensive and costly inputs (Samantaray et al. 2024). Reducing input costs through microbial treatments can increase farm profitability, particularly in low-income countries and lower-middle-income countries. Beyond their immediate gains, microbial approaches can improve soil health and increase long-term productivity, leading to sustained yields over time (Upadhayay et al. 2023). These features plausibly make them commercially feasible for individual farmers and net beneficial for broader food system sustainability.

Among private companies, Novonesis (formerly Novozymes) has consistently grown in its bioagriculture segment. From 2021 to 2023, Novonesis reported economic profits to be 7.1 billion DKK (approximately 1.6 billion USD), driven by growing demand for biofertilizers and biopesticides. The company continues investing heavily in research and development—representing 11.3% of total revenue in 2023—which reflects its commitment to scaling microbial approaches that promote profitability and societal well-being. Pivot Bio is another company that supplies biofertilizers as an alternative to synthetic fertilizers in the form of nitrogen-fixing microbes. In 2023, Pivot Bio customers avoided more than 706,000 tons of carbon dioxide equivalent emissions by reducing synthetic nitrogen fertilizer on their farms, generating over 100 million USD in annual revenue.

The current use of targeted cultivation and application of beneficial microbes across a diverse array of ecosystems and hosts, such as agriculture, aquaculture and human health, has been shown to improve health outcomes and environmental sustainability while also generating a profit (Fenster et al. 2019; Hai 2015; Wang et al. 2022; Garcias-Bonet et al. 2023). The global market for biofertilizers alone is projected to reach 6.3 billion USD, with an anticipated annual growth of 12.2%, by the end of the year 2032 (Fortune Business Insights 2024). The economic models for producing and deploying these microbial communities in these sectors can serve as viable templates for environmental and wildlife applications. The economics of producing and applying microbial agents to degrade toxic compounds and restore polluted environments, known as bioremediation, illustrate how scale-up and strategic deployment can be both cost-effective and beneficial at the ecosystem level (Helmy and Kardena 2024; Madison et al. 2022; Parnian et al. 2022).

The application of microbial probiotics can be adapted to diverse environmental conditions, such as various agroecological zones and a wide range of crops. Their adaptability makes them especially viable in low- and middle-income countries, where developing low-cost, high-efficacy strains tailored to specific conditions can engage local communities in conservation efforts and minimize losses that highly impact the livelihood of local communities. For example, microbial inoculants can offer cost-effective alternatives to expensive chemical inputs, making them accessible to smallholder farmers (Sarkar et al. 2021). Furthermore, since microbial responses to global and local impacts typically involve a shift toward pathogenic assemblages, creating a positive feedback loop that amplifies these effects is crucial for reducing the synergistic impacts of environmental degradation.

Microbes for Urgent Methane Mitigation

Methane is approximately 80 times as potent as carbon dioxide at trapping heat in the atmosphere over a 20-year period. Thus, reducing overall methane emissions is an effective means for reducing global warming in the near term. Over 150 countries have signed the Global Methane Pledge to reduce global methane emissions at least 30% from 2020 levels by 2030. Microbes both consume and produce methane, making them key allies to mitigating this greenhouse gas. Control of methane producers and enhancement of methane consumers are promising options to reduce global methane emissions.

Mitigation	Adaptation
Reduces methane emissions and global warming potential from agricultural and freshwater ecosystems.	Reduces waste and produces food and energy with a lower carbon output.

Only 2 major sinks exist for methane: reactions with hydroxyl radicals in the atmosphere, which is the largest sink at approximately 562 Tg methane/year, and methane consuming (methanotrophic) microorganisms that remove approximately 32 Tg methane/year from the atmosphere (Curry 2007; Kirschke et al. 2013). Methanotrophs also oxidize methane before it reaches the atmosphere, with methanotrophs in anoxic marine sediments thought to remove up to 80% of methane emission (Reeburgh 2007).

Remarkably, nearly 40% of the Global Methane Budget (approximately 248 Tg methane/year) comes from the combined inland freshwater and wetland emissions (Saunois et al. 2024). Mitigation of methane emissions from inland freshwater and wetland ecosystems will necessarily rely on enhancement of methanotrophic activity while simultaneously decreasing methanogenic (methane producing) activity, both of which are microbial interventions. The removal of 1 Pg methane from the atmosphere equates to a decrease of approximately 0.21° in surface temperatures (Abernethy et al. 2021); thus, strategies for mitigation and removal of methane on the order of Gg (or Mt) per year can yield meaningful changes to the rate of temperature increase. Reducing methane emissions by even 1% (2 Tg or 2 Mt) from inland freshwater and wetland ecosystems can make a significant impact on the global methane budget given the magnitude of their source.

Reservoir systems release approximately 22 Mt methane per year (Deemer et al. 2016). In reservoir systems, accumulation of organic material near the dam site stimulates microbial methane generation such that released water is a concentrated methane source (Fig. 3). Providing aeration to the lower water layer and the addition of mineral substrates, e.g., zeolite (Jackson et al. 2019), at the sediment surface near dam sites can facilitate the growth and activity of methanotrophic biofilm communities that consume methane (Chang et al. 2021). Mitigation of 10% of the methane arising from hydroelectric reservoir sources can remove 2 Mt/year from the global methane budget. To enable aeration and mineral substrate amendments at scale, systems for pumping air are needed. These aeration systems could generate net revenue for smaller reservoir and lake systems that sustain active fisheries as aeration is a mechanism to reduce eutrophication and clarify water (Akinnawo 2023). Mineral amendments can be inexpensive, depending on where they are sourced and if they require mining or other resource-intensive practices. Mitigating methane from unmanaged ecosystems, such as expanding wetlands, is less tractable than for managed systems like reservoirs. Starting with managed inland freshwater systems, fast, tractable, relatively inexpensive and possibly income-generating methane removal can be achieved in less than a decade.

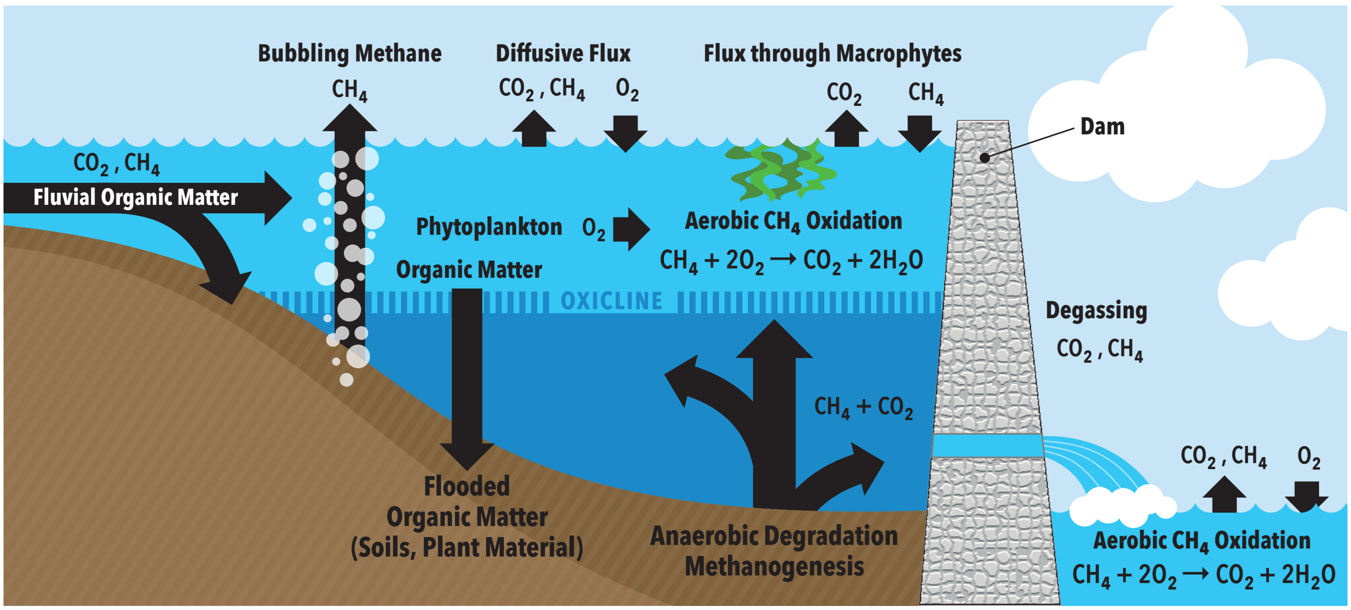


Figure 3. Methane consuming microbes in freshwater reservoirs can reduce overall greenhouse gas emissions. Figure source: IPCC.

Another major source of methane emissions (approximately 211 Tg methane/year) comes from agriculture and waste (Saunois et al. 2024). Many livestock animals are ruminants that contain a specialized fermentation compartment where microbes live and, in the process, produce methane, which the animal releases to the atmosphere. Cattle can produce between 175 and 350 g of methane per day, and enteric methane accounts for 30% of global anthropogenic methane emissions, the largest individual source of anthropogenic methane emissions globally (UNEP & CCAC 2021). To reduce emissions, chemical inhibitors that block methanogenesis reactions can be added to livestock feed. The inhibitor Bovaer® has been shown to reduce methane emissions by 30% in dairy cows (Kebreab et al. 2023). Innovative strategies being explored to reduce livestock methane also include the development of anti-methanogen vaccines, probiotics and the use of CRISPR to modify the rumen microbiome. Animal waste acts as an additional source of methane emissions, with manure management contributing about 10% of agricultural methane (EPA.gov). Microbial anaerobic digestion of manure can divert methane into bioenergy production and can reduce global warming potential by over 25% (Adghim et al. 2020). Today, there are around 20,000 biogas plants in the European Union (EU) to meet the effort to build a more sustainable energy system and reduce the EU's reliance on external sources of energy (IFEU 2022). Building on these models, microbes can be quickly used or manipulated to significantly reduce global methane emissions.

Economic Feasibility of Landfill Gas

Methane biofilters have been successfully used at waste management facilities and abandoned coal mines to reduce fugitive methane emissions by harnessing the biological activity of methanotrophs (Nikiema et al. 2007). As landfills are significant sources of greenhouse gas emissions, landfill gas systems using biofilters are effective at reducing methane and carbon dioxide emissions and capturing a needed energy source; they are estimated to capture 60%-90% of methane emissions and can reduce carbon dioxide equivalent greenhouse gas emissions by 3.9 gigatons over 30 years (US EPA; Project Drawdown). The landfill gas market is estimated at 3.8 billion USD in 2023, with a 5.5% annual expected growth rate from 2023 to 2033, positioning it as a compelling investment opportunity (Global Insight Services 2024).

Microbial approaches to methane mitigation could create economic value through reduced regulatory costs, improved public health and the benefits of lowering methane emissions in agriculture, waste and energy production. Additionally, societal benefits, including decreased air pollution, enhanced ecosystem stability and slowed global warming, further highlight the value of methanotrophic interventions within a broader climate mitigation framework. As with biofuel applications, financial incentives such as carbon credits or subsidies could improve the economic feasibility of microbial methane mitigation by offsetting implementation costs and fostering broader adoption.

Market Readiness – Considerations for Microbial Products to Deliver Social Impacts

Meeting climate goals, as well as adapting to the already changing climate, requires that we change the way we produce almost everything. Emission reductions in energy and transportation are necessary, but to make it to net zero, all sectors will need to decarbonize, particularly agriculture, food, waste, chemicals and other industrial production. Approaching this goal pragmatically and ensuring affordability for the majority of the population are the keys to success of climate policies and solutions.

In this regard, bio-based products and biomanufacturing stand to play an important role. Governments are increasingly viewing biotechnology as a key climate technology, alongside technologies for renewable energy and electric vehicles. For example, the United States is looking to advancements in biomanufacturing to dramatically decrease greenhouse gas emissions, increase carbon sequestration and develop innovative products. The European Union, China, Japan, Germany, the United Kingdom, Singapore and Saudi Arabia are similarly looking to biotechnology to meet emissions reduction goals. Bio-based processes and production are often associated with lower emissions and less land and water use than traditional approaches.

However, while microbial products are compelling in this regard, they are not always commercially practical for industrial applications, at scale, particularly when it comes to high-volume and/or low-margin applications. In general, biotechnology tools have not historically been easily accessible or commercially attractive because of the need for large budgets and long timelines. Applying biotechnology and otherwise unlocking microbial based products across more sectors and applications will require changes in the way biotechnology is pursued and applied for product development, production and commercialization.

Specifically, partnership and infrastructure will be fundamental to achieving the potential for bio-based products to drive industrial applications that support a transition away from fossil fuels and industrial raw materials. Approaches to biotech innovation must transition from a fragmented landscape of expensive, commercially risky experimentation, combined with bespoke production, to a more integrated and standardized platform-based approach that supports scaling biotech applications and the bioeconomy at large. Such a shift would resemble transformations seen in cloud computing and semiconductors, where platforms provide scalable, flexible resources, reducing costs and complexities. These platforms' scale and flexibility have been crucial in creating multi-trillion dollar market cap companies and unlocking innovation globally. The development of platforms would also allow for safety standards and regulatory processes to be promulgated worldwide, which also would reduce commercial risks.

In biotechnology, similar platform-based approaches are emerging to provide flexible, end-to-end research and development (R&D) services paired with standardized manufacturing infrastructure. These platforms consist of highly automated laboratory infrastructure and proprietary software, generating reusable biological data assets, enabling more diverse and cost-effective research campaigns, ultimately making biotech R&D more accessible and improving the speed and probability of success, all together creating more favorable conditions for commercial adoption.

By bending the R&D cost curve down and improving the speed and success rate of biotech innovations, and ensuring access to standardized manufacturing infrastructure, more companies can more readily incorporate microbes and bio-based processes into their business, potentially unlocking direct economic impact of $2 trillion to $4 trillion in the next 10 to 20 years and significantly reducing reliance on fossil fuels or scarce natural resources.

Considerations for Policymakers

Adoption of renewable energy and electric vehicles underscores the transformative impact of purposeful public policy in addressing climate change. Similarly, implementing targeted policies can accelerate the adoption of bio-based climate solutions to cut emissions or to actively remove greenhouse gases from the air.

Policy can drive biotech applications for climate both directly and indirectly. For instance, when laws, regulations or financial incentives effectively discourage practices known to worsen climate change, such as high emissions and unsustainable land use, governments and companies are likely to turn to biosolutions as a by-product of these policies. More directly, policies can provide funding and resources for research and development in biotechnology, streamline and clarify regulatory processes to bring innovations to market faster, and create financial incentives for companies that adopt bio-based solutions.

Policymakers may consider options that include streamlining regulatory approval processes and providing financial support to facilitate the development and adoption of bio-based solutions for current sectors (such as medicine, food and fuel). Environmental-focused policies will be integral for adoption, particularly where companies and customers have relied on existing policies that have traditionally encouraged less-climate-friendly approaches. In addition, fostering international agreement on biosafety standards and norms for emerging biotechnologies will be important to ensure consistent safety requirements are used globally, which can foster public acceptance of bio-based climate solutions. Nearly all of these uses that could affect climate change are outside of the containment provided by a laboratory environment. Therefore, partnership between academia and industry to determine the amount of testing required before introduction into the environment will be important and will help inform regulatory standards, providing predictable pathways for companies venturing into this market.

The transition to biotech as a climate technology presents a major opportunity for those who want jobs fighting climate change. Governments can take steps to create opportunities for new workers and to reskill and upskill workers to minimize workforce displacement associated with transitions to biotechnologies. Biomanufacturing also provides opportunities for jobs that do not require advanced or college degrees.

Bio-based solutions offer a powerful set of tools for addressing climate change, but their full potential can only be realized with adequate support. Discouraging harmful practices, providing direct support for biotech applications, fostering public education and supporting workforce development are all together fundamental to unlocking the benefits of biotech for climate.

Conclusions

Climate change is a monumental threat that needs innovative solutions. Microbes have traditionally been seen as problems, but microbes offer many solutions for climate change. Microbes can mitigate climate change by reducing greenhouse gas emissions, replacing fossil fuels and increasing carbon sequestration. In addition, microbes can help increase food and energy security while also promoting biodiversity as we adapt to a changing climate.

Action is needed quickly for humanity to mitigate and adapt to environmental change. Governments will play a crucial role in developing policies that support bio-based climate solutions that reduce overall greenhouse gas emissions while still reflecting the needs and priorities of their country. In addition, partnerships across sectors and countries will be vital for building a sustainable future. Ultimately, an effective and sustainable portfolio of climate change mitigation technologies will have multiple components, likely including both decreased reliance on fossil fuels and greenhouse gas sequestration through the use of microbes.

Implementing the highlighted solutions will take concerted efforts from a global collection of scientists, industry partners and governments. Professional societies can offer venues for partnerships and innovation. Working together, these innovations can be implemented in the near term to leverage microbes to combat climate change and build a sustainable future that benefits all of humanity.

Time is running out for humanity to address climate change and moderate its negative effects. As outlined in the AR6 Synthesis Report, "Deep, rapid and sustained mitigation and accelerated implementation of adaptation actions in this decade would reduce projected losses and damages for humans and ecosystems, and deliver many co-benefits." Microbes and microbial-based innovations will be critical assets to the collection of strategies for tackling rising greenhouse gas emissions and global environmental change. These solutions can be tailored to fit the needs of local communities and act as sources of income in sustainable ways. They can bolster the bioeconomy, drive innovation, enable supply-chain resilience and protect energy security. With microbes, humans can flourish in a changing world.

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