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Review on Bio-based Approaches for Building a Climate-Resilient Planet

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Abstract: *Climate change refers to long-term variations in atmospheric conditions that affect multiple climate-sensitive sectors, including animal and livestock productivity, crop production, fish and aquaculture production, forest and biodiversity, health and well-being, water and food quality, urban areas, and economic sectors. Bio-based approaches are a revolutionary science that holds promise for creating a greener planet, addressing hunger and malnutrition, and meeting the increasing demand for industrial raw materials derived from living organisms. These life dependent solutions stand as a beacon of hope in the quest to build a sustainable, hazard-free world. Through bio-based innovations, we can tackle the root causes of climate change, paving the way for a safer and smarter planet. This review explores the role of bio/life-based solutions in climate mitigation and adaptation, with a focus on innovative solutions like stress-tolerant crops, to safeguard global communities from climate-related disasters.*

Keywords: Bio-based, climate adaptation, climate mitigation, safe planet

INTRODUCTION

Climate change refers to long-term changes in weather conditions, such as atmospheric CO_2 levels, air temperatures, precipitation, pressure, humidity, wind patterns, sunshine intensity, cloud cover, and dust levels, posing significant challenges to humans, animals, plants, and microorganisms (Atici & Division, 2014; Cavicchioli *et al*., 2019 and Tiedje *et al*., 2022). Climate change is caused by an imbalance in atmospheric radiation, impacting ecosystems at local, regional, and global levels, causing harmful effects on both biological and non-biological components (Gemechu, 2022; Abas *et al*., 2017; Ollas *et al*. 2019; Mikhaylov, 2020; Zahed *et al*., 2021; Abbass *et al*., 2022; Vuurst and Escobar, 2023).

Population growth increases the demand for land, energy, and resources, driving deforestation, generating inedible plant tissues and resulting in further emissions (Singh, 2019; Khaksar *et al*., 2022). Intensive farming, which involves high pesticide and fertilizer use, releases nitrous oxide, contributing to soil degradation and water contamination (Saha *et al*., 2023; Ditia, 2024). Together, these activities accelerate environmental degradation, leading to pollution, ecosystem imbalance, and increased vulnerability to natural disasters. Furthermore, air and water pollution harm human health, while soil degradation reduces agricultural productivity, threatening food security (Tefera, 2021; Burlini & Sacchetti, 2020). As global temperatures rise, climate change intensifies, causing severe effects like flash floods, melting glaciers, acid rain, prolonged droughts, wildfires, and shifts in disease distribution (Yarzábal *et al*., 2021; Braide *et al*., 2020; Abbass *et al*., 2022). As permafrost thaws, it releases dormant pathogens, heightening the risk of emerging infectious diseases and disrupting ecological balance. Rising sea levels threaten low-lying coastal regions with more frequent flooding and erosion, leading to property loss, infrastructure damage, and potential displacement of communities. Saltwater intrusion into freshwater sources further disrupts drinking water supplies and agriculture. Additionally, the increase in extreme weather events, such as hurricanes, droughts, wildfires, and heat waves, contributes to food and water shortages, health crises, economic disruptions, and biodiversity loss. These impacts underscore the urgent need for global action to reduce greenhouse gas emissions and strengthen resilience to climate challenges. Without decisive action, the risks of irreversible ecosystem damage, heightened human vulnerability, and escalating disaster response costs will continue to grow (Mahadik *et al*., 2023; Yarzábal *et al*., 2021; Mora *et al*., 2022).

Climate change is causing substantial damage and irreversible losses across a range of ecosystems, including terrestrial, freshwater, cryospheric, coastal, and open ocean systems. Rapid-onset events can result in death, injury, and a range of health issues, such as infectious diseases, physical and mental stress, and the loss of medicinal plant species (Gemechu, 2022; Mikhaylov, 2020). Various sectors are affected by climate change (Figure 1), including crop production, livestock, fisheries, aquaculture, forestry, and food systems that are sensitive to environmental changes and are directly or indirectly impacted by climate change (Confalonieri *et al*,. 2007; Rocklöv *et al*., 2023; Abbas *et al*., 2018; WIPO, 2022).

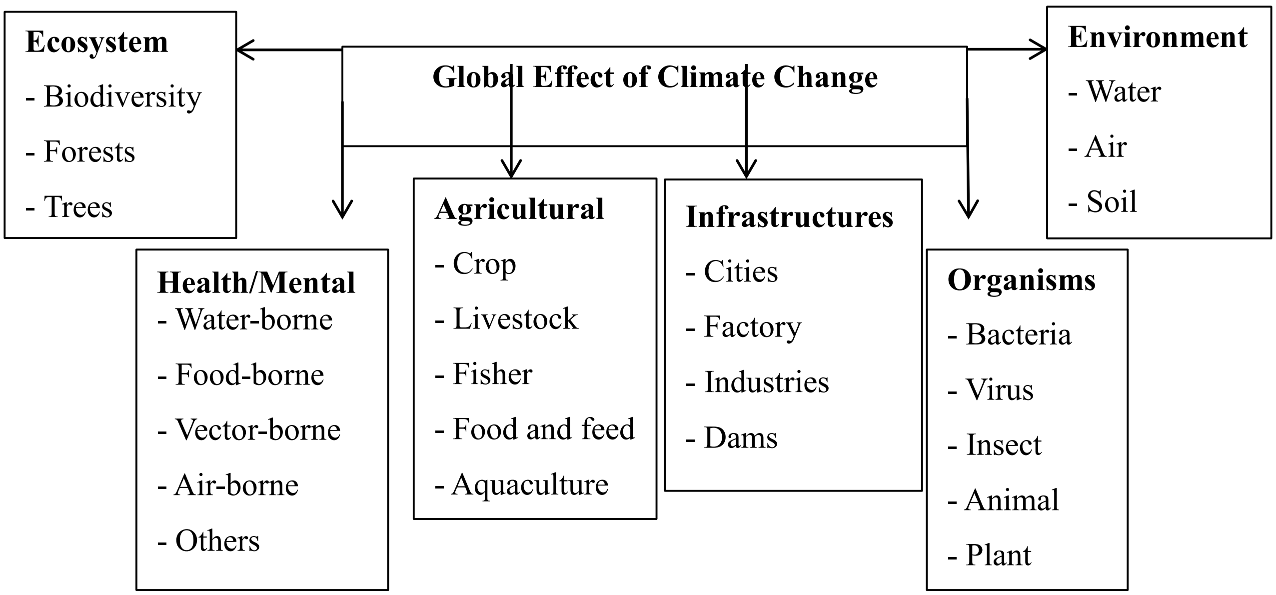


Figure 1: Multi-Sectorial Effect of Climate Change across the Globe (Constructed by authors)

Climate alteration is posing significant threats to global food security, impacting food availability, access, and stability. Rising temperatures, unpredictable weather patterns, and extreme events reduce crop yields, degrade soil quality, and disrupt food production systems. These environmental stresses can exacerbate malnutrition, limit dietary diversity, and worsen micronutrient deficiencies (Samra, 2017; Benitez-alfonso *et al*., 2023). The increasing pressure on food production and access will particularly impact regions affected by poverty (Khojasteh *et al*., 2020; Tefera, 2021).

Aquaculture, a rapidly growing food production sector, experienced an average annual growth rate of 5.3% from 2001 to 2018, driven by rising global demand for seafood, sustainable protein sources, and technological advancements (Prapti, 2022). However, this growth also raises environmental concerns, including water pollution and disease outbreaks, which highlight the need for sustainable practices to minimize ecological impacts and support food security and economic development (Prapti and Sunny, 2022). Fish provide a vital protein source and contribute to economic prosperity, particularly in developing countries (Shawket *et al*., 2019; Maulu *et al*., 2021; IPCC, 2011). Marine recreational fishing offers economic benefits to coastal communities and enhances well-being worldwide (Pinnegar *et al*., 2020).

Climate crisis is causing ample threats to the aquaculture sector, including rising sea temperatures, ocean acidification, and extreme weather events (Rahman *et al*., 2022; Pinnegar *et al*., 2020). These changes can disrupt aquaculture operations by damaging infrastructure, reducing water quality, and affecting the health and growth rates of farmed species. These changes can alter the metabolism, reproduction, and immune responses of fish and shellfish, making them more susceptible to diseases and parasites. Additionally, the shifting climate can disrupt ecosystem balance, leading to harmful algal blooms and invasive species competing with or preying on farmed fish (Maulu *et al*., 2021).

Aquaculture production and fishery resources are highly influenced by coastal and aquatic environmental conditions, including seashore, river flow, lake elevation, species variations, and wildlife productivity (Gupta *et al*., 2020; Mojumdar and Ashik, 2022). Ocean warming, increased sea surface salinity, and acidification are predicted to drastically impact marine life, particularly fish. Ocean acidification, caused by dissolved atmospheric CO_2, lowers ocean pH and reduces calcium carbonate, a crucial element for shell and skeleton formation in marine organisms (Id *et al*., 2023; Mojumdar and Ashik, 2022). Despite the vulnerability of aquaculture and fishery production systems to these climate effects, investing in building their resilience remains essential (Mojumdar and Ashik, 2022). Demographic effects include changes in reproduction rates, survival, and mortality, with some species potentially facing extinction due to habitat loss or unfavorable climate conditions (Ollas *et al*,. 2019). Climate change affects agricultural productivity at all stages, including cultivation, germination, maturation, production, and post-harvest conditions. It also affects agricultural yields, income, food prices, delivery reliability, quality, and safety, as optimal conditions become variable (Vermeulen *et al*., 2012; Vuurst and Escobar, 2023). All the abiotic factors, including high temperatures, low temperatures, salinity, drought, and other stresses, contribute to an average yield loss of 50% in agricultural crops globally (Kaur *et al*., 2018). So, addressing climate emergency is essential for maintaining food security and ensuring agricultural stability (Gupta *et al*., 2020). Climate change is causing significant changes in the livestock sector, affecting animal health and productivity. Rising temperatures, extreme weather events, and altered precipitation patterns impact growth, reproduction, metabolic activity, and milk production. Heat stress reduces feed intake, fertility rates, and nutrient absorption, leading to decreased productivity. The increased prevalence of diseases and pests heightens health risks, necessitating veterinary interventions and increasing vulnerability to food security. (El-Sayed & Kamel, 2020; Vermeulen *et al*., 2012; Tefera, 2021). Ecosystems are also jeopardized by deforestation, habitat destruction, and loss of biodiversity. Infrastructure is increasingly threatened by extreme weather events and rising sea levels, compromising the resilience of human settlements, causing displacement, and resulting in economic losses (Dhara *et al*., 2013; Franzke and Czupryna, 2021; Mora *et al*., 2022; El-sayed and Kamel, 2020; Vuurst and Escobar, 2023).

Changing the climate is expected to significantly impact global public health by altering the distribution, transmission, and severity of climate-sensitive infectious diseases (Abbass *et al*., 2022). Rising temperatures, shifting rainfall patterns, and changing seasons will influence the spread of these diseases. Warmer temperatures can expand the range of vectors such as mosquitoes, ticks, and fleas, increasing the transmission of diseases like malaria, dengue fever, Lyme disease, and Zika virus. Understanding the complex relationship between climate change and infectious diseases is essential for predicting risks and developing effective adaptive strategies (Gupta *et al*., 2020; Nel & Richards, 2022; Rocklöv *et al*., 2023). Climate change can substantially alter the distribution and dynamics of infectious diseases by affecting the complex interactions between hosts, pathogens, and vectors (Fawzy *et al*., 2020). Therefore, understanding the environmental, biological, and social factors involved in these epidemiological cycles is crucial for predicting and mitigating the impacts of climate-sensitive infectious diseases, as they are heavily influenced by environmental factors such as temperature, humidity, and rainfall (El-sayed and Kamel, 2020; Kristie *et al*., 2019). The climate emergency is contributing to an increase in disease outbreaks, including cholera, malaria, typhoid, rotavirus, hepatitis, respiratory diseases, skin infections, and more (Abbass *et al*., 2022). Rising temperatures, altered rainfall patterns, and extreme weather events are all influencing the prevalence of these diseases. Warmer temperatures provide favorable conditions for mosquitoes, while increased rainfall and flooding can contaminate water sources, facilitating the spread of waterborne diseases. Additionally, extreme weather events create environments that promote respiratory diseases and infections. As climate change continues, the risk of disease outbreaks will rise, particularly among vulnerable populations (Semenza and Paz, 2021; Khojasteh *et al*., 2020; Uwishema *et al*., 2023; Ford *et al*., 2022; and Ebi *et al*., 2022). These outbreaks can be triggered by various pathogens, including viruses, bacteria, animals, fungi, protozoa, plants, and chromists (Dhimal *et al*., 2021). The COVID-19 pandemic has raised concerns about the link between anthropogenic global warming and the rise in infectious disease outbreaks. Climate change, including rising temperatures, changes in precipitation, and extreme weather events, can create favorable conditions for the spread of infectious diseases by disrupting ecosystems and influencing vectors like mosquitoes, ticks, and rodents. This directly affects human health by increasing vulnerability to infectious diseases (Vuurst and Escobar, 2023). Human activities like deforestation, urbanization, and industrial pollution can indirectly contribute to the spread of infectious diseases by pushing wildlife into closer contact with humans. More research is needed to understand how climate change might alter the dynamics of future pandemics and whether mitigation efforts can prevent the emergence of new diseases (Franzke & Czupryna, 2021and Abbass *et al*., 2022).

Climate hazards significantly affect COVID-19 transmission, perception, response, and lived experience. Temperature, wind, and humidity affect the virus's spread, but their exact mechanisms remain unclear (Ford *et al*., 2022). Warmer temperatures and higher humidity levels may reduce virus stability in the air. Non-climatic factors, such as social determinants of health, such as population density, healthcare access, and socioeconomic status, are more influential in shaping the virus's severity and spread. Regions with higher poverty rates, crowded living conditions, and limited healthcare access experience more severe outbreaks. Government responses, public health infrastructure, novel polices and vaccine availability also determine transmission control effectiveness (Rocklöv *et al*., 2023). Understanding the synergistic effects of climate and non-climatic factors is crucial for developing adaptive strategies to reduce risks and mitigate future pandemics (Ford *et al*., 2022). According to these authors, climate extremes coinciding with the COVID-19 pandemic have heightened exposure to the virus, increased vulnerability, compromised emergency responses, and reduced health system resilience under multiple stresses. This has also led to broader socio-economic consequences (Mohommad & Pugacheva, 2021). For instance, the cumulative financial costs of the COVID-19 pandemic could amount to approximately $16 trillion for the United States alone (Mora *et al*., 2022).

Climate change has a serious impact on feed and food safety throughout the entire food production, processing, and supply chain (Vermeulen *et al*., 2012). It causes sizable challenge to global food and feed supplies, with farmers facing financial losses due to pests, diseases, and weeds, which result in stagnant or declining yields. Climate disasters can exacerbate these issues by intensifying environmental stress, increasing the prevalence of pests and diseases, and reducing crop production (Gidi, 2023). Changes in temperature, precipitation, and extreme weather events disrupt agricultural systems, leading to crop failures, lower yields, and increased contamination risks. Warmer temperatures promote the growth of harmful pathogens in crops and animal feed, raising the risk of foodborne illnesses and reducing food quality. Climate emergency also affects the availability and nutritional quality of raw materials for animal feed, further impacting livestock health and food safety (Misiou & Koutsoumanis, 2021). Additionally, higher temperatures and humidity during processing and storage increase the risk of pathogen growth and myco-toxin contamination, jeopardizing food safety. Climate-related disruptions to supply chains, such as delays from extreme weather, also heighten food safety risks. Addressing these challenges requires innovative strategies in farming, processing, and regulation to ensure food system resilience and safety in a changing climate (Herrera and Iqbal, 2016 and Heidari *et al*., 2023). Climate crisis poses significant health risks to food safety, increasing contamination in crops and seafood from myco-toxins, harmful algal blooms, animal disease pathogens, fungal toxins, toxic algae products, and chemical contaminants (Misiou and Koutsoumanis, 2021; Samra, 2017; Johne & Kappenstein, 2023 and Heidari *et al*., 2023). Furthermore, climate change impacts food across four key dimensions: food security, availability, accessibility, and utilization (Samra, 2017 and Heidari *et al*., 2023).

Climate change is causing biodiversity loss in local and regional areas, with continued greenhouse gas emissions causing irreversible changes in all major climate system components (IPCC, 2022). Climatic extremes have both direct and indirect impacts on ecosystems, with human and ecosystem vulnerabilities being interdependent (Abbas *et al*., 2018). This may lead to significant changes in terrestrial ecosystems, such as forests, deserts, grasslands, and mountain ecosystems, as well as freshwater and ocean ecosystems (Cavicchioli *et al*., 2019). Consequently, wild species—including animals, plants, and microbes may face elimination due to these climatic variations. Altering the climate also causes extensive and unpredictable damage to key economic and non-economic infrastructures, including dams (IPCC, 2022). Heavy rainfall leads to inland flooding and related damages, while floods and storms impact coastal areas, damaging infrastructure and placing financial strain on cities (Singh, 2019 and WIPO, 2022). Climate change is causing devastating economic damages in climate-sensitive sectors, impacting agriculture, forestry, fisheries, energy, tourism, and outdoor labor productivity (IPCC, 2023). It has a tremendous impact across the globe, with many of the observed changes being unprecedented over decades to millennia (Abbas *et al*., 2018; Abbass *et al*., 2022; Nel & Richards, 2022). Scientists studying climate change are urging for increased research efforts and re-examination of environmental justice aspects due to numerous reasons (Vuurst and Escobar, 2023). Immediate action is crucial to mitigate risks and reduce greenhouse gas emissions, preventing catastrophic consequences and ensuring the survival of millions (El-sayed and Kamel, 2020; Prapti and Sunny, 2022; Yu and Ji, 2023; Cavicchioli *et al*., 2019; IPCC, 2023).

Climate change is a globally pressing issue, yet no ultimate solution has been found (Zahed *et al*., 2021). Urgent, robust, and sustainable action is needed to protect living organisms from climate change health risks, focusing on interdisciplinary collaboration, advanced technologies, and data-driven solutions for food security, environmental sustainability, and agricultural efficiency (Rene & Ramesh, 2014; Badadyan, 2024). Therefore, addressing human-driven climate change is crucial to protect the planet and its inhabitants from further harm (Braide *et al*., 2020; Abbass *et al*., 2022). Globally, bio-based solutions like biotechnology is a critical tool and a highly effective and cost-efficient technology to address and mitigate climate-related disasters, demonstrating the urgent need for timely, practical, and economic solutions (Aurand and Buan, 2024; Tesfahun, 2018; Mattiasson, 2016; Núñez *et al*., 2020).

Bio-based approaches on the mitigation of climate change

Traditionally, conserving, protecting, and restoring ecosystems, along with implementing climate change adaptation strategies, minimizes biodiversity vulnerability (Yukui *et al*., 2018). Even though, adaptation can enhance agricultural productivity, health, food security, livelihoods, biodiversity conservation, and reduce risks, conventional mitigation efforts alone are now a day becoming insufficient to control climate emergency (Gaskell *et al*., 2003; Fawzy *et al*., 2020). Therefore, the urgent need to combat climate change and develop innovative technologies to eliminate greenhouse gases is crucial (Kristie *et al*., 2019). Scientists are recognizing the potential of bio-based technology including utilizing microorganisms and larger organisms from diverse environments, to manage climate change by reducing greenhouse gas emissions and implementing timely bio-based techniques (Braide *et al*., 2020; Fendrihan & Pop, 2022; Overland & Sovacool, 2020). Bio-based solutions are an interdisciplinary approach, involving animal and plant breeders, genetic engineers, bioenergy specialists, carbon sequestration experts, bioremediation scientists, crop physiologists, biotechnologists and molecular biologists. These all bio-based technologies can effectively support the study and development of stress-tolerant plants and animals, and strongly positive impact on creating safe planet and to mitigate its unavoidable future impacts (Gutti *et al*., 2013; Tesfahun, 2018 and Benitez-Alfonso *et al*., 2023; Shiomi, 2023; Fuchs *et al*., 2023 and Aurand & Buan, 2024). Bio-based approaches enable to adapt and mitigate climate hazards through myriads of techniques (Figure 2). These includes improvement of crop yields, contributes to bioremediation, production of bioenergy and bio-fertilizers, and development of new drugs, vaccines, diagnostic tools, and enhances food quality and safety using enzymes and probiotics, and addressing global challenges (Benitez-alfonso *et al*., 2023; Badadyan, 2024; Mattiasson, 2016; Khraiwesh, 2020; Mtui, 2011; Molochaeva and Gamaeva, 2024; Sakshi *et al*., 2018; Gutti *et al*., 2013; Mattiasson, 2016). They strongly contributes to the development of pollution reduction and combats climate change through waste reduction, bioremediation, carbon capture, improve nutritional profiles and using bio-based industrial imputes (Donato *et al*., 2023; Sakshi *et al*., 2018; Badadyan, 2024; Trends *et al*., 2021).

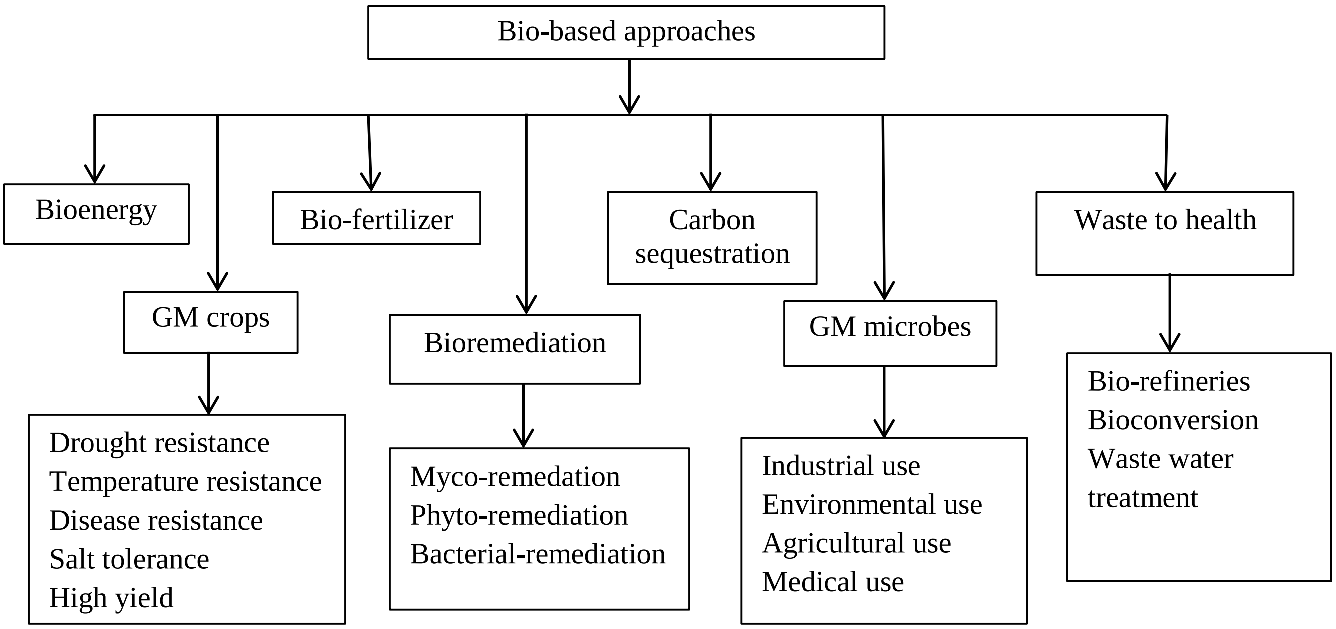


Figure 2: Bio-based approaches in mitigating of climate change (constructed by authors)

Genetically Modified Crops

Food security requires a blend of traditional and modern technologies to enhance productivity, combat pests, diseases, drought, poor soils, and climate change (Donato *et al*., 2023). Improving crop resilience and tolerance to abiotic stresses like drought, salinity, heat, and cold is crucial for combating global food security challenges posed by climate change (Khraiwesh, 2020). Climate change mitigation involves plant breeding to enhance crop tolerance and reduce its impacts, focusing on developing resistant varieties to drought, salinity, disease, insects, and weeds (Mtui, 2011; Kaur *et al*., 2018 and Gebretsadik & Kiflu, 2018). Creation of crops that can withstand both biotic and abiotic stress, thus mitigating the effects of climate change (Gebretsadik & Kiflu, 2018; Gangwar *et al*., 2023). GM crops have significantly improved global productivity and control of pests, diseases, and weeds, leading to reduced chemical pesticide use, improved crop morphology, increased productivity, and higher profitability for millions of farmers worldwide (Tesfahun, 2018). Biotechnological approaches are crucial for selecting and adapting crops to new climatic conditions, enhancing resistance to abiotic and biotic stresses induced by climate change, and playing a vital role in mitigating climate impacts (Núñez *et al*., 2020; Fendrihan & Pop, 2021; Mtui, *et al*., 2011; Khraiwesh, 2020). Advancements in genetic research are enabling long-term agricultural intensification and increased crop adaptability to global warming (Izgü *et al*., 2024). Genetic engineering enables the creation of resistant seeds and crop varieties, consuming millions of people globally and feeding millions of livestock and poultry, and is used to combat pests, diseases, drought, and extreme temperatures (Izgü *et al*., 2024; Tesfahun, 2018; Easton *et al*., 2014).

Drought-tolerant crops are crucial for maintaining growth and productivity in arid regions, as they can thrive with minimal water, rain, or irrigation, potentially transforming arid regions into productive agricultural zones and mitigating climate impacts (Yukui *et al*., 2018). Genetic engineering offers promising solutions for drought-prone regions, using tools like QTL identification, marker-assisted selection, genetic engineering, and "omics" technologies for breeding drought-tolerant crops (Núñez *et al*., 2020 and Izgü *et al*., 2024). it has been utilized to develop crops with enhanced drought tolerance by enhancing understanding of drought tolerance mechanisms and identifying potential genes (Babiye, 2019; Thabet and Alqudah, 2021; Zhang *et al*., 2022). Using cDNA libraries and complete genome sequence information in plants like Arabidopsis and rice, expressed sequence tags (ESTs) can identify drought-tolerant genes, which have been applied to crops like rice, maize, banana, and wheat to enhance drought tolerance (Beatriz *et al*., 2011; Karavolias *et al*., 2021) . This discipline got an attention in Africa. For example, the Water Efficient Maize for Africa (WEMA) partnership, led by the African Agriculture Technology Foundation, aims to develop drought-tolerant maize varieties using the best technology available worldwide for a five-year public-private partnership (Babar *et al*., 2022). Saline solutions, potentially due to climate change, are reducing plant and crop performance and productivity. Genome editing of crops like rice has shown increased tolerance to saline solutions, with edited lines being 19% shorter in saline solutions compared to wild-type plants (Karavolias *et al*., 2021). Edited plants experienced less severe biomass reductions due to salt exposure compared to wild plants. Genetically engineered organisms can survive and grow in extreme environments like salty and hot conditions due to gene modifications or insertions from related or unrelated organisms (Ranjha *et al*., 2022).

Weeds compete with crops for resources such as water, nutrients, sunlight, and space, and they harbor pests that affect crop quality. To mitigate their impact, farmers use manual weeding, plowing before sowing, and synthetic herbicides. However, these methods release CO_2 into the atmosphere, contribute to climate change by emitting greenhouse gases, and kill essential microbes that help degrade those gases. Additionally, the toxic nature of these herbicides alters soil chemistry (Yukui *et al*., 2018). Biotechnological approaches provide sustainable agriculture solutions by enhancing crop yields without causing climate change. They enable the production of herbicide-tolerant crops like canola, soybean, maize, and cotton, enhancing their adaptability and potential for mitigating climate change (Kaur *et al*., 2018). Plant biotechnology, involving crop genomics, genetic engineering, and gene editing, is crucial for creating herbicide-resistant crops and insect-resistant varieties (Ollas *et al*., 2019). Genetically engineered *Bacillus thuringiensis (Bt)* crops are widely used by farmers worldwide, reducing the need for manual weed and insect control and potentially benefiting the environment, which may indirectly help mitigate climate change (Oloo *et al*., 2020 and Ranjha *et al*., 2022).

Pests and pathogens pose a significant threat to farmers worldwide, destroying crops like cotton, maize, brinjal, and soybean. Borers, for example, are a notorious pest that reduce yield quality and lead to financial losses. Biotechnological approaches, such as genetic engineering, are being used to develop pest-, disease-, and insect-resistant crops, reducing the need for chemical pesticides and minimizing environmental impact. *Bt* cotton, a genetically modified variety, has been widely adopted for its effectiveness in controlling pests and improving yields. Similar biotechnological advances are being applied to other crops, contributing to global food security (Fendrihan & Pop, 2021).

The widespread use of genetically modified seed technology has significantly reduced on-farm fuel use and enabled farmers to transition from plow-based systems to reduced and no-tillage systems, which they have maintained for years (Brookes, 2022). The transition to GM cropping has significantly reduced GHG emissions, including CO_2, by reducing spraying in GM areas, resulting in a savings of 23.6 billion kg of CO_2 in 2020, equivalent to removing 15.6 million cars annually in the UK (Brookes, 2022). The use of modern agricultural biotechnologies is being promoted for their potential to boost yields, improve food security, and aid climate change adaptation, while also enhancing soil quality and productivity through genetically modified microbes. Microbial Biological Control Agents (MBCAs), genetically modified (GM) microbes, are environmentally friendly and less polluting solutions used to control diseases, weeds and pests in crop plants (Wesseler and Purnhagen, 2022). The integral application of advanced biotechnological interventions with traditional breeding methods is proposed as a strategy to improve crop resilience against drought stress, highlighting the significant potential of biotechnology in mitigating and adapting to climate emergency through enabling genetically robust crop cultivation worldwide (Izgü *et al*., 2024).

Bioenergy Production

Bio-based solutions play a significant role in the production of bio-based energy (Shiomi, 2023). It is considered a potentially low-carbon and renewable energy source, and it is also recognized for its potential to contribute to mitigating GHG emission (Creutzig *et al*., 2014; Allen & Hammond, 2019 and Lopresto, 2025). Biomass—organic matter available on a renewable basis—includes forest and mill residues, wood wastes, agricultural crops and wastes, and animal wastes (IEA, 2020). Biomass feed stocks include forest residues, organic wastes, and agricultural residues. Biomass can be defined as an integral part of the global carbon cycle (Shafiee *et al*., 2023). Energy derived from biomass is referred to as bioenergy (Smith *et al*., 2020), which can be deployed as solid, liquid, or gaseous fuels (IEA, 2020 and Berndes *et al*., 2014), is expected to play an important role in the mitigation of climate change (Calvin *et al*., 2021 and Vassilis *et al*,. 2020). Biomass, as a renewable energy source, plays a pivotal role in the global energy matrix (Shafiee *et al*., 2023).

Genetic engineering is being used to enhance the oil content, cellulose content, growth characteristics, and resistance to biotic and abiotic stresses in biomass crops. Algae biomass is particularly beneficial as it can reuse CO_2 large volumes, reduce emissions, produce higher biofuel per acre, and degrade faster than petro-diesel, making it a cleaner, lower-emission alternative to fossil fuels (Akhtar, 2023 and Kaur *et al.*, 2013). Algae offer a promising solution for biofuel production, reducing GHGs and creating new economic opportunities in renewable energy. Large-scale algae cultivation can reduce reliance on fossil fuels, stimulate job growth, and restore ecosystems, making it a crucial strategy for combating climate change and building a sustainable future (Shiomi, 2023). Biofuels significantly reduce GHGs, with biodiesel potentially reducing CO_2 emissions by up to 80% compared to diesel fuel (Akhtar, 2023). Genetically modified algae are also considered a well-known substitute for fossil fuels, with biofuel production serving as a primary means to mitigate CO_2 emissions (Zahed *et al*., 2021 and Shafiee *et al*., 2023). Biofuels not only reduce GHG emissions but also air pollutants like sulfur compounds, nitrogen oxides, and particulate matter, reducing health hazards and providing a sustainable energy alternative. They are enhanced through the use of genetically modified microorganisms and larger engineered organisms (Zahed *et al*., 2021 and Shafiee *et al*., 2023). Bio-based approaches significantly reduce the adverse impacts of climate change, with sustainable biomass production being a crucial strategy for mitigating environmental degradation and providing a framework for poverty alleviation in rural areas, offering a dual solution (Shafiee *et al*., 2023).

Reduction of GHG Emission

Urgently addressing the source of the problem leads to success (Mora *et al*., 2022). Climate neutrality is achieved by reducing GHG emissions, maintaining natural carbon sinks, and enhancing the sequestration and storage of carbon in ecosystems (Tesfahun, 2018). Agricultural practices such as synthetic fertilizer use, tillage, overgrazing, and deforestation contribute to a quarter of all GHG emissions into the atmosphere (Cardoso *et al*., 2020 and Emmanuel *et al*., 2022). Chemical industries significantly contribute to climate change by emitting toxic pollutants into the environment, affecting humans, animals, plants, and other resources. To protect life and resources, effective actions must be taken. Recent biotechnological advancements have been analyzed for their potential in agriculture, industry, and the environment sectors, ultimately involving in creating safe environment. Biotechnology can play a vital role in reducing GHG emissions and remediating the planet by lowering the harmful emissions (Mtui, 2011; Cardoso *et al*., 2020 and Shiomi, 2023).

Reduction of using fossil fuel by minimizing herbicide and insecticide usage, tillage with tractors, and energy in soil cultivation has got sustainable solution with GM crops (Brookes, 2022). Insect-resistant biotechnological crops also help reduce GHG emissions, as each liter of tractor diesel contributes 2.75 kg of CO_2 to the atmosphere. GM crops also offer resilience to climate stresses, reduced input requirements, and reduced carbon footprint due to fewer agricultural tasks and less carbon during food production (Mtui, 2011). The technologies significantly reduce GHG emissions from agriculture, equivalent to removing 16.75 million cars. It also offers fuel savings due to fewer or no chemical spray runs, resulting in permanent CO_2 emissions reduction (Oloo *et al*., 2020). Microorganisms, under favorable growth conditions, produce and consume three dominant gases: CO_2, methane (CH_4), and nitrous oxide, which account for 98% of the increased warming due to their role in photo- or chemoautotrophic growth (Oloo *et al*., 2020 and Tiedje *et al*., 2022).

Carbon Sequestration

Global climate change would result from the extreme rise in CO_2 emissions, making it a major environmental problem (Cardoso *et al*., 2020). To prevent our atmosphere from warming, carbon squesstration is considered as a key staratagy to mitigate climate alteration. Carbon sequestration is the process of capturing and removing CO_2 from the atmosphere, storing and converting it (Tesfahun, 2018). Recycling carbon back to the soil, along with other agents like forests, oceans, and crop plants, ultimately removes it from the atmosphere, thereby reducing its concentration (Emmanuel *et al*., 2022). CO_2 is the most abundant GHG and derived from the flue gas stream of fossil fuels (Feng *et al*., 2022).

To address the developing risks from climate change caused by the accumulation of CO_2, it is essential to develop novel technologies (Zahed *et al*., 2021). Biotic sequestration through plant photosynthesis and transgenic engineering can reduce carbon emissions into the atmosphere while producing biofuel, minimizing tillage, and improving carbon sequestration. Microorganisms also respond quickly to environmental changes and bind CO_2 to remove it (Shiomi, 2023). One efficient way to achieve this is through conservation tillage. This practice involves a tillage and planting system that covers more than 30% of the soil surface with crop residue after planting, which reduces erosion and enhances methane sequestration (Emmanuel *et al*., 2022).

Minimizing Inorganic Fertilizer

Due to excessive use of chemical fertilizers, agriculture faces diverse challenges (Shikha *et al*., 2023). These fertilizers contribute to the formation and release of certain GHGs, such as nitric oxide (N_2O), among others (Aloo *et al*., 2021 and Emmanuel *et al*., 2022). The main source of GHG emissions is fertilizer production, largely due to its energy intensity, but also due to some emissions of N_2O in the manufacture of nitrate fertilizers (Vermeulen *et al.*, 2012). The use of such chemical fertilizers has a significant impact on the occurrence of climate change (Saha *et al*., 2023). Regular large-scale applications of fertilizers, pesticides, and mulching can lead to soil health degradation and increase negative environmental impacts, contributing significantly to GHG emissions (Saha *et al*., 2023; Shikha *et al*., 2023 and Mtui, 2011). Synthetic fertilizers are known to deplete a large percentage of the soil's naturally occurring essential nutrients, both micro and macronutrients. Changes in environmental conditions due to climate alterations are likely to induce changes in plant physiology and root exudation.

Bio-based approaches play an outstanding role as an assistance tools in reducing the use of synthetic fertilizers by using genetic engineering techniques to fix soil and atmospheric nitrogen through Rhizobium species (Kaur *et al*., 2018 and Aloo *et al*., 2021). Rhizobium and Azotobacter have been used in bio-fertilizers for a long time. Rhizobium is the most popular bacterium used to produce bio-fertilizers (Shikha *et al*., 2023). Rhizobium lives in the nodules of plant roots. These nodules are natural biological factories for nitrogen fixation. The rhizo-bacterium has the ability to absorb nitrogen from the atmosphere and convert it into an organic form that can be used by the plant. Bio-fertilizer is a substance that comprises living microorganisms used to promote plant growth by increasing the availability of primary nutrients to the host plant when applied to seeds, plant surfaces, or soil (Kaur *et al*., 2018 and Tuarira *et al*,. 2019) . It is considered a better option than other conventional fertilizers since it contains a typical population of beneficial microorganisms that provide nutrients to the soil required by the plant without harming the environment (Kiran *et al*., 2023; Sreethu *et al*., 2023; Saha *et al*., 2023).

Phosphate, nitrogen, and other essential compounds are naturally present in the environment and are required for plant growth. Phosphorus nutrient deficiency is a major limiting factor for reduced yield (Yahya *et al*., 2023), as it plays a major role in stress tolerance, maturity, quality, and in nitrogen fixation in crops (Mtui, 2011). Since plants have a limited capacity to utilize these nutrients, microbes come into play to make these elements more accessible to plants (Kaur *et al*., 2018). A type of fungus, *Penicillium bilaii*, helps increase the availability of phosphate from the soil. It has the ability to produce organic acids that can dissolve phosphate in the soil, allowing plant roots to utilize it (Singh, 2020). Therefore, the integration of technologies involving inoculated phosphate-solubilizing bacteria (PSB) in agricultural systems, considering climatic conditions, is essential (Yahya *et al*., 2023).

The ever-increasing use of agrochemicals to boost crop production has created health hazards for humans and the environment (Aloo *et al*., 2021 and Tan *et al*., 2022). However, several bacteria, such as cyanobacteria, also have the ability to transform environmental nitrogen into ammonia, which plants can utilize in their nutrient cycle. Therefore, bio-fertilizers (microbes) create opportunities to use all available food sources in the soil and air (Tuarira *et al*., 2019), allowing farmers to reduce agricultural production costs while preserving the environment (Aloo *et al*., 2021). Another mechanism of biotechnology involves planting crops that can use nitrogen more efficiently. An example of such a crop is GM Canola, which has shown a significant reduction in the amount of nitrogen fertilizer that filters into the atmosphere and leaches into soil and waterways (Emmanuel *et al*., 2022).

Bioremediation

The increasing number of organic and inorganic pollutants in the environment poses a threat to the ecosystem and contributes to climate alteration. Some organic pollutants, such as pesticides, polychlorinated biphenyls (PCBs), and polyaromatic hydrocarbons (PAHs), are resistant to degradation (Bala *et al*., 2022). This is a concerning issue for both wildlife and humans. Various physiological and biological methods are being used globally to degrade these organic pollutants and improve environmental quality (Yadav *et al*., 2022). Bioremediation has become one of the best and most promising strategies for degrading organic and inorganic pollutants (Azubuike *et al*., 2016; Wesseler & Purnhagen, 2022). It is an eco-friendly, systematic, and tactical approach to creating a safe and clean environment and it is fast-growing field of environmental restoration by detoxifies environmental pollutants into less harmful or non-toxic forms (Bala *et al*., 2022; Sadawarti, 2023; Sakshi *et al*., 2018; Shiomi, 2023; Ghanaim *et al*., 2025). It is currently the most cost-effective and efficient method for removing pollutants compared to conventional methods (Chandra *et al*., 2023Smirnova *et al*., 2023; Arora, 2018).

Bioremediation can take place in three different ways, each with different demands for human intervention (Beed *et al*., 2011). First, intrinsic bioremediation occurs when the contaminated area is restored naturally over time by indigenous microorganisms. No human intervention may needed in this process to decontaminate the polluted environment (Azubuike *et al*., 2016). Second, bio-stimulating bioremediation occurs when indigenous microorganisms are stimulated by the artificial addition of specific nutrients to increase the rate of pollutant decomposition. Third, bio-augmentation relies on the artificial introduction of specific microorganisms with the capacity to degrade specific pollutants into the polluted environment (Tangahu *et al*., 2024). CH_4 is a major contributor to the accumulation of GHGs in the atmosphere, can also be mitigated by methane-degrading microbes, known as methanotrophs or methane oxidizers (Han *et al*., 2024). These microbes play vital role in reducing GHG emissions. Recent studies show CH_4 emission estimates for 2020 and 2021, two years with record-breaking atmospheric growth rates (Feng *et al*., 2022 and Tiedje *et al*., 2022).

Bioremediation can occur in three major components: the environment acts as the stadium, pollutants act as the football, and living organisms act as players (Figure 3). The targeted players in the bioremediation process are micro- and macro-organisms, including bacteria, fungi (myco-remediation), and plants (phytoremediation) (Arora, 2018 and Sadawarti, 2023). Microbes such as bacteria, fungi, and actinomycetes are responsible for decomposition. These microbes break down organic material into less complex substances, including CO_2, water, and organic acids (Chandra *et al*., 2023). Microbes are capable of breaking down a range of organic substances to gain energy and recycle carbon and nitrogen. They are ideal for bioremediation processes (Bala *et al*., 2022). Without these organisms, our planet would not exist. As essential organisms, they play a pivotal role in maintaining and sustaining the planet, making it as safe as a sofa. Microbial responses to climate change are particularly significant in terrestrial, oceanic, and urban environments. These organisms are powerful in mitigating and responding rapidly to the effects of climate change (Tan *et al*., 2022; Tiedje *et al*., 2022 and Beed *et al*., 2011) .

GM microorganisms can be used for the bioremediation of polluted soils, thereby improving soil quality, components, and productivity (Chandra *et al*., 2023 and Arora, 2018). They can also function as bio-detectors to monitor soil pollution, enabling more efficient management or prevention of contamination. Transgenic microbes can enhance nitrogen fixation, phosphorus stabilization, and nutrient uptake in the soil (Wesseler and Purnhagen, 2022). By applying genetic engineering methods to create recombinant laccase, lignin in medical waste can be broken down, reducing its environmental impact. Other recombinant enzymes, such as lipases, proteases, and cellulases, can be employed for the bioremediation of medical waste, as they can break down lipids, proteins, and cellulose, respectively (Chandra *et al*., 2023). Phytoremediation is one method of remediating polluted areas with the involvement of higher plants. These plants have the potential to convert and recycle toxins into less toxic or useful substances (Sadawarti, 2023). This process of environmental restoration can occur through various mechanisms, such as absorption, stabilization, conversion, accumulation, and eventual evaporation after detoxification (Yadav *et al*., 2022).

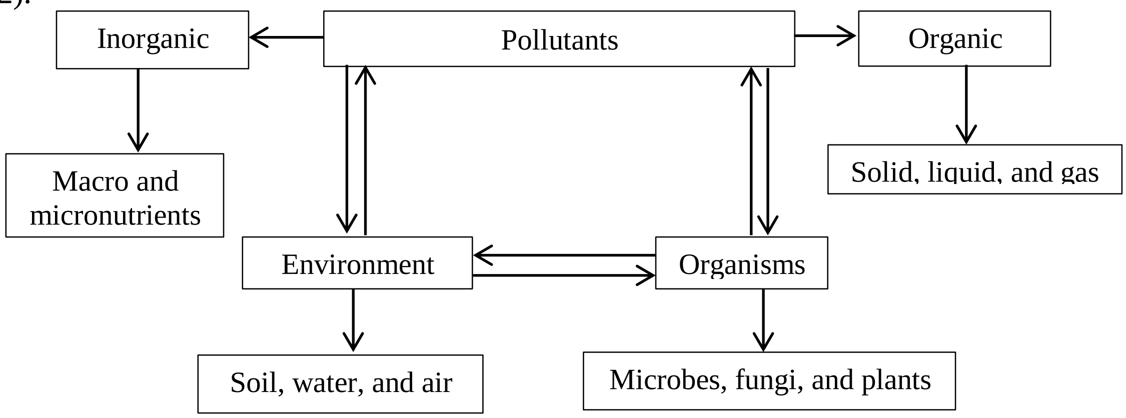


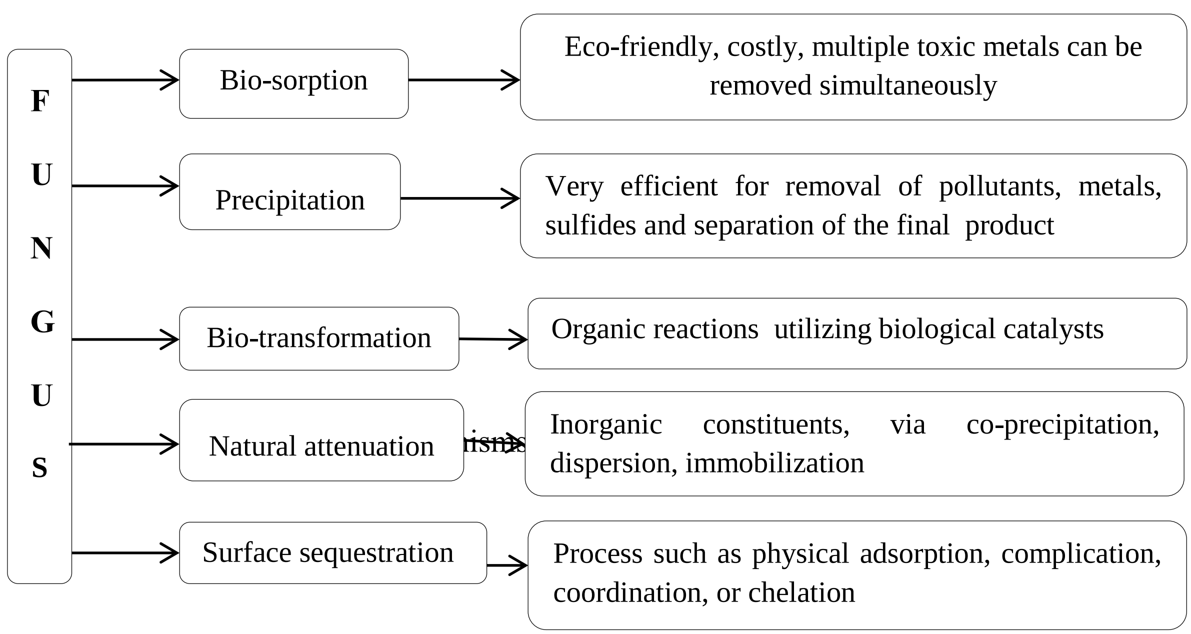
Figure 3: General representation of bioremediation process (constructed by authors)

Myco-technology

Myco-remediation is a bio-based techniques that utilizes fungi to create environmental restoration products by breaking down and metabolizing contaminants like heavy metals, pesticides, and petroleum-based compounds (Yadav *et al*., 2022 and Chandra *et al*., 2023). It is a sustainable and cost-effective method for cleaning up polluted sites and restoring ecological balance (Ghanaim *et al*., 2025). However, climate change can disrupt this process and increase natural disaster frequency, making restoration more challenging. Therefore, addressing climate change and mitigating its effects on fungal ecosystems is crucial for long-term success in achieving Sustainable Development Goals like clean water, sanitation, responsible consumption, and climate action (Vaksmaa *et al*., 2023 and Ghanaim *et al*., 2025). Fungi are essential in ecosystems, playing a crucial role in decomposing organic matter and nutrient cycling. They break down dead plant and animal materials, recycling nutrients back into the soil (Dusengemungu *et al*., 2020). Fungi form symbiotic relationships with plants, helping them absorb nutrients and protect them against pathogens. In forests, they decompose fallen leaves and branches, releasing nutrients back into the soil (Sadawarti, 2023; Kržišnik, 2023). Fungi play a crucial role in environmental remediation by breaking down harmful substances like pesticides, pharmaceuticals, plastics, and bio-plastics, and reducing heavy metal pollution (Sadawarti, 2023). Among them, mycorrhizal fungi, due to their resistance to heavy metals, can thrive in contaminated areas, aiding in metal detoxification (Dusengemungu *et al*., 2020). They also contribute to nutrient cycling and soil health by breaking down organic matter, releasing essential nutrients, and promoting plant growth (Ghanaim *et al*., 2025). Additionally, their symbiotic relationships with plants enhance their resilience to diseases and other environmental stresses. Hence, incorporating mycorrhizal fungi into agricultural systems can lead to sustainable farming practices (Kumar *et al*., 2021 and Vaksmaa *et al*., 2023).

Fungi can mitigate environmental pollutants through various mechanisms, including bio-sorption, precipitation, biotransformation, natural attenuation, and surface sequestration (Figure 4). Biosorption involves the absorption of pollutants onto fungal cells, effectively removing them from the environment (Dusengemungu *et al*., 2020). Biotransformation of fungi involves modifying pollutants into less toxic compounds through processes like methylation, demethylation, oxidation, reduction, and volatilization (Liu *et al*., 2021). These processes help reduce the toxicity of heavy metals and other toxic substances. Metals and metalloids can be bio-transformed by altering the microenvironment, influencing their solubility and mobility through oxidation and reduction processes (Dusengemungu *et al*., 2020). Methylation and dealkylation are key aspects of biotransformation, resulting in metal volatilization, further decreasing their toxicity (Bala *et al*., 2022). Surface sequestration is another mechanism in myco-remediation, where fungi trap pollutants within their mycelium (Lin *et al*., 2024). This process involves the synthesis of intracellular chelate compounds, which dilute contaminants through chelation inside fungal cells. These mechanisms demonstrate the potential of fungi in promoting environmental sustainability, allowing them to reduce pollutants over time and maintain a healthy environment (Kumar *et al*., 2021 and Yadav *et al*., 2022). Myco-remediation in polluted soils and waters is improving, benefiting climate-sensitive societies.

Fungi, genetically engineered organisms, have numerous applications in industries like enzyme production, detergents, and bio-surfactants (Yadav *et al*., 2022; Sadawarti, 2023). They are effective in degrading pollutants and mitigating climate change impacts. However, more research is needed to fully realize the potential of sustainable environmental fungal bioremediation and harness their benefits in waste management, pollution control, and sustainable agriculture. Understanding fungal genetics could help to lead the discovery of new bioactive compounds, enhancing medicine and industry (Sakshi *et al*., 2018).



Waste to wealth conversion

Climate changes are linked to waste. Wastes contain organic and inorganic materials, and their breakdown involves natural and artificial reactions and recycling processes. Toxic wastes contribute to climate crisis, eutrophication, reduce soil quality, water pollution, and emit hazards into the atmosphere (Ramadhan & Handayani, 2020, Amasuomo & Baird, 2016 and Ditia, 2024). Ganesh *et al*., (2023) also reported that, one of major contributors for environmental pollution is agro-industries and accounts around 10-15%. Therefore, bio-based technologies are efficient and cost-effective in converting toxic wastes into useful products. These technologies are essential for soil, wastewater, and exhaust air purification, addressing environmental pollution from solid waste, industrial effluents, chemicals, and persistent organic pollutants (Agarwal, 2016; Sakshi *et al*., 2018).

Bio-refineries can transform wastes into valuable feedstock for other bio-based materials, and microbes can repurpose waste carbon or nitrogen into stable products (Tiedje *et al*., 2022). Bioconversion is a method that recycles waste using living organisms, providing environmental remediation without health risks and generating useful components for organisms or humans (Sakshi *et al*., 2018). Such processes are sustainable and eco-friendly approach. Recycling wastewater effluent is also very essential process for ecosystems, treating water for irrigation and livestock production. This indicates biotechnology aids in detecting and resolving environmental damage (Gortares-maroyoqui *et al*., 2020 and Agarwal, 2016).

Researchers are exploring microbes with unique capabilities, such as turning food waste into energy or breaking down plastics, to overcome challenges in engineering or modifying microbes (Wang *et al*., 2021; Agarwal, 2016 and Ali *et al*., 2025). Microorganisms are promising element to implement biotechnological process in keeping the environment safe from pollution by recycling wastes (Nain & Singh, 2014 and Donzella *et al*., 2022). Genetically engineering microbes to capture CO_2 and convert it into useful products is a promising approach in bioconversion, which involves their use in carbon and nutrient cycling, animal, human, and plant health, agriculture, and global food web (Cavicchioli *et al*., 2019 and Braide *et al.*, 2020).

Now a day, several bio-based value added products are also derived from different wastes (Manasvi *et al*., 2024). These bio-products are reported with many literatures, including bioethanol, biodiesel, bio-fertilizers, bio-plastic, bio-pesticides, bio-herbicides, media, organic acids, enzymes, single cell protein, vitamins, carbohydrates and lipids etc (Chauhan *et al*., 2023; Saini *et al*., 2015; Ganesh *et al*., 2023; Heriyanti *et al*., 2020; Samantaray *et al*., 2024; Lopresto, 2025; Degfie *et al*., 2019; Topi, 2020; Lim & Matu, 2015; Kiran *et al*., 2023; Msuya *et al*., 2024; Ali *et al*., 2025; Ramadhan & Handayani, 2020; Ahmed *et al*., 2024; Dos *et al*., 2022; Saguibo *et al*., 2022; Adomi & Oyubu, 2023; Wang *et al*., 2021 and Donzella *et al*., 2022).

Future Perspective

Climate change is causing significant impacts on the global population, with projections suggesting it could reach nearly 9 billion by 2050. The growth of human society, driven by unsustainable consumption, production patterns, and unsustainable land, ocean, and water management, will significantly impact ecosystem vulnerability to climate change. This is contributing to humanitarian crises, where climate hazards interact with high vulnerability, making it crucial to address these issues and mitigate the impacts of climate change (Abbas *et al*., 2018). Changes in agricultural productivity have impacted livelihoods, human health, food security, and social equity. Increased epidemics, including vector-borne, waterborne, airborne, and foodborne diseases, are expected to expand globally. The Intergovernmental Panel on Climate Change estimates that 3.3 to 3.6 billion people live in regions highly vulnerable to climate change (IPCC, 2022). Unsustainable land use, overuse of natural resources, deforestation, biodiversity loss, and pollution negatively impact ecosystems, societies, communities, and individuals' ability to adapt to climate change. Increased involuntary displacement or forced migration due to flooding, heavy precipitation, tropical cyclones, droughts, and rising sea levels will lead to involuntary migration from regions with high exposure and low adaptive capacity worldwide.

CONCLUSION

Climate change is a significant global issue that is increasingly complex and challenging to manage. It impacts multiple aspects of human life, including social structures, infrastructure, the economy, geography, and basic human needs. Economic damages are particularly severe in climate-exposed sectors, affecting agriculture, forestry, fisheries, energy, tourism, and outdoor labor productivity. Collaborative work from scientists, technologists, farmers, and policymakers is needed to mitigate the hazard impact of climate change. Advanced research in bio-based approaches is crucial to save life-related security like climate resilience, food security, health security, water security, and energy security. Enhancing our understanding of native biodiversity and microbial community structures under changing climate scenarios. Urgent and systematic actions are needed to adopt timely solutions and prevent unpredictable outcomes and secure sustainably safe environment.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Availability of data and materials
Not applicable.

Competing interest
The authors declare that they have no competing interests.

Clinical trial number
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Authors' contributions
GS wrote and develop the manuscript. GG provided constructive comments. GS and GG edited and finalized the manuscript. MM and DB reviewed the manuscript. All authors strongly contribute to enhance the quality of manuscript. Finally, all authors read and approved the final manuscript.

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