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Biotechnology for the Environment: Reducing Pollution and Advancing Sustainability, Managing Waste, Bioremediation and Prevention of Environmental Contamination

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Abstract:
Pollution and environmental decay have become a ratifying issue in today's world and environmental biotechnology is essential in solving these problems. The purpose of this review is to discuss the latest advances in the field of environmental biotechnology, particularly regarding pollution control technologies that are sustainable and environmentally friendly. Designed biological systems and microbial consortia that are used to extract heavy metals and convert organic contaminants, are a significant part of biotechnological techniques for wastewater treatment. Recycling technologies and biowaste conversion technologies are also discussed which shows how the waste materials generated in farms, cities and businesses can be converted into a variety of value-added products like biofertilizers, bioplastics and bioenergy. This all-encompassing overview covers numerous applications of soil remediation, air pollution reduction and water purification, among others, in the field of environmental biotechnology. In-depth analysis of the processes, microbiological agents and applications of a basic technology used for clean-up of polluted areas, bioremediation. The generation of biofuels from biomass is just one of the renewable energy technologies that are making waste management and sustainable energy generation bedfellows. The developments allude to a shift in thinking on sustainable environmental management, in which biotechnology is used to decrease pollution and promote the cyclic use of resources. The final part of the report addresses some challenges and opportunities identified for the development of the field and calls for innovation across disciplines to maximize the social and environmental benefits of the field. For solving the various environmental issues, there is a need for a multidisciplinary approach between microbiologists, environmental engineers, biotechnologists and policymakers. Ensure that existing laboratory proven technologies such as biosorption and bioremediation are available at a reasonable cost and can be scaled up to meet the requirements of the industry, while being able to accommodate the local environmental conditions. Establish and maintain environment regulations and policies that encourage safe use of GMOs and other advanced biotechnologies for pollution control. Public support and involvement in sustainable practices can be enhanced by the launch of educational programs and campaigns that enlighten communities about the advantages. Leverage cutting-edge technologies such as biosensors to optimise operational efficiency, real-time monitoring of biotechnological processes, and environmental safety and compliance.

Keywords: Biotechnology, Environment, Pollution, Sustainability, Waste, Bioremediation

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INTRODUCTION

To address environmental issues and improve ecosystem sustainability, environmental biotechnology employs living creatures, especially microbes and their biological byproducts. The applications of this vast field of study include renewable energy generation, bioremediation, waste management, pollution control and much more. The initial steps of the proposed long-term remedies include reducing pollution, enhancing recovery of resources, and alleviating human impacts on the environment [1]. Environmental biotechnology employs strategies that are more likely to be environmentally friendly and energy efficient than chemical environmental solutions, and even harmful. The primary idea behind it is that it utilizes such as plants, fungi and microorganisms to break down or neutralize toxins or convert them into less harmful substances. To make them more successful in a variety of environments, these creatures can be genetically modified, found in nature, or augmented by bioengineering [2]. In the era of growing climate change, resource consumption, and global pollution concerns, sustainable development and environmental resilience have emerged as crucial priorities. Environmental biotechnology is one tool in this, notably. With the innovations and improvements in scientific methods, environmental biotechnology is gradually expanding to a larger field [3, 4]. The field has expanded to include synthetic biology, microbial wastewater treatment, genetically modified organisms, and nanotechnology, among other fields since its inception. The use of bioinformatics, high throughput omics technologies, and artificial intelligence (AI) has further revolutionized the ability to track, analyze and enhance ecological processes [5]. This research aimed to help understand how to utilize advanced environmental biotechnology to help limit pollution and sustain long term environmental processes.

Environmental Biotechnology for Global Issues Confrontation

Environmental biotechnology is vital to combating various modern-day issues of the environment. As climate change and other challenges such as habitat loss, pollution, and overconsumption of resources grow more dire, sustainable and innovative technology is more crucial than ever. Environmental biotechnology provides more than simply tactics for mitigation; it also presents prospects for sustainable development that can be really revolutionary. Much has been accomplished in the areas of pollution control and resource recovery. Since the rise of both industries and cities, the disposal of hazardous waste such as synthetic chemicals, persistent organic pollutants, heavy metals and more has been increased [6, 7]. Traditional waste management practices such as landfilling and incineration are becoming increasingly costly in terms of their impact on the environment and are increasingly being phased out. However, garbage can be used as useful resources through biotechnological processes like composting, anaerobic digestion and bioenergy production. A single example is anaerobic digestion, which stabilizes organic waste and generates biogas which is a renewable energy source that can help decrease the use of fossil fuels. Bioremediation is the use of biological agents to neutralize toxins, completely changing the face of site remediation. Systems based on microbes and plants are effective for remediation of oil spills, organic solvents and heavy metals. These methods can be more environmentally friendly and cost-effective than mechanical excavation and chemical treatments. Renewable energy sources like biofuels like bioethanol, biogas, and biodiesel are promoted by environmental biotechnology as a solution to the energy dilemma. Algal biofuels are also a potential source, as they can be cultivated in non-arable areas and possess a high potential for output without the problem of competing food sources and feed supplies (food-versus-fuel dilemma) [8]. Biological processes also mitigate the effects of climate change. Technologies being developed to capture carbon by using soils, forests and artificial microbes are underway. In addition to landfills and agricultural fields, methanotrophic bacteria are used to reduce the emission of methane from other sources such as landfills and agricultural fields, a green approach to fight climate change.

Managing Waste

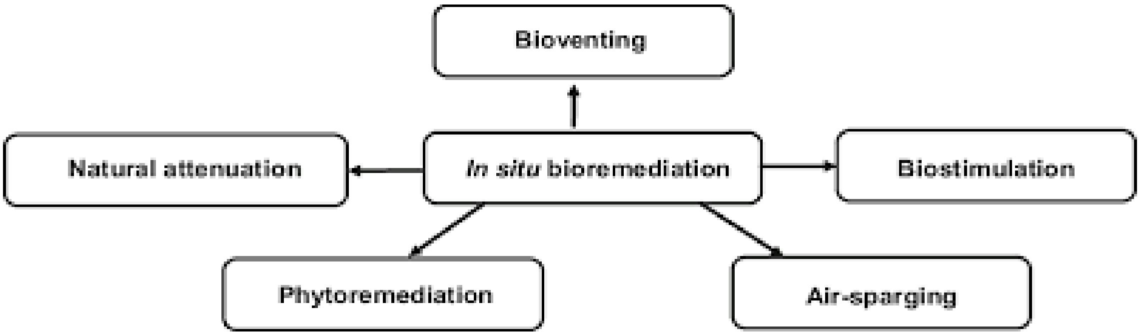
One of the main uses of environmental biotechnology is in the field of waste management. With the growth of industries and cities, the quantity of industrial and municipal waste has been rapidly growing. Waste management is often inadequate, damaging to the environment, or unsustainable over time to a large extent. Alternatives that aim to lessen the environmental impact of waste treatment while simultaneously increasing resource recovery and decreasing trash generation are offered by biotechnological technologies. Bio-based materials are being produced through bioconversion, enzymatic digestion and microbial composting, among other processes, by an increasing number of people.

Bioremediation

The removal of pollutant pollutants using microorganisms (especially bacteria, fungus or archaea) is called bioremediation. These bacteria' metabolic pathways can help degrade contaminants like heavy metals, and industrial chemicals. This is the solution to the problems with polluted soil and polluted groundwater. The use of native bacteria that were spurred by nutrients to break down the oil more quickly in the aftermath of the Deepwater Horizon disaster in 2010 is a prime example. Bioremediation was determined to be a more sustainable and economical alternative to mechanical clean-up and chemical dispersants. The development of genetically modified microbes is paving the way for new possibilities in the cleanup of harmful or long-lasting pollutants [9]. Environmental biotechnology utilizes different bioremediation methods depending on, for example, location, control and complexity. Sustainable alternatives to chemical or physical remediation procedures are being explored in these approaches, which utilize agents to degrade, convert, or remove contaminants from polluted settings.

In-situ Bioremediation

In-situ bioremediation is a process that involves remediating toxins in place instead of excavating the contaminated area. This approach will not destroy the natural structure of the site and will be less costly and impactful as a result. Some examples of techniques that fall under this category are bioventing, biosparging, and natural attenuation. In biosparging, air is injected above the water table to stimulate microbial activity that breaks down contaminants in the groundwater, and in bioventing, air is injected below the water table to promote aerobic microbial activity. Natural attenuation is a method of treating the contaminants with naturally occurring processes over a period of time to lower the concentrations of contaminants.



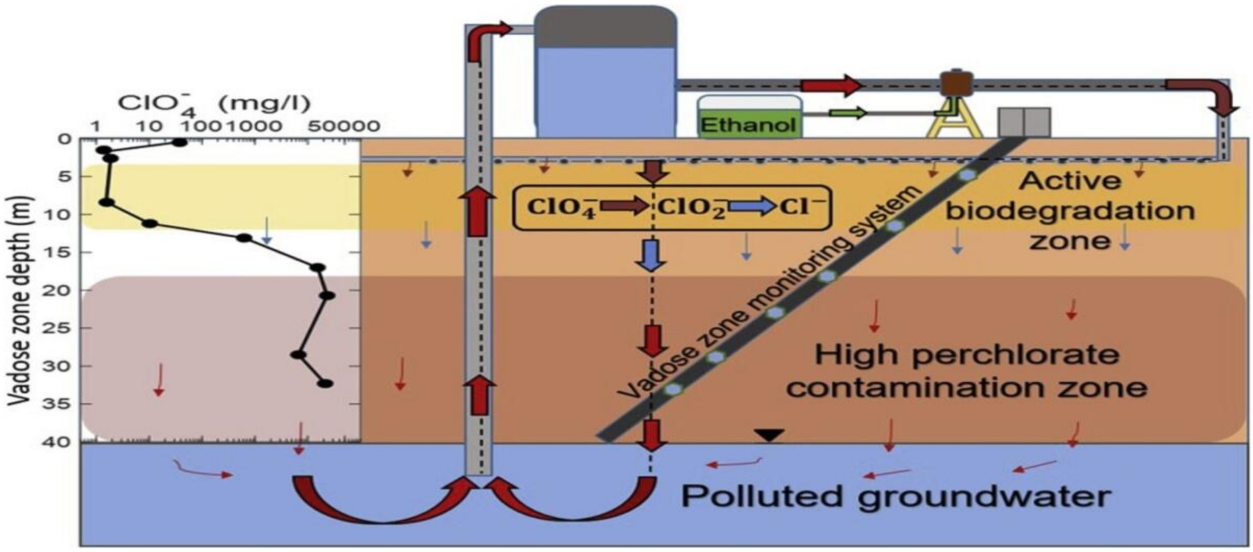
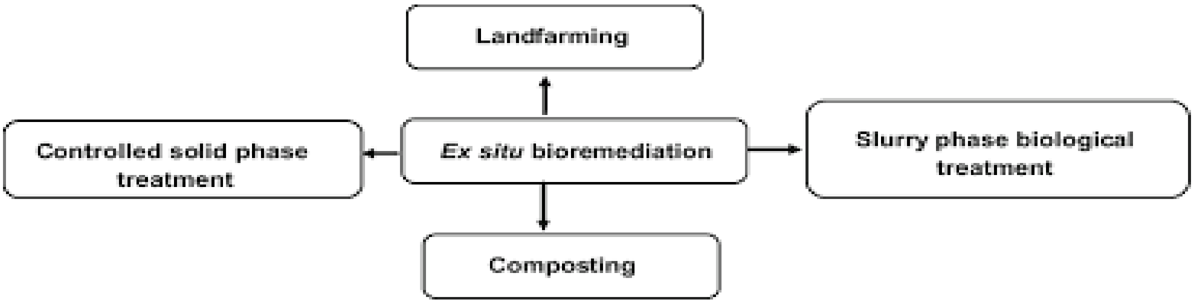


Figure 1. In-situ bioremediation combined treatment system for perchlorate contaminated vadose zone and groundwater.

Ex-situ Bioremediation

Ex-situ bioremediation is the process of moving contaminated soil, or water to another location for bioremediation. This can help to monitor and optimise the biological activity more effectively, but it comes with its own set of logistical challenges and costs. Recycling technologies like biopiling, composting, land farming, and bioreactors can be used to enhance the efficiency of microbial decomposition processes by closely monitoring the environmental factors like temperature, pH, oxygen, etc.



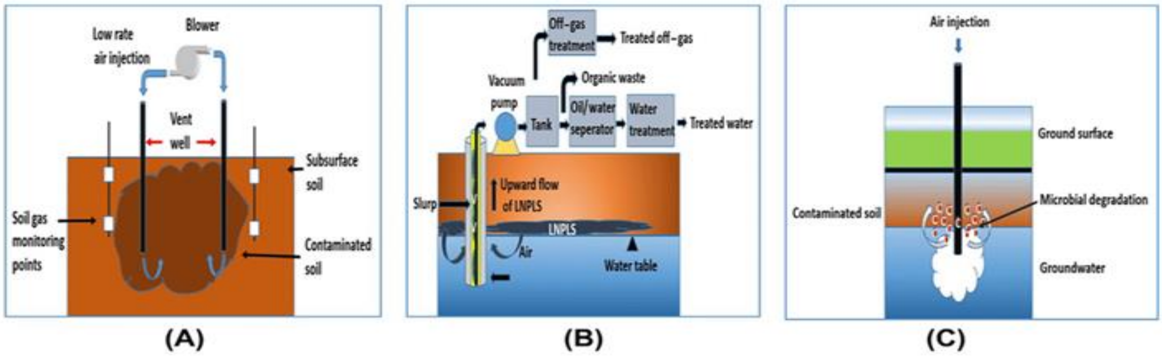


Figure 2. Illustration of ex situ bioremediation techniques: (A) landfarming, (B) biopiling and (C) bioreactor.

Figure 3. In-Situ vs. Ex-Situ Bioremediation: Strategies for Oil Cleanup.

Bio-waste Recycling

Microbiological activities have the potential to convert organic wastes into useful products—an additional contribution of environmental biotechnology. One of the significant examples is composting in which microbial degradation of food waste, agricultural waste, and grass clippings generates compost with high organic nutrients. This biofertilizer improves soil fertility and structure, which in turn decreases the need for synthetic fertilizers, which can have negative impacts on the environment. Anaerobic digestion is another significant process where bacteria is used to breakdown organic matter in an oxygen free environment to produce a biogas primarily consisting of carbon dioxide and methane [10]. The biogas is used for water heating, vehicle transportation or generating electricity. The digestate, an organic fertilizer, is a byproduct. The concepts of circular economy align with the large-scale application of Anaerobic Digestion (AD) for the treatment of agricultural wastes, municipal sludge, and industrial organic wastes, creating renewable products.

Recycling materials and wastewater treatment

Wastewater treatment is the foundation of environmental biotechnology, with applications in urban and industrial environments. Industrial waste and municipal effluents, if not treated properly, can be detrimental to both human and environmental health because of the presence of organic waste, nutrients and toxic substances. Biological treatment systems rely on the microbial population to treat organic substances and reduce excess nutrients, such as activated sludge, trickling filters, and man-made wetlands. In an activated sludge system, aerobic bacteria in aeration tanks decompose the organic contaminants and results in biosolids being transformed to biofertilizers and clean effluent. These systems are also more environmentally friendly and energy efficient compared to the conventional methods of chemical treatment, and they are capable of effectively removing impurities.

Prevention of Environmental Contamination

Environmental biotechnology offers innovative, eco-friendly solutions to minimize pollution in all its forms (air, water and soil). These biotechnology solutions are effective in restoring the environmental quality and mitigating anthropogenic pollution, which is becoming a severe problem.

Air Quality Control Emissions

Biotechnological technologies are suitable in tackling air pollution, particularly from factories. There are two well-known technologies based on microbial action to clean polluted air streams: biofilters and bioreactors. These systems are focused on airborne contaminants such as sulphur compounds, nitrogen oxides (NOx) and volatile organic compounds (VOCs). For decontamination of air, a layer of organic substances (wood chips, compost or peat) is placed in the biofilters. As they feed on the pollutants, the microbes in this matrix break them down into less toxic substances, such as water and carbon dioxide. Biofilters are a technology used in many industries, such as manufacturing paint, refining oil and handling garbage [11]. Biotrickling filters are a combination of a microbiological film and a liquid phase, which circulates in the filter to neutralize undesirable gases and harmful vapours. These can be effective in removing hydrogen sulphide and are commonly used in industrial processes that generate significant amounts of gas and have a strong odor. For example, wastewater treatment plants.

The water and soil contain cleanup.

Soil and ground water pollution, resulting from industrial effluents, agricultural runoffs and inappropriate disposal, pose threats to human health and ecosystems. The two most common approaches to successfully restore these damaged settings in environmental biotechnology are: bioaugmentation and biostimulation. To speed up the breakdown of contaminants, bioaugmentation makes use of the intentional introduction of certain microbial strains, often with genetic enhancement, into a polluted environment. The microbial strains are chosen due to their metabolic characteristics such as the ability to degrade chlorinated solvents, petroleum hydrocarbons and other recalcitrant compounds. When native microbial communities do not have the metabolic pathways to properly remediate contaminants, this method becomes even more helpful. Biostimulation, on the other hand, boosts the activity of native microbial communities by changing environmental circumstances to encourage microbial growth and pollutant breakdown. These may be in addition to oxygen, nutrients (nitrogen, phosphorus), or electron donors/acceptors [12]. Biostimulation is a complementary approach to natural attenuation that enhances the naturally occurring biodegradation potential of the contaminated site.

Renewable Energy

Given the interdependency of the climate change and fossil fuel crises, developments in environmental biotechnology are driving new renewable energy developments. The issue of producing clean energy from biomass, organic waste, and algae is being worked on with the help of biological systems, which will help in finding long-term solutions to this problem.

Biofuels

Biofuels are fuels derived from biological resources, including biodiesel, bioethanol, and bio-gas which is a renewable alternative to fossil fuel. Environmental biotechnology has improved biofuel production by improving fermentation and conversion processes, and by manipulating microbes. Maize, sugarcane, and lignocellulosic biomass are some of the feedstocks that are fermented using microbes to produce bioethanol. Recently, enzymes and genetically modified bacteria have been developed which efficiently and effectively convert the complex plant fibres (such as hemicellulose and cellulose) into fermentable sugars, which increases the efficiency and yield of the process. Once biodiesel was produced using lipids from plants or animals, now algae are being explored as a source for it. Algae can grow faster than food crops, grow on non-arable lands and have high lipid content. Biogas, a methane-rich fuel, is generated from agricultural residues, sewage sludge, food scraps and other organic waste streams in an anaerobic digestion process. This process recycles waste, and generates a by-product called digestate, which can be used as organic fertilizer. Biotechnology has been used to optimize digestion conditions and to produce more robust microbial consortia, which has improved biogas production.

Microbiological Fuel Cells

An emerging technology called microbial fuel cell (MFCs), which utilize microorganisms that are electrochemically active to generate electricity from organic wastes. Microbes produce an electric current by oxidising organic substances and transferring electrons to an anode in these systems. Multifunctional fuel cells (MFCs) are a new generation fuel cell technology which has the ability to treat organic wastes and wastewater while also producing the renewable energy (RE). Although MFCs are largely still at the R&D stage, they might present a viable option for sustainable energy solutions that are off-grid, rural and/or resource poor. The scalability and efficiency of these developments are expected to improve in the near future thanks to new system design, microbial engineering, and electrode material innovations [13].

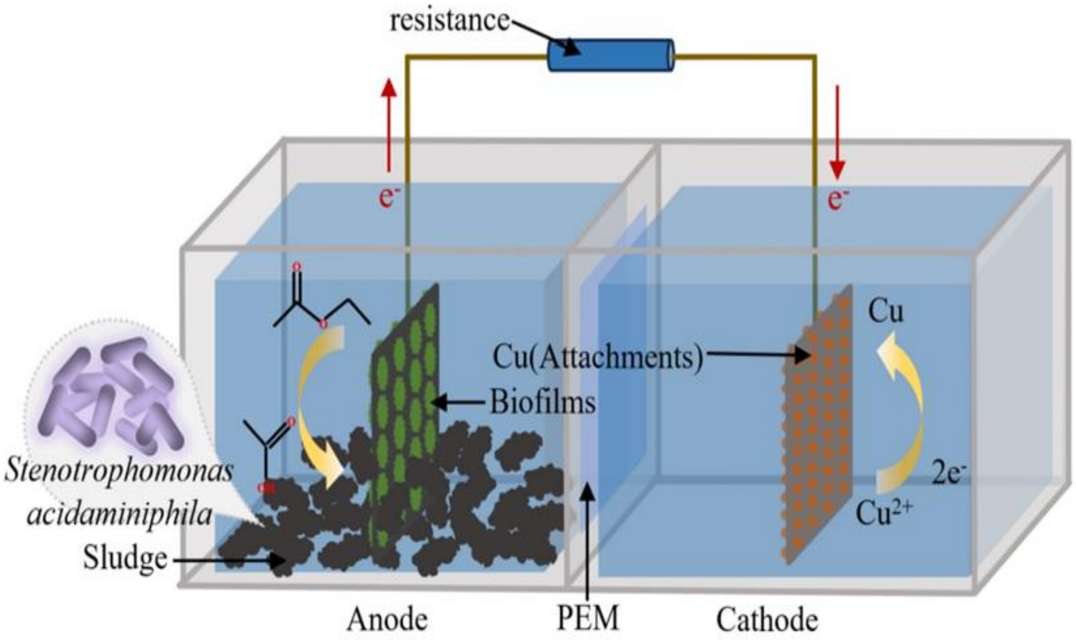


Figure 4. The schematic diagram of MFC structure.

Table 1. Working conditions of the microbial fuel cells.

Name	Anode conditions				Cathodic condition
	Oil	W01 bacterial solution	Activated sludge	Anode solution	CuSO4
MFC-1	1 g	100 mL	100 mL	500 mL	700 mL (1 g/L)
MFC-2	1 g	100 mL	100 mL	500 mL	700 mL (1 g/L)
MFC-3	2 g	100 mL	100 mL	500 mL	700 mL (1 g/L)
MFC-4	3 g	100 mL	100 mL	500 mL	700 mL (1 g/L)
MFC-5	4 g	100 mL	100 mL	500 mL	700 mL (1 g/L)
MFC-6	1 g	100 mL	100 mL	500 mL	700 mL (2 g/L)
MFC-7	1 g	100 mL	100 mL	500 mL	700 mL (3 g/L)
MFC-8	1 g	100 mL	100 mL	500 mL	700 mL (4 g/L)
MFC-9	1 g	100 mL	100 mL	500 mL	700 mL (5 g/L)

Capturing Carbon Emissions

When CO_2 is captured and stored in the atmosphere, it is referred to as carbon sequestration and is used to minimize the buildup of CO_2 and the effects of global warming. Biological methods include reforestation, soil carbon enhancement and CO_2 assimilation and biomass conversion using engineered microbes and/or algae. These biological solutions are increasingly being integrated into climate policy frameworks and will play a key role in carbon management that aligns with nature.

Sustainable Biotechnology: Recent Developments

Environmental biotechnology, broadly speaking, has seen rapid invention in recent decades, as a response to the increasing demands to alleviate pollution, waste, and climate change. The precision, efficiency, and flexibility of biological systems employed in environmental applications have been greatly improved by technological developments in genetic engineering, nano-biotechnology, and omics-based research.

Molecular Biology

For the first time, scientists are able to genetically engineer organisms to carry out specific environmental functions, revolutionizing environmental biotechnology. Scientists have engineered microbes, fungi, and plants to increase their bioenergy production, degradation of pollutants and capture of greenhouse gases. This control enables the production of biological remedies tailored to specific needs, surpassing natural options.

GMO (Genetically Modified Organisms) - Application to the Environment

In the current times, the environmental biotechnology is all about the genetically modified organisms (GMOs). Pollution remediation, and biofuel production are some of the potential uses for genetically modified organisms (GMOs) that can be modified by adding or improving genes that control metabolic pathways. Genetically modified bacteria such as Pseudomonas putida for enhanced bioremediation can break down harmful hydrocarbons such as toluene and benzene. These modified strains are more effective at degrading pollutants than the wild-type organisms, as they produce a higher number of certain enzymes. Researchers also have developed bacteria that can degrade persistent pollutants such as polychlorinated biphenyls (PCBs) [14, 15]. The aim of these efforts is to incorporate the genes responsible for these degradation processes into a more resistant microbial host of naturally occurring strains to improve degradation efficiency and make the microorganisms more suitable to degrade PCBs in different environment scenarios.

Ecological cleanup

Phytoremediation is a process of using plant and plant mechanisms to breakdown, remove, and transform contaminants to harmless products. Genetically modified and selectively grown plants can be used to remove or detoxify harmful contaminants. Phytoremediation can be used to remove harmful organic and inorganic substances from water and soil. Plants may be expected to uptake, translocate between roots and shoots, transform, mineralize contaminants and through some cases, compartmentalize them following these steps. Plants can absorb, distribute and transform organic contaminants depending on various physical and chemical properties of the contaminants, including molecular weight, water solubility, water partition coefficient, environmental conditions (including soil organic matter, water content, temperature and pH), and plant processes (including enzymes and root system). (MTBE), (TCE), and xylene are some of the other organic contaminants that can be transpired from the shoots of plants. Pyroremediation is a bioremediation method that can be used to degrade pesticides, PCBs and other organic contaminants. When plants overexpress certain catabolic genes that are necessary for pollutant breakdown, it leads to improved phytoremediation. Phytoextraction and phytodegradation of heavy metals and organic contaminants like atrazine, explosives, chlorinated solvents, PAHs, PCBs and a wide range of herbicides can be improved in transgenic potatoes, rockcress, mustard, poplar and rice. Synergistic effects between plants and microbes improve antioxidant levels and thereby helps to de-chlorinate organic pollutants. Genetic engineering has also been applied to the process of using plants to clean up contaminated soil and water called phytoremediation. Researchers have genetically modified species, such as poplar trees and Arabidopsis thaliana, to absorb heavy metals found in polluted land such as mercury, cadmium and arsenic [15]. Transgenic plants can be more cost effective and less damaging to the environment than traditional remediation methods.

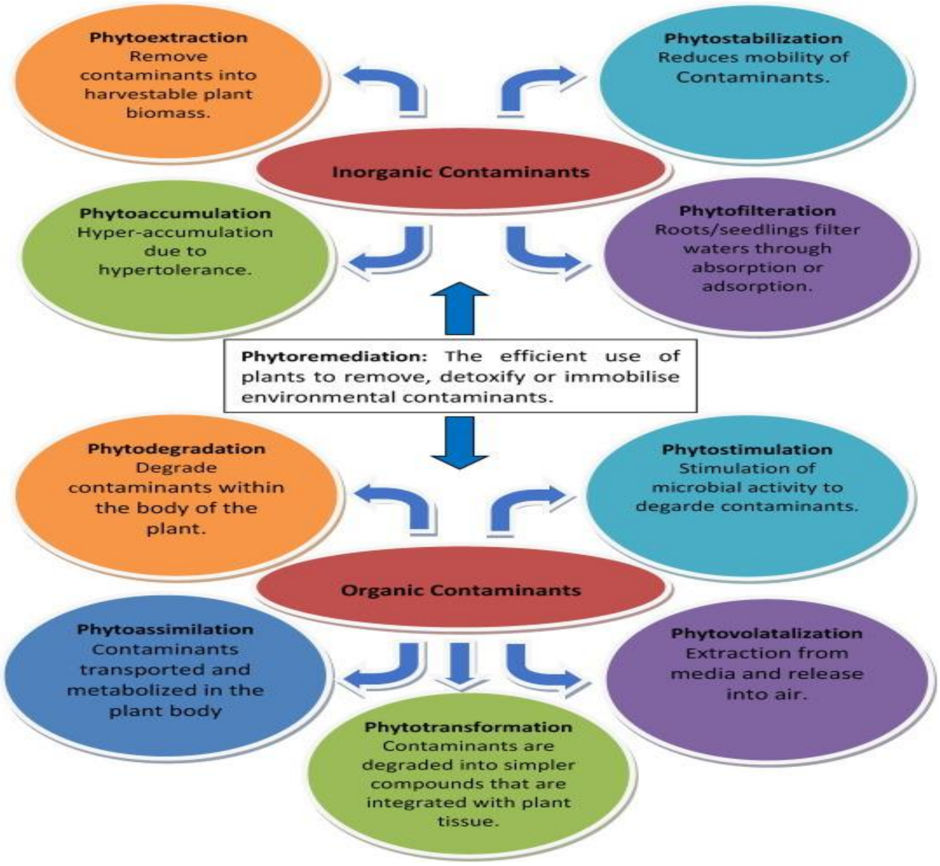


Figure 5. Phytoremediation.

Program on Environmental Biotechnology: Leveraging CRISPR and synthetic biology

With these advances in CRISPR technology, scientists can selectively target genes to either boost the efficiency of a metabolic pathway to take up heavy metals, produce biofuels, or break down pollutants. One application of bacteria with CRISPR technology is to break down complex contaminants, like petroleum compounds and plastic waste. Researchers can enhance the efficiency of the microbes, with minimal impact on the environment, by identifying and introducing specific genes, or by targeting and activating specific genes. Expanding the boundaries of constructed ecosystems, synthetic biology enhances CRISPR by allowing the building of complete biological circuits or synthetic microbial consortia.

A new approach to environmental remediation using nanoparticles

Given their small size and large surface area, nanoparticles have a high reactivity and are very efficient at interacting with molecular level pollutants. They have been extensively investigated for their ability to remediate polluted environments. Nanoparticles of metal oxides, like iron oxide (Fe_2O_3) and titanium dioxide (TiO_2), are extensively used for photocatalytic decomposition of organic contaminants. They generate reactive oxygen species (ROS) upon illumination that can convert toxic molecules into less toxic molecules. TiO_2 nanoparticles, for instance, have been used in water treatment systems, such as those treating pesticides, and in air treatment systems, including the treatment of volatile organic compounds (VOCs). Nanoscale zero-valent iron (nZVI) is an amazing material that has turned out to be extremely useful for remediation of contaminated ground water with heavy metals, chlorinated solvents and other pollutants [16, 17]. The in-situ remediation application has been widely adopted with nZVI because of its high reductant properties, which transform potentially hazardous chemicals like chromium (VI) into the less harmful chromium (III).

Enhancing Environmental Monitoring using Nanotechnology

Some examples of these include the gold nanoparticles that can be modified to selectively detect mercury in water with ultra-sensitivity, or the ability to monitor soil, water and air quality in real-time with high sensitivity and with data and information from which decisions about the environment can be made. Airborne pollutants such as NO_2 and SO_2 can be detected via sensors that include carbon nanotubes. These Nano-sensors help with pollution control and risk mitigation by providing accurate and quick environmental assessments.

Materials that utilize Complex Matrixes.

Unlike a laboratory environment, there are various contaminants in outdoor environments, variables in the environment and changing microbial communities all contained in heterogeneous matrices. This complexity often makes it difficult to achieve the desired results with biotechnological interventions. The factors that affect pollutant breakdown, such as soil moisture, temperature, pH, nutrients, and competing bacteria, play a role in bioremediation. This translates to: the things that work in one position may not work in another. Likewise, with phytoremediation, the complex dynamics of pollutants, soil organisms, and plant roots are essential to the uptake and detoxification of pollutants. Due to these intricate mechanisms, environmental biotechnology practices are hard to standardize and scale up to be broadly applicable.

The concept of delays in Response and Devotion over the Long Term is introduced.

Biological remediation processes such as phytoremediation and microbial degradation are essentially slower in comparison to physical and chemical processes. It may take months, or even years, for microbial degradation to reduce the levels of heavy metals and other persistent organic pollutants (POPs) such as polycyclic aromatic hydrocarbons (PAHs) to a significant level. This long timeframe could be an important limitation when public health or ecological function is at risk or when intervention in the environment is required right away. In addition, it is necessary to monitor and manage various biotechnological solutions over an extended period of time. Continuous monitoring to ensure the viability of microorganisms and to maintain the correct conditions. It may be dissuaded from adopting the projects if they are necessities in time and budget for cleaning up.

Ensuring optimal environment is a challenge because of the following:

In natural environments it is difficult to manage parameters such as pH, oxygen level, nutrient availability etc. that have a significant influence on the performance of biotechnological processes. For example, in aerobic bioremediation, oxygen is required for microbial degradation of contaminants, whereas bioventing/biosparging is usually necessary in subsurface/groundwater applications where oxygen is not available. Biogas production by anaerobic digestion is another way in which a consistent balance between the substrates and microbial consortiums is required [18]. Even minor variations of feedstocks or temperatures cause instability and methane production. This aggravates the situation when GMOs are deployed in the field for bioremediation as stringent environmental and nutritional conditions are necessary for the optimal functioning of altered strains which are very hard to keep in the field.

The Environmental Biotechnology Industry's Substance Resistance

Environmental Change

Climate change is a big issue on a global scale and anthropogenic activities such as burning fossil fuels and cutting trees are a significant contributor. There is an urgent need to provide solutions to both adaptation (adjusting to the impacts of climate change) and mitigation (reduction of emissions of greenhouse gases) measures to address the impacts of climate change on the environment, such as extreme weather events, sea-level rise and biodiversity loss. Renewable energy generation, ecosystem restoration, reduced carbon emissions, and atmospheric carbon capture and storage are all possible because to environmental biotechnology's sustainable, biologically based solutions. Here we explore the main ways environmental biotechnology has helped fight climate change. The term "carbon sequestration" describes the method of removing CO_2 from the air and putting it somewhere safe where it cannot be released again. Environmental process by integrating biological and engineered solutions. Some of these methods include reducing the CO_2 levels in the atmosphere by employing biological systems that can absorb and store carbon, like plants, microbes, algae and other organisms.

The soil microbial carbon sequestration to mitigate carbon emissions.

Microorganisms, particularly soil microorganisms, play a major role in carbon cycling and sequestration processes. Soil bacteria are the most important carbon sink in nature and environmental biotechnology wants to harness their potential to sequester as much carbon as possible. Microbial processes can sequester carbon in the soil for the long-term including decomposition, nutrient cycling and the formation of stable soil organic matter (SOM). Soil Microbial Communities: Soil microbial communities can be enhanced in carbon sequestration through the use of environmental biotechnology. Some microbes, especially mycorrhizal fungi, have positive symbiotic relationships with plants that enhance their nutrient uptake and carbon sequestration by the soil. Soil additives/bioinoculants can be used to increase soil carbon storage through promoting the development of beneficial bacteria, according to Zhang et al. (2024). One other biotechnological technology that can be utilised to improve soil carbon sequestration is biochar, a carbon-rich substance that is made by pyrolysing organic materials. Addition of biochar to soils increases soil carbon sequestration [19]; Also, biochar has a positive effect on soil fertility and water holding capacity, which further increases the plant growth rate and thus leads to the increase in carbon sequestration. Biochar is a very stable and can sequester carbon in even millennia, making it an excellent carbon storage method.

To produce power from renewable sources

Because it lessens the demand for burning fossil fuels and the resulting emissions of greenhouse gases, renewable energy is essential in the fight against climate change. By utilizing biological systems to produce biogas, biofuels, and other types of bioenergy, environmental biotechnology aids in the generation of renewable energy. Instead of adding to the atmosphere's carbon footprint, these renewable energy sources recycle CO_2, making them carbon neutral or even carbon negative.

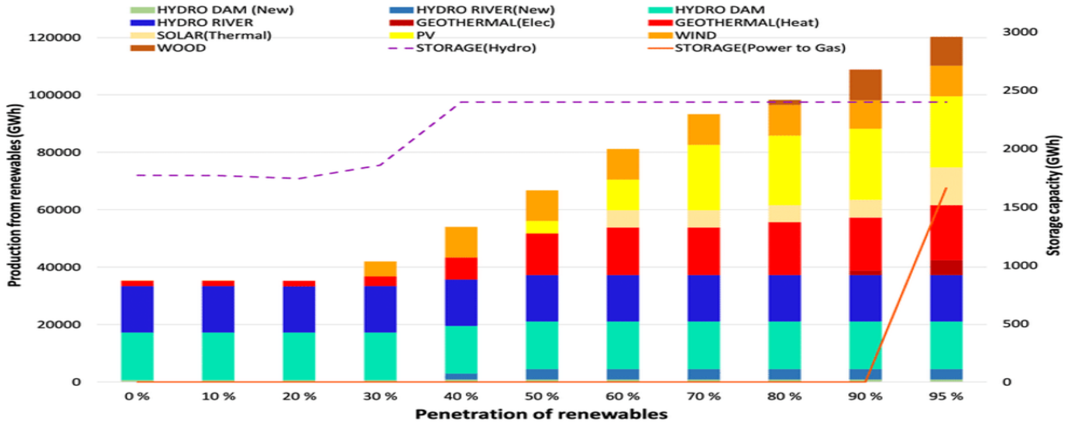


Figure 6. The ability of different renewable energy production and storage schemes.

Production of Energy from Biomass

Biofuels are a renewable source of energy that can be produced from biomass and are made up of ethanol, biodiesel, and advanced biofuels. Environmental biotechnology plays a key role in the development of better microbial strains, enzymes and fermentation processes to enhance biofuel production methods. The non-food biomass resources that can be utilized to produce second generation biofuels include agricultural byproducts, forestry byproducts and energy crops. Such biofuels do not have the same environmental impacts as first-generation biofuels derived from food crops such as sugarcane and corn. Environmental biotechnology (EBT) has been developed which uses microbes and enzymes to degrade the complex lignocellulosic structure of plant biomass to fermentable sugars. Algae are also being explored as a new source for biofuels, called third generation, and their very fast rate of growth. Apart from the lipids produced by the microalgae, the biomass of the algae can also be used for production of biofertilizers, animal feed and biodiesel. Algae-based biofuels are considered highly sustainable due to their ability to grow in non-arable land or wastewater, and not requiring significant amounts of water or land like food crops.

The Anaerobic Digestion and Biogas Engines

Biogas, as a sustainable energy, produced by the anaerobic digestion of organic waste, is another important contributor to reducing GHG emissions. An anaerobic digestion process is a process where microbes break down organic materials in the absence of oxygen. The biogas produced is a mixture of methane (CH_4) and carbon dioxide (CO_2). Biogas is a renewable energy source, mainly composed of methane, and has a number of potential uses, such as fuel for transportation, power generation and heating. A typical use of anaerobic digestion in waste-to-energy is to produce biogas from organic waste, such as those generated in agriculture, food industry or municipal solid waste. Significant developments in environmental biotechnology have led to the production of special microbial consortia which can break down a wider range of organic material and produce higher yields of biogas, making anaerobic digestion more efficient. Due to the improvements in the bioreactor design anaerobic digestion systems are now more efficient and scalable. Anaerobic digestion has the potential to provide carbon negative energy in certain situations, wherein more carbon dioxide is absorbed and stored than is released [20]. To avoid emissions of methane, a powerful greenhouse gas, while also providing renewable energy, one example is digesting agricultural waste that would normally degrade and release methane into the atmosphere. The solid matter produced by the anaerobic digestion process could be used to make biochar or other carbon-rich products to further enhance the system's carbon sequestration potential.

A new technology may enable scientists to use bacteria to help clean up the environment

The creation of microbes engineered for bioremediation is one field where synthetic biology is expected to make a big splash. Conventional bioremediation involves microorganisms in the environment, while synthetic biology allows for the design of strains that can break down contaminant molecules more efficiently or completely than naturally occurring bacteria, for example by adding or enhancing metabolic pathways to degrade a hazardous substance such as plastics, heavy metals or persistent organic pollutants (POPs). To break down complicated contaminants that aren't broken down by nature, such dioxins or polychlorinated biphenyls (PCBs), it is possible to create microbes to do the job. Synthetic biology has also provided the ability to create microbes that can grow in environments where natural microbial communities could not, including at radioactive waste sites and in deep-sea oil spills. In addition, synthetic biology has the ability to produce communities of designed microbes called microbial consortia. These communities can then work together to deconstruct combinations that are complex contaminants. These consortia can be designed to perform additional roles, such as one strain being able to degrade a given pollutant, while another strain degrades the degradation products and renders them more environmentally friendly.

The Biological Indicators and Biosensors for Environmental Monitoring

Another interesting application of synthetic biology to environmental biotechnology is biosensors: systems that are biological in nature and designed to detect and respond to specific environmental conditions or contaminants.

Synthetic biology can be used to create microbes that generate detectable signals, such as color changes, or fluorescence, to identify certain contaminants, including heavy metals, hydrocarbons and industrial chemicals. These biosensors offer a more sensitive and cost-effective alternative to traditional analytical techniques for real-time environmental monitoring of contamination, Biosensors that can be placed in contaminated water bodies can detect toxic elements such as arsenic and mercury and provide an early warning of contamination [21]. Synthetic biology is also important for measuring ecosystem health and bioindicator can be designed organisms that may alert to changes in environmental parameters such as temperature, pH, oxygen levels and other factors. The development of field-deployable biosensors capable of real-time data on ecosystem conditions and pollutant levels could revolutionize environmental monitoring. This would enable more focused and faster remediation to be undertaken.

Metal Recovery by Bioleaching

Another field where extremophiles are predicted to have an increasing impact is bioleaching, which involves the use of microbes to remove metals from trash or ores. Bioleaching has been a key technology for the mining industry to recover valuable metals from low-grade ores. However, with the microbial engineering, extremophiles capable to retrieve metals from increasingly challenging materials, including e-waste and industrial waste streams are also being developed. Bioleaching is also more environmentally friendly and less energy-intensive than traditional mining and metal extraction methods, which often require significant amounts of energy and resources. Bioleaching also offers an alternative to traditional mining and metal extraction processes, which are often more energy-intensive and resource-intensive, thus reducing the environmental impact. Microbial engineering could be applied further to enhance the bioleaching process using microorganisms [22]. These microorganisms may be able to do more in the environment or may be modified for specific metals.

Naturally Decomposing Polymers and Plastics

Among the most pressing environmental issues of the day, plastic pollution poses a threat to ecosystems, animals, and human health. Biodegradable polymers and plastics are a potential substitute to the traditional plastics derived from petroleum and are developed in significant part by environmental biotechnology. To reduce plastic waste build-up in the long-term, these materials are designed to break down faster and more safely in the environment. One is the storage molecule polyhydroxyalkanoates (PHAs) which is a biodegradable polymer produced by microbes. Plastics made from PHAs have many of the same characteristics as traditional plastics, but they also biodegrade. To make the generation of PHA by microorganisms more efficient, scaleable and cost-effective for industrial use, several optimization strategies are being investigated [23]. Biotechnology is not just being used to develop biodegradable polymers, but also in developing new bio-based materials with enhanced characteristics, such as higher strength to degradation in very harsh environments. These materials can be used in various applications, such as packaging, construction, medical devices, and textiles.

Conclusion

To address the increasing concerns about pollution control and sustainable development, advanced environmental biotechnology is crucial. This field aims to remediate, convert, and even lessen the impact of environmental contaminants with the help of plant, microbial and enzyme-based metabolism that is more environmentally friendly and sustainable. Great strides have been made in this regard in recent years due to developments in bioremediation, bioaugmentation, phytoremediation, biosorption and bio-waste conversion. These technologies help clean up contaminated sites, recover resources and help convert waste into energy. Compared with traditional physical and chemical methods, biotechnology methods are known to be less polluting, less energy intensive and can be more adaptable to different ecological settings and less costly. Further, biological systems have become even more efficient and selective in their ability to target heavy metals, organic toxins and industrial effluents, also by incorporating molecular tools, synthetic biology and genetic engineering. Environmental biotechnology as a whole contributes to the conservation and circular economy goals by strengthening sustainable agriculture, the management of water resources, and production of renewable energy. But there are challenges such as scaling up, engaging the public, securing government consent and optimising technology which have to be addressed to make it a success. It is important to conduct continuous research efforts, support policy measures and work across disciplines to achieve long term environmental sustainability and pollution management. It will enable us to reap the benefit of the future use of environmental biotechnology.

References

1. Dhull, P., Lohchab, R. K., Kumar, S., Kumari, M., Shaloo, & Bhankhar, A. K. (2024). Anaerobic digestion: Advance techniques for enhanced biomethane/biogas production as a source of renewable energy. BioEnergy Research, 17(2), 1228-1249.
2. Gómez, A. M., & Martínez, J. C. (2024). Biotechnology and Bioethics: Navigating the Complexities of Moral, Social, and Legal Implications in a Genetically Engineered World. Innovative Life Sciences Journal, 10(1), 1-7.
3. Holland, C., & Shapira, P. (2024). Building the bioeconomy: A targeted assessment approach to identifying biobased technologies, challenges and opportunities. Engineering Biology, 8(1), 1-15.
4. Ilyas, H., Afzal, A., Abbas, Z., Noor, S., Ullah, I., Rafique, R. S., ... & Ishaq, M. U. B. M. (2024). Commands of Synthetic Biology to Modernize and Re-design the Biological Systems. Advancements in Life Sciences, 11(3), 549-557.
5. Jones, E. M., Marken, J. P., & Silver, P. A. (2024). Synthetic microbiology in sustainability applications. Nature Reviews Microbiology, 22(6), 345-359.
6. Kaka, K.G., Zanna, M.G., Danwanzam, A.A. & Zannah, U. (2025). Occurrence of Hydrocarbon-degradation by Some Selected Bacteria Associated with Hydrocarbon Polluted Soil in Maiduguri Borno State. International Journal of Pure and Applied Science Research, 12(6) 12-25.
7. Aparicio, J. D., Raimondo, E. E., Saez, J. M., CostaGutierrez, S. B., Alvarez, A., Benimeli, C. S., & Polti, M. A. (2022). The current approach to soil remediation: a review of physicochemical and biological technologies, and the potential of their strategic combination. Journal of Environmental Chemical Engineering, 10(2), 107141.
8. Arif, A. (2024). The Role of Greenhouse Gases, Aerosols, and Deforestation in Climate Change: a Multidisciplinary Assessment of the Interaction Mechanisms between Human Activity and the Environment. Int J Med Net, 2(2), 01-14.
9. Awogbemi, O., & Von Kallon, D. V. (2024). Recent advances in the application of nanomaterials for improved biodiesel, biogas, biohydrogen, and bioethanol production. Fuel, 358, 130261.
10. V. Codina Girones, S. Moret, F. Mar ` echal, D. Favrat, Oct. 2015. Strategic energy planning for large-scale energy systems: ´ A modelling framework to aid decision-making. Energy 90, Part 1, 173–186.
11. J. DeCarolis, H. Daly, P. Dodds, I. Keppo, F. Li, W. McDowall, S. Pye, N. Strachan, E. Trutnevyte, W. Usher, M. Winning, S. Yeh, M. Zeyringer, May 2017. Formalizing best practice for energy system optimization modelling. Applied Energy 194, 184–198.
12. M. Z. Jacobson, M. A. Delucchi, G. Bazouin, Z. A. Bauer, C. C. Heavey, E. Fisher, S. B. Morris, D. J. Piekutowski, T. A. Vencill, T. W. Yeskoo, 2015. 100% clean and renewable wind, water, and sunlight (wws) all-sector energy roadmaps for the 50 united states. Energy & Environmental Science 8 (7), 2093–2117.
13. F. Kern, K. S. Rogge, Dec. 2016. The pace of governed energy transitions: Agency, international dynamics and the global Paris agreement accelerating decarbonisation processes? Energy Research & Social Science 22, 13–17.

14. G. Mavromatidis, K. Orehounig, J. Carmeliet, Mar. 2018. Uncertainty and global sensitivity analysis for the optimal design of distributed energy systems. Applied Energy 214, 219–238.
15. Balarabe, U.I. & Danwanzam, A.A. (2025). Role of Methanogens and Methanotrophy In Environmental Methane Metabolism; A Review. Biological and Environmental Sciences Journal for the Tropics, 22(02), 79-95.
16. S. Moret, V. Codina Girones, F. Mar ` echal, D. Favrat, 2014. Swiss-EnergyScope.ch: A Platform to Widely Spread Energy ´ Literacy and Aid Decision-Making. Chemical Engineering Transactions 39, 877–882.
17. S. Ntanos, G. Kyriakopoulos, M. Chalikias, G. Arabatzis, M. Skordoulis, Mar. 2018. Public Perceptions and Willingness to Pay for Renewable Energy: A Case Study from Greece. Sustainability 10 (3), 687.
18. J. Rogelj, M. den Elzen, N. Hohne, T. Fransen, H. Fekete, H. Winkler, R. Schaeffer, F. Sha, K. Riahi, M. Meinshausen, 2016. Paris Agreement climate proposals need a boost to keep warming well below 2 ◦C. Nature 534 (7609), 631–639.
19. W.-P. Schill, Oct. 2014. Residual load, renewable surplus generation and storage requirements in Germany. Energy Policy 73, 65–79.
20. Mohan, C., Robinson, J., Vodwal, L., & Kumari, N. (2024). Sustainable Development Goals for addressing environmental challenges. In Green Chemistry Approaches to Environmental Sustainability (pp. 357-374). Elsevier. Najar, I. N., Sharma, P., Das, R., Tamang, S., Mondal, K., Thakur, N., ... & Kumar, V. (2024). From waste management to circular economy: Leveraging thermophiles for sustainable growth and global resource optimization. Journal of Environmental Management, 360, 121136.
21. Qadir, M. F., Khan, K. S., Naveed, M., Raza, T., & Eash, N. S. (2024). Potential eco-friendly techniques for water, soil, and waste management. In Environmental Nexus for Resource Management (pp. 27-44). CRC Press.
22. Rawat, M., Chauhan, M., & Pandey, A. (2024). Extremophiles and their expanding biotechnological applications. Archives of Microbiology, 206(6), 247.
23. Singh, S., & Shyu, D. J. (2024). Profiling of Microbial Community and Their Role in Solid Waste Treatment. In Environmental Engineering and Waste Management: Recent Trends and Perspectives (pp. 415-447).