# Introduction to Environmental Biotechnology

Environmental biotechnology is the broad application of biotechnology for the protection and restoration of the environment and for the conservation and recovery of the planet's resources. Applied biotechnological processes such as bioremediation, biofiltration, and phytoremediation are increasingly used to help solve environmental pollution problems. The sustainable application of these processes requires careful assessment to ensure that the technology does not cause harm to the environment, economy, and society at large. Several internationally agreed goals—including the UN Sustainable Development Goals—now underline the impact of environmental biotechnology across multiple disciplines, highlighting its role in ecosystem preservation and the transition towards sustainable development.

Environmental biotechnology involves using microbial processes to remove various forms of environmental pollution and waste. Historically, many different types of waste have been disposed of by being converted into a potential useful product. The arrival of modern science led to the recognition that these processes are microbial-based, as is both the ultimate pollution control and the useful product. Waste management and management of other natural resources are two of the major issues that need to be addressed in order to improve and sustain the quality of our environment. The latter deals with the judicious and careful management of all natural resources such as water, land, air, forests, wildlife as well as human resources.

## Key Concepts in Biotechnology

Environmental biotechnology encompasses a variety of natural and engineered processes. Although some applications may appear beneficial in certain contexts, they can be problematic in others. Likewise, processes can be classified as environmental processes or plant processes based on whether they occur in natural or engineered environments.

Two primary biotechnological strategies contribute to environmental sustainability: waste management and resource recovery. Bioremediation embodies these concepts, guiding waste management toward protective disposal and resource recovery toward sustainable reuse. Biodegradation forms the cornerstone of bioremediation, relying on the metabolizing capabilities of living organisms—essentially, 'biological superpowers.' Tracing the history of bioremediation reveals a progression from natural biodegradation through bioaugmentation and biostimulation.

## 1. Bioremediation

Bioremediation is the use of biological machinery to clean up contaminated water, soil, and other environments. Microorganisms are specialized in degrading, detoxifying, or accumulating pollutants and metabolizing toxic materials. Enzymes from micro-organisms degrade oils and convert them into harmless carbon dioxide and water. Some species of Pseudomonas grown on contaminated soil adsorb and accumulate pollutants from the polluted environment. The microorganisms grown in the nutrient-rich medium are added to the contaminated site to accelerate the rate of bioremediation. This process is called bioaugmentation. In a polluted environment, the growth of native populations can be stimulated with the addition of nutrients like nitrogen and phosphorus to increase biodegradability. This process is called biostimulation.

Biodegradation refers to the breakdown of organic contaminants by micro-organisms into compounds, such as carbon dioxide, methane, water, inorganic compounds, or new biomass. Metabolic functions of eukaryotic and prokaryotic organisms are responsible for the transformation or breakdown of materials that could be harmful to the environment; for example, bacteria possess a high metabolic diversity and are capable of performing reactions such as phototrophic reactions or the reduction of metals. Ordinary materials, such as food and fiber, can be degraded by micro-organisms under certain conditions. When conditions are favorable for micro-organism growth, the decomposition process can be described as natural or spontaneous biodegradation or composting, as is the case for the treatment of sewage, industrial effluent, and municipal solid waste in wastewater treatment plants using activated sludge.

The term biodegradation can be used to describe the mechanism of biodegradation (enzymes or microbial activity) or the end result (environmentally safe degradation of xenobiotics). Biodegradation is useful in waste management, where the microbial ability can be exploited to reduce the quantity and hazard of waste materials and to transform waste into useful fertilizers. The gradual degradation of material by living organisms and biosynthesis by living organisms is called biological treatment.

## 2. Biodegradation

The term biodegradation signifies the natural ability of various microorganisms to decompose and break down complex chemical substances. In essence, it refers to the capacity of certain living organisms to transform and convert waste materials through natural processes, thereby returning them to the ecological cycle in a purified, biologically stabilized, and assimilable form. As an important and effective natural capability of specific living organisms, biodegradation involves the application of these organisms to the degradation of pollutants in the environment. It represents a waste treatment method that aligns more closely with nature compared to conventional, physical, and chemical treatment methods. Beyond the conventional vision of waste decomposition and environmental protection, new innovations focus on treating various types of waste to recover valuable substances and even create living environments for soil and sea products. Managing and protecting the environment are not only essential to ensure the continuity of present human life but also a requirement for human survival. Using nature to treat nature will optimize the treatment process and reduce residual waste and environmental pollution.

## 3. Bioaugmentation

Bioaugmentation is a strategy employed to enhance the biodegradation of contaminants. It is implemented when an environmental site lacks the native microbial population capable of breaking down harmful compounds. By introducing externally sourced microorganisms, bioaugmentation provides the necessary biological resources to accelerate contaminant degradation. This approach has been effectively applied in the cleanup of residual pesticides at agricultural field sites and the reduction of organic contaminants in petroleum industry wastewater.

Sustainable waste management aims to recover resources from waste by utilizing biodegradable materials. Treatments that convert materials into non-toxic products, coupled with energy recovery through combustion, transform wastes into valuable energy resources. Agricultural crop residues contain both carbon and organic nutrients, making them economical supplementary resources for cost-effective biogas production. By incorporating crop residues, the anaerobic digestion process can be controlled and optimized. The conversion of biodegradable biowastes into energy not only generates renewable fuel but also stabilizes the material, reducing production costs and preventing environmental pollution associated with crop residue accumulation.

## Sustainable Practices in Biotechnology

Environmental biotechnology serves as a link between the goal of sustainability and industrial processes because certain microorganisms and enzymes can be used to determine the environmental status or to monitor environmental contaminants. As a part of industrial microbiology, new products manufactured by industrial microbiology have immense importance in agriculture, industry, and environment. Six decades ago, the products were improved by random mutation and selection approach but, at present, genetic engineering has provided the tools to change the traits of living things and serve human needs. Scientists can now add new characters, improve the existing characters, and predict the modification of organisms with the application of CRISPR technology. The field of agricultural biotechnology aims at the sustainable production of crops to meet the demands of a rapidly growing population and to fulfill the demand for staple food and nutritional security of a growing world population without jeopardizing the natural resources and the environment.

Waste generated in households or industries can be converted to energy by using different technologies. In the case of the bioconversion of waste to energy, different species of microbes take part during the process. The use of microbes in fuel cells and as enzymes for energy generation are the emerging areas in energy generation. In the case of solid waste and bioorganic waste management, the treatment of waste by microbes is an important aspect of waste volume reduction and recovery. The proper treatment of solid waste helps to maintain the environment and generate energy and by-products such as manure and biogas in an eco-friendly manner. The controller can also make use of other bioorganic wastes for agricultural purposes by direct application and following a suitable treatment.

## 1. Waste Management

Environmental biotechnology encompasses a series of processes that combine biological and engineering techniques to address environmental problems in a sustainable way. The use of biotechnologies in waste management aims at the treatment and stabilization of waste to eliminate or reduce harmful effects on the environment and biota. The final targets of these treatments are the reduction of waste volume, the elimination of existing noxious properties, and the recovery of remaining resources. The recovery of resources after treatment of waste stems from three different approaches: the transformation of the waste to a useful product (e.g., energy production using biogas or a secondary fuel using waste oils), the utilization of waste as a raw material for product manufacturing (e.g., the use of kraft mill inorganic waste for the preparation of synthetic zeolites, the utilization of kraft mill organic wastes for the growth of microalgae or the production of fertilizer after anaerobic digestion), and the recovery of the original constituents from the waste (e.g., anaerobic digestion of animal manure for the recovery of energy and production of fertilizer, composting of organic solid waste for production of fertilizers).

An appropriate waste management plan optimizes the productive use of raw materials and products and considers re-use, recycling, and recovery as much as possible. Waste must be treated and used in such a way as to minimize environmental damage. Waste management options vary according to economic development level, cultural habits, available technology, legislative frameworks, and service budgets. The current goal of waste management, waste-to-energy recovery, has additional incentives because it can help reduce the dependence on fossil fuels and provide alternate sources of energy.

## 2. Resource Recovery

Resource recovery is the process of extracting potentially useful materials or energy from waste or by-products. Recovery involves concentrating one or more compounds or elements contained in the waste into a product which has ecological or economic value such as nutrients and organic matter. Such processes include organic matter and/or nutrient recovery from domestic and industrial wastewater characterization and possible up-cycle for limited agriculture and other suitable uses. Wastewater contains significant concentrations of carbon and nutrients such as nitrogen and phosphorus. N and P are essential nutrients and necessary for sustainable agriculture. Accumulation of N and P in water bodies beyond critical limits leads to eutrophication and environmental pollution. Wastewater is also rich in its content of organic carbon and has religious or cultural significance. Besides, demand for renewable and sustainable energy sources is increasing rapidly. Organic fraction of municipal solid waste, that is often a neglected and wasted resource, is rich in organic carbon.

The organic carbon rich biowaste can be used as a substrate in anaerobic digesters to bioconvert to methane gas. Anaerobic digestion offers a promising way of utilizing solid waste in an environmentally friendly manner. The synergistic digestion of different feedstock can overcome the problem of inadequate nutrient (C/N) present in single feedstock. Hence, hacking can be adopted to increase the methane generation from the biowaste. Recovery of these components from wastewater and solid waste will reduce the nutrient loading, while preserving the nutrients and energy lost in waste streams. This approach of getting benefit out of waste plays an important role in the sustainability of resource management and energy conserving activities, mitigating environmental pollution, and reducing dependence on non-renewable energy sources. Moreover, the addition of recovered nutrients and organic carbon to bioinoculants enhances their beneficial attributes and makes them environment friendly and cost effective. Use of organic matter recovered from excess wastewater, organic-containing solid wastes, and nutrient rich wastewater for limited agriculture and other uses could save a part of the organic matter lost in urban waste streams. Besides adding economic products to the farmer and others, it would help in preserving the dwindling natural resources and also supply nutrients to the soil.

## Applications of Environmental Biotechnology

Environmental biotechnology advances sustainable methodologies while addressing the challenges posed by an ever-growing human population. Integrating environmental concerns with biotechnology has created a broader discipline whose applications include agriculture, industry, energy production, and environmental monitoring. It aids in the development of “green products,” such as bioinsecticides, biosensors, biopesticides, and biofertilizers as well as transgenic plants that are stress-tolerant and/or resistant to insect pests, diseases, and so forth. Bioremediation presents an effective method for cleaning up herbicide- and pesticide-contaminated soils, and microorganisms modified through genetic engineering may produce more efficient enzymes. Environmental biotechnology supports sustainable development through cleaner production, cleaner energy, more efficient agriculture, bioprotection, and environmental quality monitoring.

Biological technologies achieve pollutants' reduction and/or transformation in residual waters, vapors, sludges, and solid wastes by transforming harmful pollutants into useful products or totally eliminating them. Therefore, they play an important role in reducing the environmental problems created by rapid industrialization, uncontrolled effluent disposal, soil pollution, disposal of domestic and industrial solid wastes, and mineral exploitation. Some current practices that are directed toward sustainable waste management include waste poverty assessment; waste minimization; reuse, recycling, and recovery; domestic waste composting; industrial waste treatment; anaerobic digestion of wastewater and organic solid wastes; and sanitary land-filling of domestic as well as industrial solid wastes.

## 1. Agricultural Biotechnology

Agricultural biotechnology exploits living organisms and their products to maintain soil fertility and develop pest-resistant, high-yield crops, thereby addressing global food shortages. Additionally, microorganisms find applications in the fermentation of dairy products such as cheese and curd. Seaweed extracts, for example, supplied by the company Kelpak, serve as commercial plant growth promoters on fields. Biotechnology techniques also cater to the requirements of the silk industry. One of the indirect applications in agriculture involves biological control, which safeguards crops against pests through predation, parasitism, hyperparasitism, antibiosis, phytotoxicity, competition, symbiosis, and camouflage.

These microbial activities significantly enhance the fertility of agricultural soils, decreasing reliance on environmental-polluting pesticides and fertilizers. Surplus biomass emerging from these industries can be used as additional feed to increase milk production in dairy cattle.



## 2. Industrial Biotechnology

The degradation of industrial wastes or pollutants has become necessary with the rapid growth and development. Environmental pollution affects various components such as water, air, soil, and living beings. The Bhopal Gas Tragedy was one of the worst industrial disasters in the world. Pollution has become a serious problem in the rapidly industrializing world. It is interesting that those industries polluting the environment also use environmental biotechnology to reduce pollution and to some extent produce clean products. Many industries, especially the food industries, reuse industrial wastes to make human-friendly products.

Industrial wastes cause serious problems and also reduce soil fertility because of the presence of chemical toxins. The hazardous wastes secreted by industries need to be taken care of in an eco-friendly way to spoil the environment. Interestingly, a number of industries have been preparing so much degradable as well as biodegradable waste. The significant role played by environmental microorganisms (fungi, bacteria, or yeast) in synthesizing useful metabolites and their role in environmental pollution control is highlighted. Microbial enzymes act on pollutants and convert them into less noxious or even non-toxic compounds, which is a continuous phenomenon. Today, pollution control specialists use microbial enzymes in environmental pollution management.

## 3. Environmental Monitoring

Environmental Biotechnology The scope of environmental biotechnology is very wide. It is associated with environmental problems like pollution of land, water, and air, plus waste accumulation, and the subsequent need for efficient management and utilization of resources. Developing feasible, eco-friendly, and cost-effective methods of environmental management and protection is a desirable objective. The goal can be achieved by harnessing microbial diversity and employing microbial technology in different areas of the environment. Therefore, to reach the desired goal, it is necessary to maintain sustainability. Environmental Biotechnology Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs. At the environmental level it includes maintenance and restoration of biodiversity; at the economic level it involves the development of nondepleting economic base; and at the social level it entails the accomplishment of social equity. Environmental management by bio-remediation of waste accumulation, sustainable agricultural practices by bio-fertilizers, bio-pesticides, and bio-monitoring of environment by biosensors can pave the way for sustainable development.

Historical Background Waste material has been part of prehistoric times and even humans were producing waste during the growth and development phase. The disposal of used materials is necessary to maintain a healthy environment, but it was ignored in the earlier period and both biological and archaeological evidences indicate the accumulation of animal bones, suggesting that freezing and decaying process continued to take place, producing an unhealthy environment over a period of time. This is the first stage of accumulation of waste materials or garbage produced by human beings. Industrial development reduces the disposal time of garbage or the wastes, and simultaneously causes environmental pollution. Some synthetic materials like plastics are non-biodegradable and their slow rate of decay in natural conditions has caused the accumulation of wastes and thereby caused environmental pollution.

## Microbial Processes in Environmental Biotechnology

Microbial fuel cells utilize synthetic biology approaches and the novel mushroom body structure of the octopus brain to improve the efficiency of hydrogenase enzymes; this strategy enhances the sustainable performance of microbial fuel cells. The design incorporates genetic regulatory networks from the basal ganglia of a rat brain that resemble the mushroom body’s structure of an octopus, and compares the performance of microbial fuel cells with and without the production of hydrogenase enzymes. The application of hydrogenase enzymes addresses existing limitations and offers effective solutions in microbial fuel cell technology. A single yeast cell of Saccharomyces cerevisiae from a microbial fuel cell acts as a prospective bio-catalyst that harnesses electrons from the interior carbon compound and transports them to the anode. The extreme condition-tolerant outer membrane vesicle has the potential to be a favorable electron acceptor of anaerobic respiration and significantly contributes to an increase in power density.

The anaerobic digestion process in bioremediation technology is encompassed within the concept of bioenergy. It contributes bioenergy in the form of biogas and is a popular green energy source obtained from biodegradable materials such as animal manure, municipal waste, plants, sewage, organic waste, and crop residues. Natural enzymes can break down the carbonaceous organic materials of biodegradable waste in this fermentation process, which occurs without oxygen. Common carbonaceous materials in organic waste can be converted to biogas through this anaerobic process by natural bacteria.

# 1. Microbial Fuel Cells

Environmental biotechnology is a field that uses living organisms to solve environmental problems. The field uses microorganisms to produce energy or transform harmful pollutants into useful products for humans, animals, plants and the environment. The aim is a closed and sustainable life cycle. For some time, biotechnology has been used in agriculture, e.g. for the production of organic fertilisers and bio-pesticides or in the area of waste disposal through anaerobic digestion or the sustainable use of water resources by water treatment. Innovations, especially in the field of genetic engineering, enable new possibilities. Nonetheless, the complexity and the long timeframe of the inventions and their impact do not allow for a quick solution for many environmental problems that exist. Environmental legislation on the other hand often imposes stricter rules and thresholds for environmental protection and reparation. Therefore, public perception of genetically modified organisms (GMOs) is not constructive, such that very often, environmental biotechnological development suffers. Ideally, each new invention should comply with the objectives of an environmentally sustainable development, specifically the conservation of natural resources and the maintenance of ecological processes. The Sustainable Development Goals (SDG) provide an excellent guideline. The six goals that contribute directly to reducing the environmental impact of human activities should also be addressed by environmental biotechnology. Concretely, this begins with the responsible consumption and reduced generation of wastes and should end in a sustainable waste management that recovers resources from wastes and feeds these back into the production process.

Microbial fuel cells are devices that generate electricity by using bacteria and mimicking nature's degradation processes. A microbial fuel cell is a bio-electrochemical system (BES) that uses microorganisms as biocatalysts to catalyse the conversion of biochemical energy, such as chemical energy in organic matter, into electrical energy. When the organic matter is oxidised by degradation, electrons can be released. Microorganisms utilise these electrons in their metabolism for the synthesis and degradation of new substrates by using the electron transport chain (ETS). The electrons released by an ETS are transported to an electron acceptor, e.g. O_2, which enables the microorganisms to keep electrons and protons separated. In situations where the microorganisms can transfer the electrons to an electrode instead of oxygen, a current can be generated and electrons and protons can recombine by forming water.

## 2. Anaerobic Digestion

Anaerobic digestion (AD) is a biological process of the anaerobic degradation of organic or inorganic waste. In this process, microorganisms break down materials into biogas, which is used as bioenergy, and digestates, recyclable materials that can be reintegrated into the environment safely. AD consists of many different interacting microbes working synergistically to degrade different organic and inorganic substrates under anaerobic conditions. These microbes include sugar fermenting, volatile fatty acid producing, acid-consuming, and methanogenic microbes. The biogas predominantly consists of methane and carbon dioxide and can be used to replace fossil-derived natural gas. Methane is approximately 28 times more potent a greenhouse gas than carbon dioxide.