International Journal of Scientific Research in Science and Technology
Available online at : www.ijsrst.com
Print ISSN: 2395-6011 | Online ISSN: 2395-602X
doi : https://doi.org/10.32628/IJSRST23113265

Design and Optimization of Biotechnological Processes for Wastewater Contaminant Remediation

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ARTICLEINFO

Article History:

Accepted : 15 July 2023
Published : 22 July 2023

Publication Issue :
Volume 10, Issue 4
July-August-2023

Page Number :
693-706

ABSTRACT

The pollutants in industrial, agricultural and domestic wastewaters grow as an insult not only to ecosystems but also to human health. Taking up on the utilization of microbial and enzymic systems towards the degradation process, biotechnological remediation is rather more eco-friendly compared with other common modes of chemical and physical treatment. Paper classified the contaminants from wastewaters, discussed impacts prior to advancing its mode of basic principle behind biotechnological remediation. Scalability of treatment efficiency and mitigatory factors from the remediation point of view can be addressed through pathways presented under this treatment with the incorporation of advanced bioprocesses like biotechnology along with nanotechnology. The potential scalability and environmentally favorable mitigation form bases for suggesting aims and futures towards the integration of such frameworks of sustainable wastewater treatment.

Keywords : Wastewater Remediation: The Biotechnological Processes Involving Bioremediation Along With Microbial Degradation, Enzyme-Based Treatment, Nanotechnology and Genetic Engineering For Environmental Sustainability.

1. Introduction

1.1 Scope and Objectives

This paper underlines designing and optimization of biotechnological processes focused on contaminant remediation in wastewater. This would include the knowledge of the principles involved in biological degradation of contaminants, proper choice of the right biocatalysts, and then optimization of process parameters so that the high performance can be observed. It reviews many modes by which these high-technology packages combined with calculation resources can be employed for this development so that through treatment procedure spectra of water contaminates, better biotechnology can be generated.

1.2 Significance of Wastewater Contaminant Remediation

Presently, it is estimated that almost 80% of the water discharged has not undergone treatment as yet and still continues to seek outlet through its normal sources in nature; this leads to its further dispersion and consequently, inducts pollution towards aquatic and land-based ecosystems as well. Such untreated wastewater carries heavy metals, organic pollutants, and pathogens with dangers to public health. Effective remediation protects the water resources, supports biodiversity, and reduces climate changes due to the impacts of pollution. Biotechnological approaches are increasingly considered to be specific with least secondary pollution for being sustainable alternatives.

1.3 Overview of Biotechnological Approaches

Biotechnological technologies make use of the microorganisms and enzymes as well as specially designed biotic systems in breaking down or transforming the contaminants into lesser harmful forms. Among the systems utilized, some of these depend on the natural metabolic modes by biological organisms. More novel discoveries in genetic engineering as well as in synthetic biology usher further potentialities for biotechnological remediation including specifics in the management of complex contaminations as well as processes.

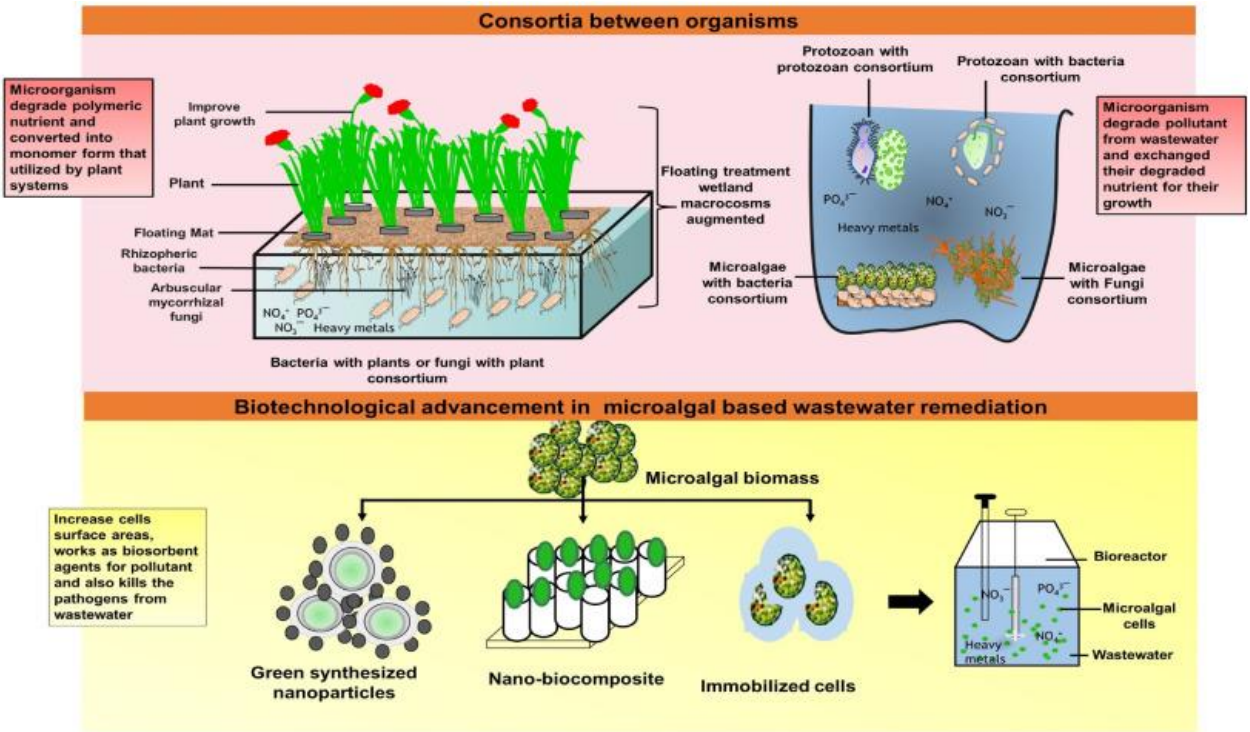

Figure 1 Bio-inspired remediation of wastewater(ScienceDirect, 2022)

2. Fundamentals of Wastewater Contaminants

2.1 Classification and Types of Contaminants

The mixture of contaminants is complex in origin, composition, and their impact on the environment due to variability. In effect, these contaminants could be generally referred to as organic, inorganic, biological, and emerging pollutants. Organic contaminants encompass mainly hydrocarbons, phenols, and pesticides. Industrial effluent discharges, agricultural runoff, and domestic wastes primarily originate from these. Recalcitrant compounds are usually found in the environment for a long time and thus have a significant impact on aquatic ecosystems and human health.

Generally, some common inorganic pollutants which abound in wastewaters arising from mining, electroplating, and industrial applications contain heavy metals like lead, mercury, and cadmium. Thus, these metallic salts could bioaccumulate in water aquatic species, thereby yielding toxic effects that cascade further downstream along the food chain. Other nutrient salts are important inputs because man especially through detergent and fertilizer which find their ways into water bodies leading to algal blooms as nutrients dissolve the levels of oxygen within it.

Household sewerages and hospital effluent is ample biological contaminated stuff in plenty especially pathogenic microbes. These microorganisms break down direct health conditions, mainly areas where such waste is used without proper treatment, whereby water sources are to be applied for human use and farming purposes. Other emerging pollutants include microplastics, nanoparticles, and residues from pharmaceuticals, which is an emergent threat that is growing rapidly with potential effects on long-term environmental and humans. These chemicals seem to circumvent the traditional treatment hence, require site-specific targeted remediation techniques.

2.2 Chemical and Biological Impacts of Contaminants on Ecosystems

Pollution in the wastewater would possibly expose the ecosystem to very radical chemical and biological effects. The nutrient-rich water appears to promote eutrophication, which enables algal growth besides other aquatic flora. This may enhance biological productivity for a short period, but consumption of dissolved oxygen in the decaying process leads to hypoxic or anoxic conditions, thus hurting aquatic fauna. These have been found existing in most of the eutrophic lakes as well as alongside the coastal parts of the entire worldincluding the infamous "dead zones" of the Gulf of Mexico.

Heavy metals in effluent are not toxic but also non-biodegradable substances that accumulate by sediments and water organisms. Bioaccumulation has been disturbing the physiological processes in fish and other aquatic organisms. Health-related problems in human beings rose up because human consumed the seafood infected with the aforementioned pollution of mercury, which cause serious damage to the nervous system; in addition, the health impact arose from the cadmium of carcinogenic nature. Other than this, residuals of pharmaceuticals such as antibiotics and synthetic hormones may have a bearing on the behavior pattern as well as the reproduction in the aquatic animals. This therefore means that the effluent from the laced wastewater with antibiotics is the one attributed to the increased antibiotic resistance. The effluent from the wastewater has become more crowded with microplastics which contribute considerably to the danger to human health. Microplastics have emerged also to be increasingly used as carriers for other pollutants such as heavy metals and hydrophobic organic compounds. The latter have resulted in effects at the species-level both through physical barriers and chemical toxicity, multi-trophic level impacts. There has been rising concern over emerging contaminants among them nanoparticles and endocrine disruptors. They have been created to impact ecological effects though less known to include hormonal systems disruption and the production of oxidative stress in organisms.

2.3 Current Challenges in Wastewater Treatment

Direct major concerns of wastewater treatment are the demerits of conventional practices. The perceptions developed during the past decades are that the classical operations like sedimentation, filtration, and activated sludge process turn out to be inadequate for the modern flows of wastewater. The treatment process passes satisfactorily for effective removal of suspended solids and relatively biodegradable organic content, but resistant organic contaminants, heavy metals, and emerging pollutants are not attacked effectively.

This presents with some major drawbacks. Firstly, no complete degradation of the recalcitrant pollutants can occur. Microbes cannot biodegrade PAHs or synthetic dyes; thereby the compounds require AOPs or specific biological treatment systems. These are expensive systems as well as energy-intensive; so could not be employed in those areas where resources are scarce. The second major drawback is due to conventional treatment techniques-toxic by-products form end. For instance, chlorination is probably one of the most frequently used disinfection steps in removal of pathogens, but the process also leads to by-products that include trihalomethanes, which are identified as carcinogens.

Another major concern of energy use in wastewater treatment. Aeration constitutes one of the largest fractions in the activated sludge process and constitutes about 50-60% of all the energy applied in the treatment plants. This high energy usage further intensifies the problem of the emission of greenhouse gases. It has major problems relating to the nature of sludge resulting as the by-product of this traditional treatment process, including environmental as well as operational and disposal ones. Sludge is a residue that forms after concentration in water from high metals content as pollutants, other contaminants; such waste constitutes one of the toughest problems concerning the sludge disposal or even safe use.

Emerging contaminants are hard to remove since their molecular size is very small and holds much chemical complexity. Its micro-plastics size falls within the range of micrometer, and it cannot be filtered using any traditional system; most definitely, drug residues and synthetic hormones need advanced treatment techniques like membrane filtration and advanced oxidation. In this regard, it indicated that there was no existence of standardized legislation or framework to monitor this particular kind of contaminant in order for regulation to happen. Recently, new kinds of industrial and technological revolutions have developed changed compositions of wastewater, meaning changes require development of adaptive methods towards these waters for treatment.

Table 1: Key Challenges in Wastewater Treatment and Their Impacts

Challenge	**Description**	**Environmental Impact**
Incomplete degradation	Failure to remove recalcitrant pollutants such as PAHs and dyes	Persistence of toxic compounds in water bodies
Energy-intensive processes	High energy demands for aeration and advanced treatment technologies	Increased carbon footprint and operational costs
Secondary pollution	Formation of harmful by-products, e.g., trihalomethanes during chlorination	Potential health risks and ecological toxicity
Sludge management	Difficulties in handling and disposing of sludge containing concentrated pollutants	Risk of soil and groundwater contamination
Emerging contaminants	Limited removal of pharmaceuticals, microplastics, and nanoparticles	Long-term ecological impacts and bioaccumulation risks

3. Biotechnological Framework for Wastewater Remediation

3.1 Principles of Bioremediation

Bioremediation is an environmental-friendly process wherein biological agents, that is, majorly the microbes metabolise or transform those pollutants of wastewater to less harmful and harmless matter. A great biotechnological base of this can be ascribed by which microbial metabolism of a contaminant comes under forms of their energy source or nutrient that they consume in living beings. For example, under aerobic conditions, aerobic microorganisms will oxidize organic pollutants to carbon dioxide and water; however, under oxygen-deprived conditions, anaerobic microorganisms will reduce a contaminant to produce methane, hydrogen, or lesser harmful compounds.

Its great advantage is that bioremediation is quite flexible to most of the contaminants, such as heavy metals, hydrocarbons, and pesticides. It also performs operations under mild conditions with lower energy input compared with physicochemical methods. Still, the efficiency depends on factors like the concentration of the contaminant, environmental factors, such as pH and oxygen levels, the competing populations of microbes that share similar niches and use up the available materials for growth.

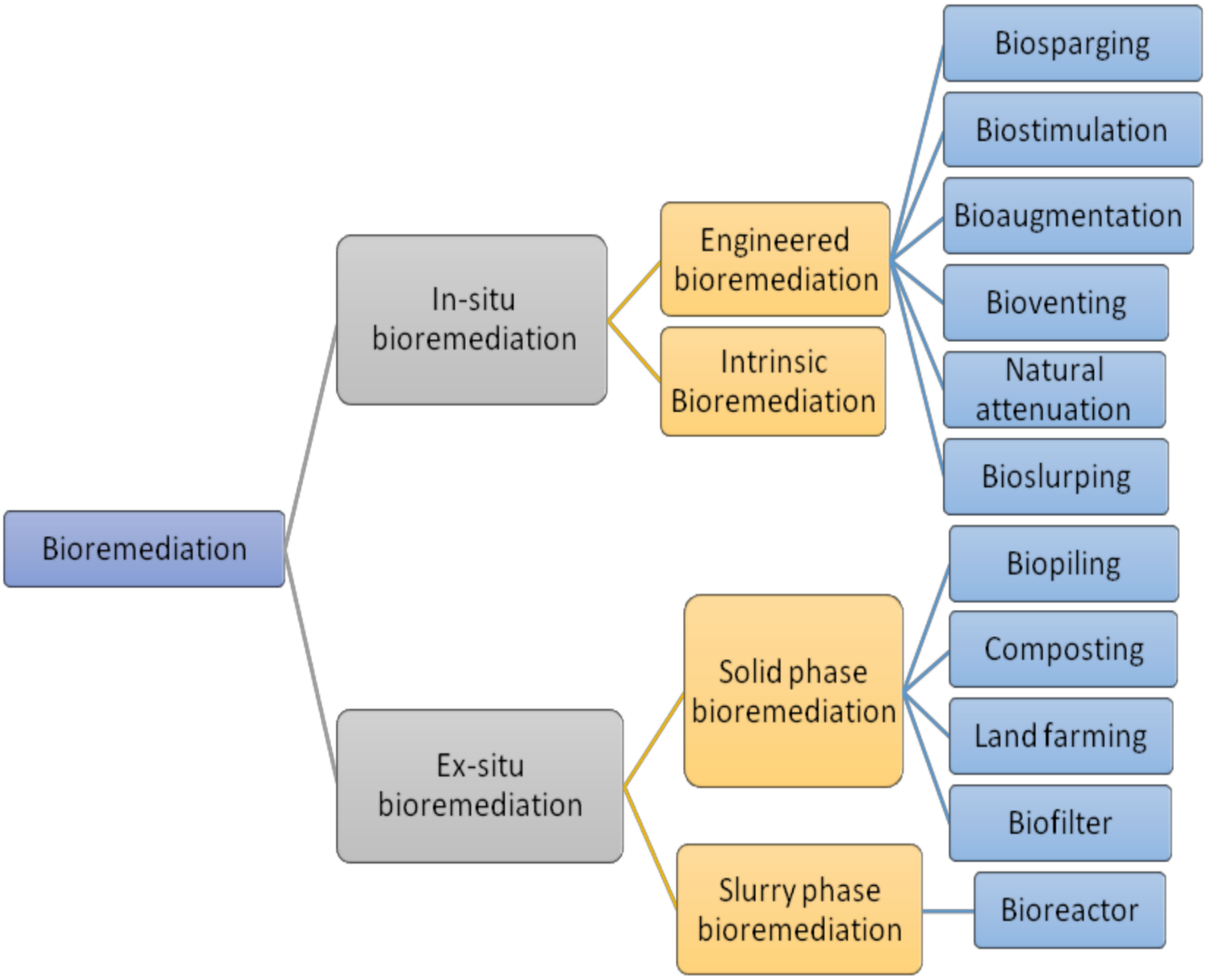

Figure 2 Recent Strategies for Bioremediation of Emerging(MDPI,2023)

3.2 Microbial Systems for Contaminant Degradation

Their various metabolic activities are the foundation of the core of biotechnological wastewater treatment. Between bacteria, fungi, and algae, they are commonly employed to degrade massive amounts of contaminants. Of the many bacteria that exist, those in Pseudomonas, Bacillus, and Rhodococcus are probably the most studied organisms about their hydrocarbon-degrading and other organic pollutants-degrading capabilities. For example, Pseudomonas putida assimilates aromatic hydrocarbons as carbon sources and degrades them to less complicated nontoxic compounds through multiple enzymatic mechanisms.

For instance, white-rot fungi, which include Phanerochaete chrysosporium, break down complex pollutants like dyes and lignin that are formed through the action of extracellular enzymes such as laccase and manganese peroxidase. These enzymes cleave high molecular weight organic compounds into small-sized molecules that are more available for metabolism. Other bioremediation methods involve nutrient uptake in algae, Chlorella, and Spirulina, among others, and they aid in lowering the eutrophication of water bodies. Algal-based systems also offer the possibility of biotransformation of heavy metals through biosorption and bioaccumulation.

Table 3 Microbial agents in Wastewater treatment

Microorganism Type	Examples	Target Contaminants	Mechanism of Action
Bacteria	*Pseudomonas*, *Bacillus*	Hydrocarbons, Phenols	Enzymatic degradation via metabolic pathways
Fungi	*Phanerochaete chrysosporium*	Dyes, Lignin	Extracellular enzyme production (e.g., laccase, peroxidase)
Algae	*Chlorella*, *Spirulina*	Nutrients (N, P), Heavy Metals	Biosorption, Bioaccumulation

3.3 Enzyme-Based Biotechnological Processes

Microbial enzymes have, in the recent past gained attention as they are very specific and efficient in degrading pollutants. Among the oxidoreductases are the laccases and peroxidases that efficiently cleave phenolic compounds and dyes among other aromatic pollutants. These enzymes catalyze oxidation reactions that break down the complex molecules into simpler, more easily biodegradable substances. For example, laccase produced from fungi Trametes versicolor has been utilized for the decoloration of synthetic dye containing textile industry effluent and removed COD and color very effectively.

Hydrolases are the most commonly used enzymes for hydrolyzing esters, fats, and other similar organic substances. Lipases and esterases are some examples of the types through which industrial wastes containing fats and oils may be hydrolyzed. These enzymes work at intermediate conditions and therefore require less toxic chemicals and high energy. The enzyme process used sometimes is more efficient and stable through immobilization. These immobilized enzymes attached to solid supports such as alginate beads or silica gels can be recycled; they can tolerate extreme conditions within the operating environment; thus, more economical for wide application.

4. Design of Biotechnological Processes for Wastewater Treatment

4.1 Bioprocess Design Principles

This means there are principles of biological, chemical, and engineering science principles in the removal of contaminants to make it effective due to the design of the process. The selection of a biological agent is part of bioprocess design generally, but represents which microorganisms or enzymes effectively degrade these contaminants. This all determines the nature of wastewater or pollutant concentration even environmental conditions.

Generally, bioprocesses can be classified as being either suspended growth systems which include activated sludge, or attached growth systems including biofilm. Suspended growth systems suspend the microbial biomass in wastewater, allowing microbes to have direct contact with the contaminants. Attached growth systems involve fixed support, trickling filters, or rotating biological contactors, so that microbes have extended retention time while hydraulic retention times consequently drop. These advanced wastewater treatment plants in big size use hybrid systems, which, in turn, use the above methods as a combination for better optimization of process.

The rates of microbe activities depend on several process parameters like pH, temperature, oxygen supply and nutrient concentration. For example, in aerobic systems the aerators or diffusers should be able to provide sufficient rate of oxygen transfer. However, systems that involve anaerobes should have low supply of oxygen since it increases methanogen and other anaerobic microbe activities.

4.2 Selection of Biocatalysts for Contaminant Degradation

The biocatalysts would be the basis of a process that has been developed for wastewater treatment. This is because biocatalysts depend on the type of pollutants and what one would like to obtain from the treatment process. Essentially, complex mixtures of pollutants require more than one species of microbes in their degradation. More viable to degrade than the single strain, the multiple species consortia have been proved.

Enzyme-based systems are used to selectively remove dyes or pharmaceuticals. Such systems have much substrate specificity. Cost however is a cause of the problem besides low operational stability. Techniques of genetic as well as protein engineering are now in practice with enzymes to enhance catalytic efficiency and substrate range and providing them thermal stability so that enzymes may be used commercially as well.

4.3 Reactor Configurations and Process Integration

The configuration of bioreactors fundamentally determines the efficiency as well as scalability of biotechnological wastewater treatment processes. Some such examples include stirred-tank reactors, packed-bed reactors and fluidized-bed reactors with each offering specific advantages for specific applications. Fluidized-bed reactors, for example, are uniquely effective for the treatment of high strength wastewater due to better mixing and mass transfer.

These emerge as integrated systems coupling bioprocesses with physicochemical treatments for the treatment of complex wastewater streams. These are membrane bioreactors which integrate biological treatment with ultrafiltration or microfiltration membranes delivering superior contaminant removal, together with possible water reuse, also bioelectrochemical systems encompassing microbial fuel cells-integrating microbial activity, together with electricity generation toward an effective recovery of energy in addition to treatment.

Table 4 Common configurations of bioreactors with their applications

Reactor Type	Description	Applications
Stirred-Tank Reactor	Well-mixed system, suitable for aerobic/anaerobic	General wastewater treatment
Packed-Bed Reactor	Fixed bed of support material for biofilm growth	Treatment of industrial effluents

Fluidized-Bed Reactor	Particles suspended in fluid for enhanced mixing	High-strength wastewater treatment
Membrane Bioreactor (MBR)	Combines biological and membrane filtration	Advanced treatment and water reuse

5. Optimization of Biotechnological Processes

5.1 Optimization Techniques in Bioremediation

Biotechnological processes should be optimized towards the acquisition of more efficiency, minimization of costs, and optimization of the environment within the process of handling wastewater. Optimization generally calls for readjustment of some operation parameters meant to result in maximum removal of pollutants with use of less resources towards that purpose. The Response Surface Methodology is one of the widely applied methods in optimizing bioremediation. This method applies a statistical approach that measures the interaction between several factors and identifies the optimal conditions for the process. An example is the successful application of RSM in studies on the optimization of nutrient concentration, pH, and temperature for the bacterial degradation of hydrocarbons in industrial effluents.

Another powerful technique comprises of Taguchi methods that proves especially very useful when there is an existence of environmental variability along with searching for a robust process condition. That kind of techniques has already been successfully implemented while optimizing fungal bioreactors for dye decolourization. There are factors considered such as agitation speed, an initial concentration of dye that aims at gaining maximum decolourization efficiency. Above that, machine learning algorithms nowadays find practicality in predicting and optimizing outcomes after using bioremediation through mechanisms as are of an ANN. Such models might examine complex datasets and obtain better performance by capturing nonlinear relations existing among the variables.

Hence, designs can further go in depth with biocatalysts. The two traditional ways toward enzyme efficacy improvement along with stability are directed evolution and site-directed mutagenesis. Such efforts have produced an example like the synthesis of thermostable enzymes that will hydrolyze persistent organic pollutants at extreme conditions, enabling the treatment process with the help of Escherichia coli by developing strains for such industrial applications.

5.2 Process Parameter Tuning for Enhanced Efficiency

Optimum control of parameters is essential to obtain an ambient in which the microbe or enzyme activity occurs. In addition, temperature, pH, DO, and nutrient supply heavily influence the rates by which contaminants are biodegraded. For example, as a function of microorganism type, the best maintenance temperature range for a microbiological process is, reportedly, between 25-37 degrees Celsius. Similarity, mesophilic range 30–40°C results in best performance for the process of anaerobic digestion; whereas cases favor the thermophilic condition of 50–60°C that may further enhance the methane production.

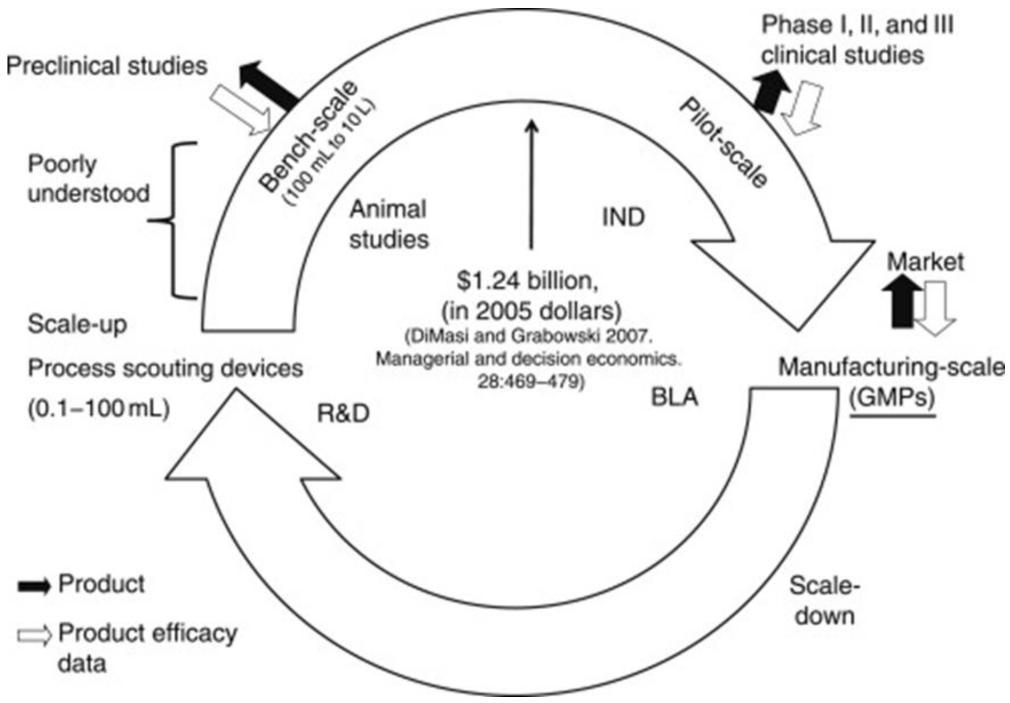

Figure 3 Bioprocess Optimization - an overview(ScienceDirect,2020)

Wastewater pH: The pH level in water determines the control action towards enzymatic action and survival of microbes. Most bioprocesses have optimal performance at neutral to near-alkaline pH values, within the range of 6.5–8.5. Acidophiles prefer acidic pH values, like Acidithiobacillus ferrooxidans, that are used in cleaning up acidic industrial waste streams, such as mine wastes. This is because, in an aerobically operated system, the maintenance of dissolved oxygen levels becomes crucial because otherwise the rate of inadequate oxygen supply ends up becoming the limiting factor towards microbial respiration and thus the efficiency of biodegradation. Improvement of aeration systems using fine bubble diffusers and jet aerators is very common for enhancing oxygen transfer efficiency in the case of large scale modern wastewater treatment plants.

The C:N:P ratio is another major parameter-the more, specific nutrient balance. The ideal C:N:P ratio results in microbes having a high rate and activity. The most commonly employed ratio is about 100:5:1 for C:N:P in wastewater treatment. In case the given values deviate from these figures, nutrient deficiencies or excesses can affect microbial metabolism. Most of the monitoring systems used in a process adopt real-time sensors that permit the dynamic changes in such parameters for consistent and efficient operations.

5.3 Computational Modeling and Simulation in Biotechnological Process Design

It is a critical factor of biotechnological process design and optimization using the applied computational modeling and simulation tools. They simulate biochemical and physical interactions in bioreactors; hence, researchers can predict the performance of a system under certain conditions. Kinetic modeling is one of the most common methods used where mathematical equations describe microbial growth and substrate utilization. Models like Monod kinetics and Michaelis-Menten equations are most often used to optimize rates of organic pollutant degradation.

Another simulation tool is computational fluid dynamics that is fluid flow, mass, and heat transfer in bioreactors. CFD has really done a lot of work which has been extensive and enables one to predict the flow patterns that are supposed to characterize regions of poor mixing or oxygen transfer through optimizing reactor design like fluidized bed, packed bed reactors. Indeed, aeration systems with CFD simulation were developed to improve the transfer of oxygen in large-scale aerobic bioreactors, which in the long run would result in high microbial activity and thereby saving energy.

Machine learning models have been interfaced increasingly with simulation tools to analyze the enormous data sets from wastewater treatment systems. The models predict the change in contaminant removal efficiency with changes in operation and provide the optimal conditions for the operation of the reactor. Further, dynamic simulation software like BioWin and GPS-X allow real-time optimization of the wastewater treatment process with inclusion of sensor and control system data. These have been very effective in municipal treatment plants that generate efficiency in energy production and also meet the needs raised by regulatory bodies.

6. Advanced Technologies in Biotechnological Wastewater Treatment

6.1 Genetic Engineering of Microorganisms for Enhanced Remediation

Short story, this was genetic engineering which transformed biotechnological wastewater treatment to take place at some fantastic evolution stage. With such a form of science, people could actually manage to obtain new bacteria engineered with greater abilities to degrade. Recombinant DNA is highly used in an effort to deliver the specific gene into a set of microorganisms and subsequently to strengthen them with the new pathways to metabolize recalcitrant pollutants. Indeed, genetically engineered strains of Pseudomonas had been engineered for degrading chlorinated solvents including trichloroethylene.

The gene-editing technology is really great, especially in using the technique of CRISPR-Cas9, since this brought this field forward for enhancing the precise modification of the genomes for microbes. This technology paved way toward successfully implementing bacteria to be in a more resistant form about toxic environments, including its exceptionally high concentration of heavy metals or extreme pH conditions. For instance, engineering strains of Escherichia coli with resistance due to cadmium and lead is really powerful for using bioremediation practices upon industrial wastewater.

The design and synthesis of artificial microbial consortia with complementary metabolic functionalities is another synthetic biology application of synthetic techniques. Synthetic consortia can be designed and synthesized to simulate the type of ecosystems that are found in nature wherein different species have symbiotic relationships with each other so that difficult-to-degrade mixtures of pollutants may be broken down. For example, synthetic consortia made up of hydrocarbon-degrading bacteria combined with metal-resistant fungi have been constructed so that oil spills and heavy metals in wastewater can be simultaneously cleaned up.

6.2 Application of Nanotechnology in Bioprocesses

Nanotechnology is very prospective. It makes even biotechnological wastewater treatment processes very superior. More and more applications of metal nanoparticles, carbon nanotubes, and magnetic nanocomposites have made ways as catalysts or as adsorbents that significantly increase the efficiency in cleaning out contaminants. As such, because iron oxide nanoparticles present massive surface area with huge potential of its good adsorption properties, many authors consider it widely in application towards removing As and heavy metals from any system.

Nanotechnology also enhances the enzyme-based process through the immobilization of enzymes on nano-structured supports that allow stability and reusability. For example, it was proved that laccases immobilized on carbon nanotubes are significantly more active in comparison with free enzymes during textile dyes degradation. Magnetic nanoparticles are especially promising as the immobilized enzymes or microbial cells can be easily recovered and reused via magnetic separation techniques.

In addition, nanosensors are introduced into bioreactors to monitor in real time critical parameters such as contaminant concentrations, pH, and microbial activity. Sensors can be applied for dynamic adjustment of process conditions such that the overall efficiency and reliability of wastewater treatment systems increase.

6.3 Role of Synthetic Biology in Process Design

This field is at the amalgamation of genetic engineering, computational modeling, and automation in the design of tailored biological systems for the treatment of wastewater. Focusing on synthetic gene circuits that would determine the behavior of microbes for their precise regulation of metabolic pathways, this field has thus far been used to engineer, for example, bacteria that produce biosurfactants for efficient remediation of oil spills.

Modular biobricks or standardized genetic elements are widely used in synthetic biology for the assembly of complex metabolic pathways. Biobricks have been used to design microbes that can degrade multiple pollutants simultaneously. Synthetic microbes endowed with genes for aromatic hydrocarbon degradation and heavy metal resistance show great promise for the treatment of industrial effluents.

Biohybrid systems comprising of living cells genetically engineered using artificial materials are as intriguing for synthetic biology as the aforementioned bioreciprocal interactions are. Their potential derivations may result from the prospective capability of photocatalysis in pollutant removal coupled up with photosynthetic microbes along with nanomaterials. The existing model regarding processes of biotechnologically wastewaters treatment, allows opening up to efficient sustainable applications.

7. Monitoring and Evaluation of Biotechnological Processes

7.1 Analytical Techniques for Process Monitoring

Monitoring the biotechnological processes in wastewater is necessary in ensuring efficiency of operation and fulfillment of environmental regulations. Analytical methods are also vital to quantify contaminants, monitor microbial activity, and monitor performance. Spectroscopic methods are widely used in determining parameters like COD, BOD, and concentration of specific pollutants like dyes and phenols. Such methods offer a real-time control of the process through its critical rapid and non-destructive analyses.

GC and HPLC are the methods most applied in the detection and quantification of complex organic pollutants such as PAHs and pharmaceutical products. Such methods are highly sensitive and precise. Trace-level amounts of pollutants in wastewater have been detected using these techniques. Combining these techniques with mass spectrometry affords highly informative information regarding the chemical structure of degrading contaminants and their products that helps during the assessment of the biodegradation pathways.

The main tools used in molecular biology are to monitor microbial activity inside bioreactors. Those include quantitative PCR and next generation sequencing which can establish the amount of quantification of active functional genes that break the pollutant and the recognition of the active microbial community which is existing in the system. Biosensors integrated in a bioreactor are increasingly common since they would also provide real-time monitoring of critical factors such as pH, dissolved oxygen, and contaminant concentrations. For instance, the enzymatic biosensors were used with a lot of success in monitoring the degradation of pesticides in wastewater by their determination using organophosphate.

7.2 Performance Metrics and Efficiency Evaluation

Some performance criteria of the biotechnological process could be removal efficiencies of contaminants, stability while operating, and environmental effects that the biotechnological process can cause. Percent COD and BOD removal efficiencies are basic measures in calculating the quantity of organic load removed from the water treatment. For high values exceeding 90% removal efficiencies in both COD and BOD for the removal in the case of sophisticated high-order bioreactor systems, like MBR membrane bioreactors, indicates well optimization of the process.

Nutrient removal efficiency is also very critical for waters that have high nitrogen and phosphorus concentrations. Such waters result in eutrophication in water bodies. Nitrogen removal through nitrification and denitrification can be measured directly through changes in ammonium and nitrite, as well as concentration of nitrate ions.

Levels of removal for phosphorus come through either chemical precipitation and biological uptake into the cellular mass by microbes, most often at levels greater than 85%.

Another parameter that is assessed in the sustainability evaluation of biotechnological processes is energy. In general, a comparison between technologies for treatment purposes can be carried out by means of metrics which include energy required per unit of contaminant removed. For instance, one could think of kWh/kg COD removed. Such emerging systems include, among others, microbial fuel cells. Microbial fuel cells offer a dual benefit: their ability to remove contaminants from wastewater and the recovery of energy simultaneously.

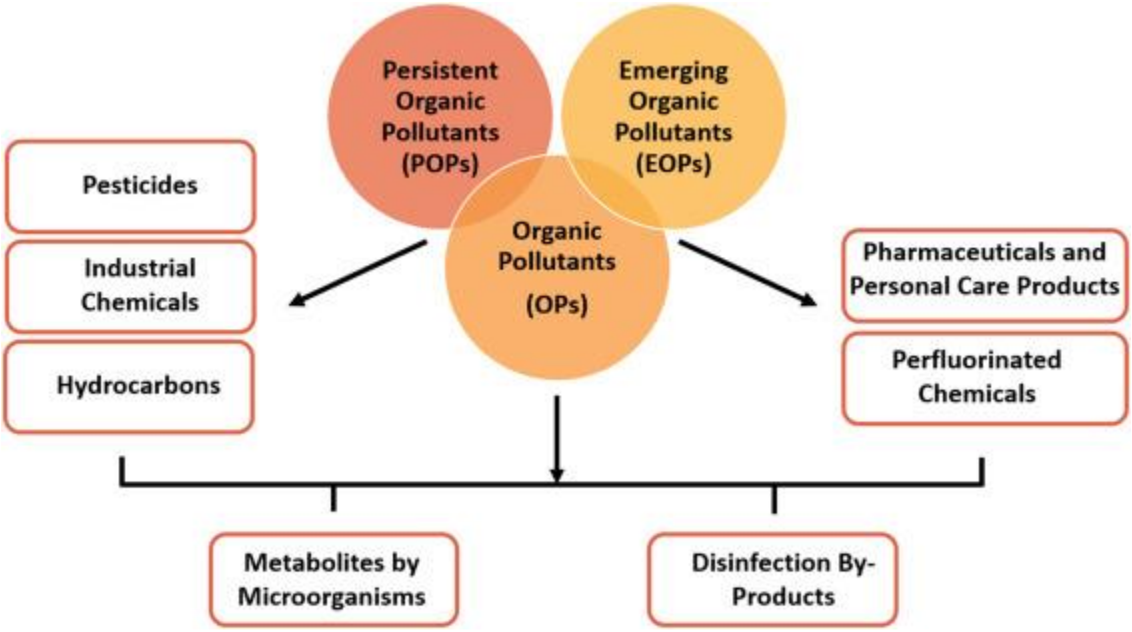

Figure 4 Analytical methods for determining environmental contaminants(ScienceDirect,2023)

7.3 Risk Assessment and Environmental Impact Analysis

The biotechnological processes to be applied in the treatment would have to consider the risk and environmental considerations. It would involve all the secondary pollutants that may probably be released during the period of the treatment process, such as the toxic intermediates or byproduct of micro-biodegradation. It would involve incomplete degradation in the resultant production of more toxic materials requiring other steps of additional treatments.

Life cycle assessment is a measure of the environmental impact of a wastewater treatment system. It measures all the resource extraction that occurs during production, the process of disposing of wastes, and every process involved in it. This calculation results in an indication of the footprint on the environment. The metrics that are used for LCA include greenhouse gas emissions, water and energy usage, and solid wastes generated. For example, most conventional activated sludge processes are energy-intensive since aeration is applied. Anaerobic digestion systems have almost negligible environmental footprint since, in many cases, they even produce biogas intended for renewable energy sources.

Biotechnological systems also have to contend with risks due to microbial contamination or the emergence of resistance. GM products are always released into the environment in a very controlled manner, and measures to contain it might be encapsulation or immobilization to prevent risks. Monitoring and periodic risk assessment are continually done to make sure these biotechnological wastewater treatment systems operate safely and sustainably.

8. Challenges and Future Directions

8.1 Technical and Economic Barriers in Biotechnological Solutions

While a significant technical milestone has been achieved, yet many technical and economic barriers have to come in the way of large-scale implementation of biotechnological wastewater treatment systems. Probably the most important is that the composition of wastewater is very diverse and dramatic effects can be made on the performance of biological processes. For example, industrial effluents carry highly toxic compound concentrations, such as high metals or solvents concentration but inhibit microbial activities leading to the pre-treatment that enhances complexity and associated high costs of operation.

It also presents added difficulties in scaling up laboratory-scale bioprocesses to industrial applications. Such applications often involve dealing with large volumes of wastewater where conditions remain optimal for microbial or enzymatic activity can often be very challenging. Such large systems are normally associated with common problems including poor mixing, mass transfer limitations, and biofouling requiring novel engineering solutions.

The most binding economic factors for low- and middle-income economies, especially, are the constraints for executing high-end biotechnological systems. These include generally the high capital costs, for instance, especially for pieces of equipment such as MBRs or biosensors; besides, cost and energy charges during recurrences times when using the technologies most often prove to be pricey. Ecomonic options - low-cost biofilms or natural microbial consortia - need to be considered in terms of suitability to biotechnological treatment of water-wastewater for this resource-constrained environment.

8.2 Emerging Trends in Wastewater Remediation Technologies

Wastewater treatment through biotechnologies is being developed into modern systems using novel cutting-edge technologies such as nanotechnology, synthetic biology, and advanced artificial intelligence. AI-based system has designed optimization of dynamic process parameters. The efficiency in the removal of contaminants brings energy consumption down in the whole process. It is utilized in predicting the behavior of microbial consortia under different environmental conditions thus enabling real-time adjustments to be made in the operation of the bioreactor.

Nanotechnology still remains a relatively new player which enhances the performance of the bioprocess. Most of the nanomaterials used, such as graphene oxide and titanium dioxide nanoparticles, are mainly for the photocatalytic application in the degradation of recalcitrant pollutants when exposed to light. They are very effective in hybrid systems where integration of biological and physicochemical processes can be achieved toward more holistic treatment of wastewater.

Thus, the concept of synthetic biology is applied in designing tailored microbes for specific purposes. For example, microbes can be engineered to degrade pharmaceutical residues into less harmful metabolites. Metabolic modeling and genome-scale reconstruction are methods of designing even more robust strains of microbes that better survive environmental stresses such as salinity or extreme temperature conditions.

8.3 Long-Term Sustainability and Scalability

Huge efforts should be made in the saving of as much water and resources as possible by adopting a multidisciplinary approach in the direction of maintaining long-term scalability in biotechnological systems of wastewater treatment. For example, nutrient recovery technologies such as struvite through precipitation are likely to be integrated into anaerobic digestion that would allow for renewable energy production together with the recovery of valuable resources from wastewater.

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