SUSTAINABLE DIMENSIONS OF MICROBIOLOGICAL REMEDIATION OF WASTEWATER

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Sustainable Dimensions of Microbiological Remediation of Wastewater

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FOREWORD

Water is essential to ecosystems, communities, and economies. Yet today, access to clean and safe water is one of the biggest challenges we face globally. As industrialization speeds up and environmental pressures increase, we urgently need sustainable and innovative ways to treat wastewater. One of the most promising solutions may lie in nature itself, particularly in the amazing abilities of microorganisms.

This book, Sustainable Dimensions of Microbiological Remediation of Wastewater, offers a valuable and detailed exploration of how microbiological methods can change our approach to managing wastewater. It covers topics ranging from native microbial communities and biofilms to genetically modified organisms and constructed wetlands. The chapters compiled here present a wealth of research, applications, and innovative ideas. What makes this volume stand out is its dual focus. It provides scientific depth while staying grounded in practical application.

The authors skilfully balance foundational concepts with the latest developments, ensuring that readers are well-informed and motivated. Whether discussing the use of microalgae for biofuel production or the implementation of membrane bioreactors for targeted treatment, each chapter supports a broader vision connected to global sustainability goals and a circular economy. By combining insights from microbiology, environmental science, and sustainable engineering, this work serves not only as a technical reference but also as a spark for rethinking how we relate to water and waste. It will certainly be a valuable resource for students, researchers, practitioners, and policymakers. In promoting nature-based, microbial solutions, this book highlights a simple yet profound truth: the journey to a sustainable future may be microscopically small, but its effects can be immense.

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PREFACE

The global water crisis, intensified by industrialization, urbanization, and environmental degradation, underscores the urgent need for sustainable wastewater treatment solutions. As contaminants ranging from heavy metals to organic pollutants threaten water security, microbiological remediation has emerged as a cornerstone of eco-friendly, efficient, and scalable wastewater management. By harnessing the natural capabilities of microorganisms, these approaches transform wastewater from an environmental burden into a resource for recovery and reuse, aligning with the principles of a circular economy and Sustainable Development Goal 6: Clean Water and Sanitation.

Sustainable Dimensions of Microbiological Remediation of Wastewater offers a comprehensive exploration of microbial technologies, blending scientific rigor with practical applications. Each chapter is meticulously crafted to deepen the understanding of microbiological approaches, from pollutant removal to resource recovery, addressing both established and cutting-edge techniques.

Chapter 1, Wastewater Types, Toxicity, Pollution and Approaches for Treatment, lays the foundation by detailing the sources and impacts of wastewater contaminants, setting the stage for microbial interventions. *Chapter 2*, Microbial Remediation: A Sustainable Approach for Wastewater Treatment, introduces the potential of microbial consortia for sustainable wastewater treatment. *Chapter 3*, Indigenous Microorganisms in Wastewater Remediation, explores biofilm technologies leveraging native microbial communities, while *Chapter 4*, Genetically Modified Microorganisms as a Biotechnological Tool for Wastewater Treatment, examines engineered microbes for enhanced remediation.

Chapter 5, Recent Advances in the Performance of Microbial Bio-films in Wastewater Remediation, delves into biofilm optimization, and *Chapter 6*, Microalgae: An Emerging Tool for Treatment of Industrial Wastewater and Biofuel Production, highlights the dual role of algae in pollutant removal and bioenergy production. *Chapter 7*, The Role of Cyanobacteria in Wastewater Treatment and Carbon Sequestration, addresses opportunities and challenges in cyanobacterial applications, followed by *Chapter 8*, Biosorption: A Sustainable Environmental Remediation Technology for Wastewater Treatment, which focuses on microbial adsorption mechanisms.

Chapter 9, Principles and Applications of Membrane Bioreactors in Wastewater Treatment, explores advanced bioreactor systems, while *Chapter 10*, Microbial Communities in Constructed Wetlands for Sustainable Wastewater Remediation, emphasizes nature-based solutions. *Chapter 11*, Bioremediation of Heavy Metal Contaminated Wastewater, addresses heavy metal removal, and *Chapter 12*, Current Trends, Challenges, and Future Prospects in Microbial Wastewater Treatment, synthesizes emerging trends and future directions.

This book aims to serve as a vital resource for environmental researchers, engineers, policymakers, and students, offering a dynamic balance of theoretical insights and practical solutions. By bridging microbiology, environmental engineering, and sustainability, it seeks to inspire innovative approaches to wastewater remediation, paving the way for a water-secure and sustainable future.

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CHAPTER 1

Wastewater Types, Toxicity, Pollution, and Approaches for Treatment

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Abstract: Wastewater, a by-product of human activities, is a complex mixture of organic and inorganic substances, including pathogens, heavy metals, and various toxic chemicals. It originates from diverse sources such as domestic sewage, industrial processes, and agricultural runoff, each contributing distinct types of pollutants. Domestic wastewater primarily contains biodegradable organic matter and pathogens, while industrial and agricultural wastewater are rich in hazardous chemicals, pesticides, and nutrients, including nitrogen and phosphorus. Unchecked discharge of untreated or inadequately treated wastewater leads to severe environmental pollution, resulting in the contamination of surface water, groundwater, and soil. The toxicity of wastewater is influenced by the concentration and nature of contaminants, including pharmaceutical residues, endocrine-disrupting compounds, and heavy metals like mercury and cadmium. These toxic substances can cause acute and chronic health effects, disrupt ecosystems, and contaminate food chains. Recognizing the scale of these challenges, modern wastewater management necessitates the use of advanced treatment techniques aimed at reducing pollutant loads and toxicity. This chapter discusses a variety of treatment methods, including conventional approaches and innovative approaches like membrane bioreactors, constructed wetlands, and advanced oxidation processes (AOPs), which offer promising solutions for treating complex, high-toxicity wastewater streams. Moreover, the potential of emerging technologies, such as nanotechnology, bioremediation, and electrochemical treatments, is explored as part of sustainable wastewater management. In conclusion, addressing the toxicity and pollution caused by wastewater requires an integrated approach combining conventional and advanced methods. By adopting innovative technologies and

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improving treatment efficiency, we can significantly mitigate the environmental and public health risks associated with wastewater pollution. This chapter underscores the importance of ongoing research and development to ensure safe and sustainable wastewater management for future generations.

Keywords: Advanced oxidation processes, Bio-remediation, Environmental pollution, Sustainable, Wastewater management, Toxicity.

INTRODUCTION

Water is an essential natural resource that sustains life. Natural water reservoirs, such as lakes, rivers, streams, and oceans, are integral components of the hydrological cycle. Over the past century, however, environmentally unfriendly practices, rapid population growth, and increasing urbanization have led to a growing demand for clean and freshwater resources. Therefore, the availability of freshwater has been severely depleted, while wastewater generation continues to increase [1 - 3]. Wastewater is water that has been contaminated as a result of human activities. It is no longer suitable for direct use and originates from various sources, including agricultural, industrial, domestic, and commercial activities. In addition, wastewater may result from sewer infiltration, inflow from external sources, and surface runoff. Wastewater may contain physical, chemical, or biological contaminants. Water resources are becoming increasingly scarce around the world as a result of the growing disparity between freshwater consumption and availability. As a result, access to potable water has emerged as one of the most pressing issues worldwide. Ecological systems are seriously threatened when human waste or garbage is discharged into aquatic bodies, adversely affecting livelihoods. To protect aquatic ecosystems, it is essential to understand the sources of wastewater and the pollutants they contain. In developing nations, a large proportion of the population relies on contaminated, untreated water that can harbor pathogenic microorganisms, leading to waterborne illnesses such as cholera, diarrhea, giardiasis, hepatitis, and typhoid. In many countries, wastewater is commonly reused for agricultural purposes, which contributes to environmental degradation and poses significant public health risks.

Characteristics of Wastewater

Based on its characteristics, wastewater can be classified into three primary categories: chemical, physical, and biological wastewater. The most common and basic physical characteristics include colour, odour, turbidity, and temperature. The colour of wastewater can be easily observed with the naked eye, and it can sometimes indicate its age. Fresh water typically appears grey or brownish grey; however, when hydrocarbons in water break down, the level of dissolved oxygen can be reduced to zero, turning the water black and causing it to become septic and stale. The odour of wastewater is generally due to gases produced during the decomposition of organic compounds. Fresh wastewater emits a relatively mild smell, which is less unpleasant than that of septic wastewater. The most distinctive scent of stale or septic wastewater is hydrogen sulphide, which is produced by anaerobic microbes that convert sulphates into sulphides. The significance of odour is largely psychological, causing stress rather than direct physical harm. Offensive odours can affect appetite, water consumption, and breathing, and may induce nausea, vomiting, and other mental health effects. Wastewater is typically turbid or cloudy, containing materials such as faeces, paper, oil, vegetable debris, and fruit skins. Water temperature plays a critical role in the survival of aquatic life, chemical reaction rates, and the suitability of water for various uses. Rising temperatures can alter the composition of fish species in receiving water bodies. Warm wastewater from households and industrial activities can increase the temperature of wastewater above that of the source water. The chemical properties of wastewater generally include pH, total solids, suspended solids, chloride and nitrogen content, oils, fats, dissolved oxygen, grease, gases, chemical oxygen demand (COD), and biochemical oxygen demand (BOD). Wastewater contains bacteria and other living organisms, including algae, fungi, and protozoa. Many opportunistic bacteria, such as *Enterococcus faecalis*, *Enterobacter cloacae*, *Proteus vulgaris*, *Pseudomonas aeruginosa*, *Klebsiella pneumoniae*, and *Escherichia coli,* can be transported by wastewater, potentially causing a variety of systemic diseases, particularly in individuals with weaker immune systems [4, 5]. Wastewater also contains obligate pathogens from the *Salmonella* and *Shigella* genera, as well as enteropathogenic strains of *Escherichia coli*, which can cause gastroenteritis, shigellosis, or salmonellosis [6].

Importance of Wastewater Management

Effective management of wastewater is pivotal for protecting the environment, safeguarding human health, and sustaining natural resources. The entire process of wastewater management ensures that industrial and human excreta are discharged without posing any hazard. This process primarily includes the collection, treatment, and reuse or disposal of effluent from domestic, industrial, and agricultural sources [7]. The main objective of wastewater management is to enhance the chemical, physical, and biological quality of wastewater by removing solids, organic contaminants, and sludge. Therefore, wastewater management involves handling wastewater in a way that protects the environment and public health, as well as economic, social, and political stability. Generally, four conventional treatment methods are used in the treatment of wastewater: preliminary, primary, secondary, and tertiary treatment [8]. Wastewater management is essential due to the following reasons:

CHAPTER 2

Microbial Remediation: A Sustainable Approach to Wastewater Treatment

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Abstract: Microbial remediation is an eco-friendly and sustainable method for treating wastewater that uses microorganisms like bacteria, fungi, and algae to break down organic pollutants, heavy metals, and toxins. Compared to conventional chemical or physical treatments, it is more cost-effective, energy-efficient, and has a lower environmental impact. Microbial consortia enhance pollutant degradation through cooperative interactions, making this method effective for industrial, municipal, and agricultural wastewater treatment. In industrial contexts, microbes can degrade petroleum hydrocarbons, dyes, and metals; in municipal systems, they reduce nitrogen and phosphorus levels, helping prevent eutrophication, and in agricultural systems, they break down pesticides and animal waste. Genetically modified microorganisms (GEMs) offer even greater potential by functioning in harsh environments or targeting persistent pollutants, though they raise environmental and ethical concerns. Despite challenges such as fluctuating microbial activity and changing environmental conditions, ongoing research aims to improve microbial resilience and treatment efficiency through genetic engineering, optimized consortia, and advanced bioreactor design. This chapter explores the principles, applications, challenges, and future directions of microbial wastewater treatment.

Keywords: Eutrophication, Genetically Engineered Microorganisms (GEMs), Heavy metals, Microbial remediation, Pollutants, Sustainability, Wastewater.

INTRODUCTION

In recent decades, water pollution has gained significant attention and become a significant environmental issue on a global scale [1]. The global economy now faces significant challenges in ensuring energy stability and environmental preser-

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vation as a result of rapid industrialization and population growth. Natural resources such as water and fossil fuels have been heavily utilized to fulfil human needs [2]. Numerous factors, including mineral extraction, urban development, automated processes, and a growing population, contribute to pervasive water contamination [3]. The release of hazardous materials from industries and household waste into sewage systems is the main cause of the daily rise in water pollution.

Furthermore, mining and smelting of metalliferous ores, uncontrolled and controlled waste disposal, accidental and process waste spills, and the use of sewage sludge in agricultural fields are some of the activities that cause pollutants to leak into clean water bodies as leachate, contaminating our ecosystem. Rapid urbanization has increased the concentration of hazardous heavy metals in water, leading to physiological, genetic, and environmental problems. Heavy metal intrusion into the water has affected seed viability and complicated the conventional regeneration plan. Cadmium, fluoride, and lead are among the most commonly found contaminants in wastewater.

Wastewater from the paper industry is produced in vast quantities and contains heavy metals such as mercury and arsenic, two of the most prevalent heavy metals, along with high concentrations of chlorinated, phenolic, and lignin-derived pollutants, as well as sulfonated compounds. Wastewater and manufacturing debris releases into waterways have been connected to metal pollution in aquatic life. These metals readily attach to suspended particles, accumulate in riverbeds, and may later be released into surrounding water bodies, posing a serious risk to human health [4].

Industrial wastewater affects both the animal and plant life in the environment and also impacts groundwater quality. When these hazardous metals are consumed through tainted food and water, they can build up in humans and animals, which can have even more detrimental effects. Metals such as copper (Cu), cadmium (Cd), lead (Pb), and zinc (Zn) are commonly found in nature, particularly in water bodies. These metals are highly mobile and soluble and can seriously harm human health and the environment. Compared to organic chemicals, heavy metals pose distinct challenges and represent a major portion of inorganic pollutants [5]. Although plants and animals require trace amounts of metals, high concentrations of these elements can be harmful and cause oxidative stress because of the production of free radicals [6]. These heavy metals are hazardous because they can interfere with enzyme activity or replace essential metals in biological pigments [7, 8]. Consequently, heavy metal contamination disrupts microbial biodiversity and renders soil unusable for plant growth. With the growing number of polluted areas worldwide, a workable strategy to limit the spread of contaminants while reducing toxic levels is crucial. One promising approach involves the use of microorganisms to remove toxins from a contaminated environment. Biological treatment of aquatic systems involves using natural microorganisms to transform and detoxify pollutants in the environment.

Microbial and physicochemical processes are combined to treat wastewater, and the choice of treatment method is mostly dictated by operating expenses, the quality and origin of the wastewater influent, and the effluent's intended use [9]. A natural process called bioremediation employs plants, fungi, and bacteria to break down, decrease, and remove pollutants from water, thereby cleaning contaminated areas and restoring them to a safe state. Bioremediation is a method of environmental cleanup that is becoming increasingly common because it is both economical and environmentally friendly. There are several approaches to bioremediation, including physical, chemical, and biological methods. Physicochemical processes such as ozone treatment, carbon adsorption, electrocoagulation, and flocculation are commonly used in wastewater treatment. In microbial remediation, microorganisms such as *Pseudomonas, Bacillus, Achromobacter, Aspergillus, and Rhodococcus* play important roles in pollutant degradation.

One type of remediation that occurs in the natural environment is called phytoremediation. This strategy is predicated on chemical, biochemical, microbiological, and biological interactions between plants and pollutants. The breakdown of contaminants by fungi such as *Aspergillu*s species and *Actinomycetes* is known as fungal bioremediation. Cyanobacterial bioremediation involves the use of cyanobacteria to degrade organic pollutants and absorb nutrients from contaminated environments. Textile wastewater contains numerous environmentally hazardous substances, such as organic dyes, vibrant colours, high chemical oxygen demand (COD), heavy metals, phosphate, nitrates, and sulphates. By absorbing these nutrients, microalgae can grow and convert them into beneficial biofuels, such as biodiesel. Bioremediation can also contribute to the cleanup of radioactive pollutants by transforming radioactive substances into less harmful forms through biological processes. To remove or immobilize pollutants, less toxic forms of contaminants are produced during the remediation process. The procedures require the use of naturally occurring microbes that degrade dangerous contaminants and utilize them as nutrients for growth. Therefore, bioremediation is effective only in environments that support suitable microbial activity [2]. In this chapter, we briefly highlight the potential of various wastewater treatment technologies, particularly natural microbial bioremediation.

CHAPTER 3

Indigenous Microorganisms in Wastewater Remediation: Unlocking Sustainable Solutions through Biofilm Technology

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Abstract: Indigenous microorganisms offer a promising, sustainable solution for wastewater remediation by utilizing their natural adaptability and resilience. Indigenous biofilms are particularly effective at biodegrading pollutants, including organic compounds and heavy metals, through processes such as biosorption, biotransformation, and bioaccumulation, which are supported by the extracellular polymeric substances (EPS) that make up the biofilm matrix. Studies show that indigenous microorganisms, naturally adapted to their local environments, usually require little or no pH adjustments, helping lower both treatment costs and environmental impact. Moreover, biofilm-based remediation offers superior pollutant tolerance and enhanced microbial activity over traditional planktonic approaches, making it ideal for both municipal and industrial wastewater settings. While the potential of indigenous biofilms is clear, challenges still remain, including the need for optimal substrate selection and seasonal environmental management to maintain biofilm stability. Advancements in microbial ecology and genetic engineering may further augment these systems, providing a scalable solution for future wastewater treatment demands. This chapter evaluates recent advances in the application of indigenous microbes in biofilm-mediated wastewater treatment, with emphasis on their unique metabolic pathways, structural biofilm matrix, and cost-effectiveness compared to conventional methods. It also underscores the importance of indigenous microorganisms in achieving eco-friendly wastewater treatment, providing a pathway for further research and application in large-scale environmental remediation projects.

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Keywords: Biodegradation, Biofilm-based remediation, Extracellular Polymeric Substances (EPS), Indigenous microorganisms, Pollutants, Sustainable wastewater treatment, Wastewater bioremediation.

INTRODUCTION

The term "indigenous microorganisms" refers to the unique and diverse assemblages of microscopic life forms that have naturally colonized and adapted to the specific physicochemical conditions of any given ecosystem. These are not transient inhabitants but stable microbial communities with a long evolutionary history in their specific environment. This prolonged coexistence has equipped them with specialized physiological and metabolic capabilities that are finely tuned to the challenges and resources of their native habitat [1]. A key attribute of these locally adapted microbial populations lies in their inherent ability to interact with and transform the biogeochemical cycles within their ecosystems, playing crucial roles in processes such as the degradation of organic pollutants, the cycling of essential nutrients, and the sequestration of toxic heavy metals [1]. Indigenous microorganisms, unlike exogenous or introduced microbial strains, are well-adapted to their natural habitats and are able to thrive there [2, 3]. Their genetic makeup and physiological machinery have been shaped by generations of exposure to the specific environmental parameters, including temperature fluctuations, pH variations, nutrient availability, and the presence of both natural and anthropogenic compounds. This pre-adaptation often translates to a higher degree of resilience and metabolic efficiency when confronted with environmental stressors and contaminants that are characteristic of their native locale [2, 3]. The metabolic versatility and remarkable genetic diversity inherent in indigenous microbial communities make them particularly effective at tackling complex organic contaminants, including recalcitrant chemicals, persistent insecticides, and the complex structures of hydrocarbons [4]. Unlike conventional treatment methods that may struggle with these substances, the diverse enzymatic repertoire present within these native microbial consortia often includes pathways specifically evolved for the breakdown and detoxification of such compounds. This intrinsic capacity for bioremediation, driven by the synergistic actions of various microbial species within the community, underscores the significant potential of harnessing indigenous microorganisms for sustainable environmental management and restoration [4]. Furthermore, their established ecological roles within the ecosystem allow for a more integrated and potentially less disruptive approach than the introduction of foreign microbial entities.

Indigenous microbial communities are not merely inhabitants of wastewater systems; they are the driving force behind the essential biogeochemical cycles that support treatment processes and helpmaintain of ecological balance within these complex environments. Their inherent metabolic capabilities and complex interspecies relationships are fundamental to the efficient removal of pollutants and the transformation of nutrients. The established presence and evolutionary adaptation of these native microorganisms make them uniquely suited to the dynamic and often challenging conditions prevalent in wastewater treatment plants and natural water bodies receiving wastewater discharge. A prime example of the critical role played by indigenous microbes in biogeochemical cycling within wastewater systems is the nitrogen cycle, a cornerstone of nutrient removal. Autotrophic bacteria belonging to the genera *Nitrosomonas* and *Nitrobacter* are key players in this process [5]. *Nitrosomonas* species mediate the oxidation of ammonia (NH_3), a common nitrogenous pollutant in wastewater, to nitrite (NO_2^-). Subsequently, *Nitrobacter* species further oxidize nitrite to nitrate (NO_3^-). This two-step nitrification process is crucial for the removal of toxic ammonia and the conversion of nitrogen into less harmful forms that can be further processed through denitrification by other indigenous bacteria under anaerobic conditions, ultimately leading to the release of nitrogen gas (N_2) into the atmosphere [5]. These autotrophic nitrifiers thrive in specific microenvironments within the wastewater system, often forming biofilms that provide a stable matrix for their activity and protection from environmental fluctuations. Furthermore, the breakdown of complex organic materials, a primary objective of wastewater treatment, is largely facilitated by a diverse array of indigenous heterotrophic microbes [5]. These microorganisms possess a wide range of extracellular enzymes capable of hydrolyzing large organic polymers such as carbohydrates, proteins, and lipids into smaller, more readily utilizable substrates. This initial breakdown not only reduces the organic load of the wastewater but also generates a pool of simpler organic compounds that serve as carbon and energy sources for a multitude of other microbial interactions within the ecosystem [5]. The metabolic activity of these heterotrophs is influenced by factors such as the availability of oxygen, the nature of the organic substrate, and prevailing temperature, leading to a dynamic succession of microbial populations as the wastewater treatment process progresses. Beyond individual metabolic capabilities, symbiotic connections are a common and crucial feature of these indigenous microbial ecosystems in wastewater [6]. These intricate relationships, inwhich different microbial species interact closely, often involve the utilization of one species' metabolic waste products as a substrate by another. This metabolic handoff maximizes the efficiency of resource use within the system, reducing the accumulation of intermediate compounds and promoting a more complete degradation of pollutants [6]. For instance, the organic acids produced by fermentative bacteria during the initial stages of anaerobic digestion can act as readily available carbon sources for sulfate-reducing bacteria or methanogenic archaea in later stages. Such syntrophic interactions are essential for the overall

CHAPTER 4

Genetically Modified Microorganisms as a Biotechnological Tool For Wastewater Treatment

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Abstract: Wastewater treatment has been transformed by genetically modified microorganisms (GMMs) to increase pollutant removal efficacy while minimizing environmental impacts. Although this approach is conventional, it does not address persistent and hazardous contaminants. GMMs overcome these constraints through better metabolic capacities, increased resistance to unfavorable circumstances, and targeted breakdown of dangerous substances (cadmium, lead, mercury, nitrogenous wastes, and complex organic components). These microbes are more efficient than natural strains and can be modified to produce specific enzymes that break down or immobilize resistant contaminants. They also have applications as biological indicators that fluoresce or change color in the presence of contaminants for use in biosensing applications where real-time contamination can be monitored. This chapter examines the use of GMMs in wastewater treatment, focusing on advances in genetic engineering to further improve their effectiveness. Biosafety and the environmental risks posed by GMM release are also discussed. The most promising application of GMMs is their potential to disrupt wastewater treatment procedures and lead to more environmentally sustainable practices, greater resource recovery, and cleaner water.

Keywords: Bioremediation, Biosensing, Environmental biotechnology, Genetic engineering, Pollutant degradation.

INTRODUCTION TO GMMS IN WASTEWATER TREATMENT

The ever-increasing quantity and diversity of urban, industrial, and population waste streams represent major challenges for conventional treatment approaches. As such, a new approach, *i.e.*, genetically modified microorganisms (GMMs), has emerged that uses advances in genetic engineering to enhance microbial capacities

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in wastewater treatment. The specialty of these tailored microorganisms is that they can perform specialized tasks such as breaking down recalcitrant pollutants, detoxifying harmful substances, and recovering nutrients, thereby overcoming the limitations of common biological treatment approaches. The main advantage of GMMs is their ability to target and metabolize contaminants that other natural microbial populations cannot degrade. Removing complex organic chemicals, heavy metals, and xenobiotics from industrial effluents using traditional biological treatment may be difficult. Adding specific genetic features allows GMMs to be modified to generate enzymes or metabolic pathways that synthesize such compounds, rather than producing less hazardous and nontoxic byproducts [1]. One example of using microbial genomes to degrade synthetic colors, halogenated chemicals, or polycyclic aromatic hydrocarbons (PAHs) might involve the modification of genes encoding oxygenases, dehalogenases, or laccases. Another way GMMs are used in wastewater treatment is to reduce nutrient contamination, including excess nitrogen and phosphorus, from wastewater, often from domestic and agricultural runoff, causing aquatic environments to become eutrophic. GMMs increase the effectiveness of nitrification and denitrification processes by adding genes that maximize ammonia oxidation or nitrate reduction pathways. Genetically modified organisms that accumulate polyphosphate can also be used to increase phosphorus removal by storing and recovering phosphorus for use in agriculture [2]. Recycling nutrients that are polluted not only mitigates the harmful impacts of nutrient pollution on the environment but also helps promote the concept of the circular economy. Their ability to remove contaminants and release nutrients offers distinct opportunities for managing industrial effluents. Human welfare and the environment are under immense threat from toxic contaminants that are released from several industrial operations into effluent water, such as hydrocarbons, cyanides, and phenols. However, there are several limitations to using GMMs in wastewater treatment, including biosafety and environmental effects [3]. The outright negative ecological effects of GMOs and the benefits of their use make it imperative that strict measures be taken to contain them and conduct risk assessments. These concerns are being tackled by synthetic biology through kill-switch systems, limited gene circuits, and dependency on synthetic nutrients that are not available in ecosystems. The economic viability and scalability of GMM-based wastewater treatment systems have not been the subject of much research. While research in labs has shown promising results, those technologies still need to be made operationally stable and cost-effective enough to be applied on an industrial scale before they continue to be used. GMMs can be fully realized through cooperation among government organizations, businesses, and academia to overcome these obstacles [4]. In this chapter, we have discussed how genetically modified microorganisms are providing solutions to the most important environmental problems and how they are a revolutionary approach to wastewater treatment. By utilizing biotechnology, pollutant degradation can be improved, nutrients and resources can be recovered, and renewable energy can be made. However, they cannot be implemented successfully if problems related to biosafety, legal issues, and public acceptance are not carefully addressed. Further innovation is also needed to increase scale and reduce cost. As this area of study continues to develop, GMMs have the potential to transform wastewater treatment and meet global sustainability goals.

FUNDAMENTALS OF MICROBIAL BIOREMEDIATION

Appreciating the rudiments of microbial bioremediation requires examining the tenets of natural and engineered microbial degradation, the principal contaminants in wastewater, and the microbial goals that drive the process. Microbial bioremediation is one of the key biotechnologies that utilize microorganisms and their enzymes to mitigate the effects of various pollutants in soil, water, and air. Microorganisms are more reliable for pollution control since they can either metabolize or alter toxic pollutants [5].

Natural *vs.* Engineered Microbial Degradation

Intrinsic bioremediation, or natural microbial degradation, refers to the process by which naturally occurring microorganisms in the environment break down contaminants without (or with minimal) human assistance [6]. Naturally occurring metabolic pathways in these microbes allow them to degrade pollutants to less hazardous, more basic fractions: carbon dioxide, water, or biomass. This process is driven by microbial enzymes that are particularly suited to the environmental circumstances and types of contaminants present. One of its main benefits is the affordability and sustainability of natural bioremediation. Thus, constraining it to the local capacities of the local microbial communities may not be sufficient to deal with the complex contaminant. In addition, the performance of natural microbial degradation may be restricted by pH, temperature, oxygen levels, and nutrition availability. These restrictions have been overcome by the development of synthetic microbial decomposition techniques. These involve modifying the environment and engineering microbes that can degrade contaminants in one way or another. Two examples of engineered bioremediation are bioaugmentation, in which specific microbial strains are introduced into the contaminated site, and biostimulation, which results from increasing environmental conditions to favor indigenous bacterial activity [7].

Genetic engineering is important for engineered bioremediation by enhancing microbial capabilities. Methods such as CRISPR-Cas9, plasmid transfer, and synthetic biology introduce new enzymatic pathways to enhance the resistance of

CHAPTER 5

Recent Advances in the Performance of Microbial Biofilms in Wastewater Remediation

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Abstract: Microbial biofilms are structured communities of microorganisms, mainly bacteria, encased in a self-produced matrix that attaches to surfaces. These biofilms play a crucial role in wastewater remediation by effectively removing pollutants such as heavy metals, organic contaminants, nitrogen, phosphorus, and pathogens. Biofilms provide increased surface area for microbial activity, enhance biodegradation through microbial synergy, and provide protection against harsh conditions like high pH and low temperatures. Thicker biofilms handle higher pollutant loads and reduce sludge production, thereby lowering waste management costs. Innovations like nanomaterials and 3D-printed scaffolds improve biofilm growth, stability, and pollutant removal. Performance is influenced by environmental factors (temperature, pH, salinity, and nutrients) and by biofilm structure (thickness, density, and porosity). Accordingly, a thorough investigation into recent progress in optimizing microbial biofilm performance is essential for advancing sustainable and efficient wastewater remediation strategies.

Keywords: Biofilm support materials, Integration, Microbial biofilms, Sustainability, Wastewater remediation.

INTRODUCTION

Over 70% of the Earth is covered by water, but only 3% of that is fit for human use; the other 97% is saline water [1]. At least one month each year, almost 4 billion people worldwide suffer from water scarcity [2]. Access to safe and clean water is one of the main challenges of modern society, as freshwater supply and demand are becoming more out of balance, leading to dwindling water supplies worldwide. The environment and public health are seriously threatened by waste-

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water produced by various industrial and urban processes due to hazardous substances. Many ecosystems are contaminated when wastewater containing both organic and inorganic contaminants from various businesses is released into the environment. As a result, the timely treatment of industrial and urban wastewater is a crucial area of study for developing technologies that will enhance wastewater quality and comply with environmental regulations. Many researchers have concentrated their efforts on developing novel wastewater treatment methods to address environmental problems caused by contaminated water [3]. Chemical techniques like oxidation, chlorination, and biological treatments, as well as physical techniques like membrane filtration, adsorption, and coagulation/ flocculation, have been developed to limit pollutant risks and minimize wastewater discharge [4]. Nevertheless, the physical and chemical approaches have high operating costs and energy requirements. Utilizing biological agents, including bacteria, fungi, and plants, is a low-cost and environmentally beneficial substitute for the chemical and physical methods of environmental restoration that are currently in use. There are several methods for using bacteria to remediate wastewater, including dead or alive, floating, or immobilized [5]. Zhang *et al*. (2022) investigated how well microalgae cleaned up the contaminated water of the River Kaduna. They found that some physicochemical factors changed and the amount of contaminants, like TDS (9.9%), chloride (11.5%), Pb (71.0%), Ni (74.0%), Cd (70.0%), TSS (66.7%), BOD (33%), COD (24%), nitrate (42.9%), alkalinity (62.5%), sulfate (37.5%), conductivity (9.8%), and turbidity (71%), significantly decreased [6]. Because typical wastewater treatment plants face various constraints, bioremediation has gained recognition as an environmentally acceptable method for decontaminating hazardous chemicals to ensure environmental safety and preservation. As part of the bioremediation process, microbial populations—which include bacteria, fungi, and algae—are employed, which typically neutralize,mineralize, decompose, and frequently remove a variety of inorganic and organic contaminants from contaminated environments and wastewater [7]. Biological remediation is a widely utilized remediation technique that uses a wide range of metabolic capacities of bio-inoculants to improve and lessen environmental toxins. It works well, is safe for the environment, compatible, and economically viable. In order to develop sustainable *ex situ* and *in situ* biological remediation processes for the efficient removal and reduction of hazardous pollutants, cutting-edge environmental research is being carried out based on the remediation strategy and the current contaminants. Pollutants are treated on-site by *in situ* biological remediation and off-site by *ex situ* bioremediation. For the mitigation and reduction of environmental contaminants, *in situ* approaches are more advantageous and cost-effective than *ex situ* procedures, since they disrupt the site less and incur lower transportation costs [8]. A well-organized community of microorganisms immobilized in an extracellular polymeric substance (EPS) matrix produced by the microorganisms is known as a biofilm. EPS provides protection against environmental hazards on biotic or abiotic surfaces, contaminants, and predatory protozoa. EPS is made up of humic chemicals, proteins, lipids, polysaccharides, nucleic acids, and surfactants [9].

Biofilm-mediated remediation, one of the numerous approaches, has been recognized as a cost-effective and environmentally responsible substitute for environmental cleanup. Due to their exceptional adaptability, efficiency, genetic diversity, and cellular simplicity, microbial communities hold great potential for restoring damaged ecosystems. Detoxification of hazardous metal pollution can be achieved by indigenous microbial communities through biomineralization, biotransformation, biosorption, and bioaccumulation. Biofilm-mediated remediation has been considered a safe, effective, and well-organized alternative to planktonic microorganisms for the removal or degradation of contaminants (Fig. **1**). It is currently employed as a cutting-edge remediation substitute for the biological breakdown of pollutants in the environment [10].

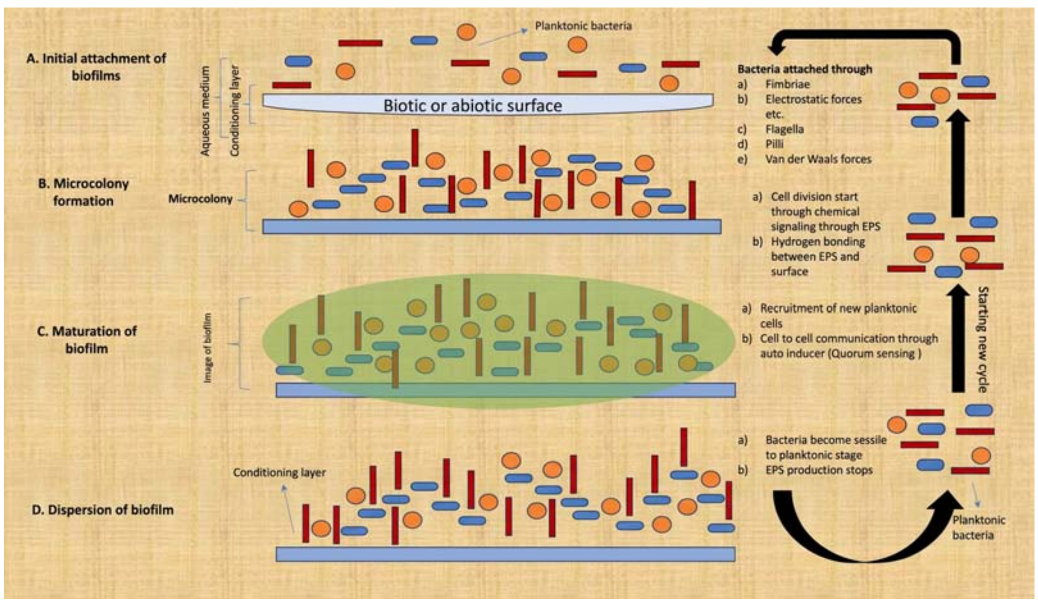

Fig. (1). Process of biofilm formation.

WASTEWATER POLLUTION SOURCES AND CAUSES

Wastewater refers to contaminated or polluted water. This contamination can occur due to physical (suspended solid particles), chemical (arsenic, lead,

CHAPTER 6

Microalgae: An Emerging Tool for Treatment of Industrial Wastewater and Biofuel Production

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Abstract: The world's rising population, along with rapid industrialization, has increased environmental problems such as wastewater (WW) discharge and global warming. Finding effective WW treatment systems is critical for environmental protection and water resource conservation. In this view, microalgae culture emerges as a viable solution for both WW treatment and biofuel production. In recent years, there has been greater emphasis on microalgae-based technology because of its superior performance in WW treatment, nutrient restoration, and the production of alternative biofuels or other valuable commodities. Microalgae have shown enormous potential for treating WW and sewage in recent decades. Despite the availability of cutting-edge WW treatment technologies, finding a reliable, cost-effective, and environmentally friendly solution is still tough. Microbes' inherent ability to filter water by digesting and eliminating contaminants holds great potential. Microalgal biofuels are one of the most promising renewable energy sources for long-term sustainability, having the potential to replace fossil fuels. The main challenges associated with oil crops and lignocellulose-based biofuels are also not present in microalgae biofuels. This chapter highlights recent breakthroughs in the field, highlighting the potential of microalgae-based technologies for WW treatment and biofuel generation.

Keywords: Bioremediation, Biofuel, Contaminants, Cost-effective, Emerging contaminants, Microalgae, Sustainable, WW treatment.

INTRODUCTION

The rapid growth of the global population and the acceleration of industrialization have led to significant environmental challenges, particularly in the management of WW and in the quest for sustainable energy sources. As urbanization continues

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to expand, the discharge of untreated or inadequately treated WW into natural water bodies has become a pressing concern, resulting in pollution, ecosystem degradation, and public health risks. Concurrently, the reliance on fossil fuels for energy production has contributed to climate change, necessitating the exploration of alternative renewable energy sources. In this context, microalgae have emerged as a promising solution, offering dual benefits in WW treatment and biofuel production [1, 2].

Microalgae are photosynthetic microorganisms that thrive in aquatic environments, utilizing sunlight, carbon dioxide, and nutrients to grow rapidly. They possess unique characteristics that make them highly efficient in biomass production, often outpacing traditional terrestrial crops. With an estimated 30,000 to 1,000,000 species, microalgae represent a largely untapped resource, with only a fraction being commercially cultivated. Their ability to absorb nutrients such as nitrogen and phosphorus from WW not only aids in bioremediation but also contributes to the production of high-value biomass that can be converted into biofuels, including biodiesel, bioethanol, and biogas [3, 4].

The integration of microalgae into WW treatment systems offers a sustainable approach to mitigating the adverse effects of pollution. Microalgae can effectively remove contaminants, including heavy metals, pharmaceuticals, and emerging pollutants, through various mechanisms such as biosorption, biodegradation, and nutrient uptake. This process, known as phycoremediation, not only improves water quality but also enhances the overall efficiency of WW treatment facilities. Furthermore, the biomass generated during this process can be harvested and processed into biofuels, creating a circular economy that promotes resource recovery and energy sustainability [5, 6]. In addition to their environmental benefits, microalgae have significant economic potential. The global biofuel market is rapidly expanding, driven by the need for cleaner energy sources and the reduction of greenhouse gas emissions. Microalgae-based biofuels offer several advantages over traditional biofuels, including higher yields, lower land requirements, and the ability to utilize non-arable land and WW for cultivation. This makes microalgae an attractive option for countries seeking to diversify their energy portfolios and reduce their dependence on fossil fuels. Despite the promising potential of microalgae, several challenges remain in their widespread adoption. Factors such as high production costs, technological limitations, and regulatory hurdles must be addressed to facilitate the integration of microalgae into existing WW treatment and biofuel production systems. Ongoing research and innovations are crucial to overcoming these barriers and unlocking the full potential of microalgae as a sustainable solution for environmental and energy challenges.

This chapter aims to provide a comprehensive overview of the role of microalgae in WW treatment and biofuel production, highlighting recent advancements, challenges, and future directions. By examining the multifaceted benefits of microalgae, we can better understand their potential to contribute to a more sustainable and resilient future. Through collaborative efforts among researchers, industry stakeholders, and policymakers, the integration of microalgae into environmental management and energy production can pave the way for innovative solutions to address the pressing challenges of our time.

MICROALGAE AND THEIR MARVELS

Microalgae use sunlight more effectively than land plants, leading to higher growth and biomass production that can exceed those of vascular plants by orders of magnitude [7]. Microalgae may be grown without competing for land resources, yet they provide approximately half of the oxygen in the environment. Microalgae are a highly underutilized resource. Microalgae have recently been used to detoxify a wide range of toxicants from agricultural, industrial, and residential sources. Many microalgae species, including *Botryococcus* sp., *Scenedesmus abundans, Chlorella variabilis, Chlorella* sp., *Scenedesmus obliquus, Scenedesmus* sp., *Chlorella sorokiniana*, and *Chlorella vulgaris*, have been reported to be useful for treating domestic WW [8 - 10]. Microalgae absorb carbon (C), nitrogen (N), phosphorus (P), and micronutrients, which are subsequently transformed into organic molecules [11]. The amounts of critical nutrients, such as N, and other renewable minerals, like P, found in WW are appropriate to contribute to carbon neutrality. Primary photosynthetic products are subsequently transformed into high-value chemicals, making this strategy economically attractive. As a result, the use of microalgae may help reduce the effect of global warming without polluting the environment.

Gathered algae biomass may also be converted into high-value biobased chemicals, such as alcohols, hydrocarbons, biohydrogen, and health supplements, to offset its production costs [12]. New breakthrough techniques may generate up to 70 tons of biomass and 15,000 L of oil per hectare of land every year. In order to produce biobased fuels that may be utilized commercially in automobiles and aircraft, microalgae can increase the output of high-quality biomass [13]. Microalgae were shown to mitigate 2.7% of global warming, 22.6% of ozone depletion, and 57.4% of eutrophication [14]. Therefore, combining wastewater treatment with microalgae to produce biofuel is a potential strategy. Additionally, microalgal biomass has other uses, such as serving as a feedstock for the production of lipids, proteins, carbohydrates, and vitamins. In addition to producing protein-rich feed, using microalgae for bioremediation may recover resources for cost-effective reuse *via* the biorefinery of microalgal/bacterial

CHAPTER 7

The Role of Cyanobacteria in Wastewater Treatment and Carbon Sequestration: Opportunities and Challenges

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Abstract: Global environmental pollution is increasing due to population growth, industrialisation, and improved living standards, which produce more wastewater and greenhouse gas emissions. Global warming is primarily driven by increased carbon dioxide (CO_2) emissions from the burning of fossil fuels. In this context, cyanobacteria have emerged as a promising solution for sustainable wastewater treatment and carbon dioxide reduction because they can survive harsh environmental conditions. Through photosynthesis, they increase oxygen levels, help remove heavy metals, reduce biological and chemical oxygen demand, decrease turbidity and mineral content, and eliminate harmful microbial contaminants. The use of cyanobacteria offers flexibility and efficiency in wastewater treatment, as they can be used as single-species or mixed cultures. This is a low-cost technology that is an alternative to the traditional tertiary wastewater treatments. Cyanobacteria are also able to withstand extreme conditions, including high and low temperatures, acidic pH, high salinity, and heavy metals, making them well-suited to different wastewater management systems. This chapter discusses the importance of cyanobacteria in CO_2 fixation and wastewater treatment, including their cultivation, mechanisms, and the factors that influence their performance. Moreover, this work examines the application of cyanobacteria for sustainable wastewater treatment and carbon sequestration, focusing on recent developments, limitations, and future research opportunities.

Keywords: Bioremediation, Carbon sequestration, Contaminants, Cyanobacteria, Environment, Pollution, Sustainable, Wastewater treatment.

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INTRODUCTION

Cyanobacteria or blue-green algae are a family of gram-negative prokaryotes that are significantly involved in biogeochemical cycles of the planet. They are among the oldest organisms on Earth, as fossils of these photosynthetic organisms date back more than 3.5 billion years. The ability to engage in oxygenic photosynthesis is one of the features of cyanobacteria, as they use sunlight, water, and carbon dioxide to generate oxygen and organic compounds that contain a large amount of energy. This ability alone played a crucial role in oxygenating Earth's atmosphere during the Great Oxidation Event [1 - 3]. Cyanobacteria are highly morphologically diverse, including unicellular and filamentous morphotypes, and grow in diverse environments, including freshwater and marine systems, as well as extreme environments such as deserts and hot springs. They have chlorophyll a, phycobiliproteins (phycocyanin and phycoerythrin), and carotenoids, thereby facilitating the collection of light at various wavelengths [4]. Their photosynthetic mechanisms are extremely efficient, allowing them to survive in low-light conditions in deep water or shaded areas. They have specialised cellular structures (such as thylakoids, which contain the photosynthetic machinery) and carboxysomes, which increase the efficiency of carbon fixation [3, 5]. Nitrogen fixation in cyanobacteria, such as *Anabaena* and *Nostoc,* occurs in heterocysts, specialised cells that shield nitrogenase enzymes from oxygen, allowing them to convert atmospheric nitrogen into bioavailable forms. proteinaceous microcompartments that contain ribulose-1,5-bisphosphate carboxylase/ oxygenase (RuBisCO), which improves the efficiency of carbon dioxide fixation [6, 7]. Such flexibility in cyanobacteria is also explained by their robust metabolic pathways and their ability to use a variety of carbon and nitrogen sources. In addition, they have adaptations for biofilm formation and the production of extracellular polymeric substances (EPS), which make them more resilient in the environment and provide structural support for wastewater systems. Cyanobacteria are part of the world's ecosystem, as they can survive under adverse conditions, including high salinity (*Spirulina* sp.), high temperatures (*Thermosynechococcus* sp.), and acidic environments (*Gloeothece* sp.) [8 - 10]. Cyanobacteria are fundamental components of global ecosystems. They are important for primary productivity in aquatic environments, as they serve as an essential food source for different trophic levels. Other photosynthetic organisms, such as the *Prochlorococcus* species, are the most abundant in the sea and fix large quantities of carbon. Their photosynthetic process is essential for balancing atmospheric carbon and oxygen concentrations, and their nitrogen-fixing ability increases nitrogen levels in soil and water bodies, which sustain agricultural and ecological processes [11 - 13]. Cyanobacteria have become potential agents in wastewater treatment because they capture and assimilate nutrients, including nitrogen and phosphorus, which are the major causes of eutrophication [14].

Cyanobacteria-mediated technologies have been applied to a range of wastewater types, including industrial, municipal, and agricultural runoff. In addition, cyanobacteria can be used to degrade organic pollutants and reduce heavy metal toxicity *via* biosorption and bioaccumulation. Their metabolic interactions with other microorganisms in bioremediation processes also enhance the effectiveness and efficiency of the wastewater treatment system [15, 16].

Cyanobacteria's high photosynthetic efficiency allows them to capture and fix carbon dioxide at high rates; therefore, they are useful in carbon sequestration programs. The biomass produced by the process can be used in multiple ways, such as for biofuels, bioplastics, and fertilisers, and can contribute to the circular economy [17]. Cyanobacteria are important for climate change mitigation strategies because they absorb carbon dioxide and reduce greenhouse gas emissions. The ability of cyanobacteria to treat wastewater and absorb carbon, in addition to their other benefits, highlights the potential of this science to serve as a sustainable solution to two of the most urgent global environmental issues: water pollution and climate change. In this review, the mechanisms, benefits, challenges, and future of these applications will be explored [18, 19].

MECHANISMS OF WASTEWATER TREATMENT USING CYANOBACTERIA

Cyanobacteria are used in wastewater treatment due to their ability to assimilate nutrients, degrade organic pollutants, and interact synergistically with other microorganisms in bioremediation systems. These systems are not only efficient but also economical and eco-friendly, and can be used to solve a broad spectrum of wastewater treatment problems.

Nutrient Uptake and Removal of Nitrogen and Phosphorus

Cyanobacteria use nitrogen in different forms, such as ammonium (NH_4^+), nitrate (NO_3^-), and nitrite (NO_2^-), which are taken up and incorporated into the cellular biomass. Nitrogen-fixing cyanobacteria such as *Anabaena* sp. and *Nostoc* sp. fix nitrogen in the atmosphere (as nitrogen, N_2) to bioavailable forms (*e.g.*, ammonia) by the action of the nitrogenase enzyme in heterocysts. Cyanobacteria are also known to participate in denitrification in wastewater systems, in which nitrate is reduced to nitrogen gas (N_2), thereby removing excess nitrogen [20, 21]. Cyanobacteria absorb phosphate (PO_4^{3-}) ions directly from wastewater, incorporating them into essential cellular components such as nucleic acids, ATP, and phospholipids. Under phosphorus-limiting conditions, some cyanobacteria can accumulate phosphorus as polyphosphate granules, which they later use. This potential will reduce the effects of eutrophication, particularly in agricultural and urban wastewater streams [22, 23].

CHAPTER 8

Biosorption: A Sustainable Environmental Remediation Technology for Wastewater Treatment

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Abstract: Biosorption is emerging as a sustainable and environmentally friendly method for wastewater treatment, providing an efficient and economical option for the elimination of heavy metals, dyes, and other hazardous pollutants from industrial effluents. This procedure employs biological materials, including algae, fungi, bacteria, and agricultural waste, to adsorb contaminants through processes such as ion exchange, complexation, and micro-precipitation. In light of increasing environmental concerns about traditional wastewater treatment methods, biosorption is distinguished by its biodegradability, low operational costs, and capacity for the regeneration and reuse of biosorbents. This chapter examines the concepts, methods, and different categories of biosorbents, offering a comprehensive overview of their application in pollutants removal. The chapter examines the determinants of biosorption effectiveness, including pH, temperature, and biosorbent properties, while emphasizing current progress in the domain. Challenges and future approaches are also discussed to advance biosorption as a feasible and scalable technique for extensive industrial wastewater treatment.

Keywords: Biosorbents, Biosorption, Eco-friendly, Environmental remediation, Heavy metals, Industrial effluents, Pollutants, Sustainable, Wastewater treatment.

INTRODUCTION

Microbes, plants, and algae are examples of biological materials that can be used in biosorption to remove pollutants from water by passively absorbing organic

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molecules, heavy metals, and other contaminants. A practical and environmentally acceptable technology for eliminating pollutants from wastewater and industrial effluents, this technique utilizes the intrinsic affinity of biological materials for toxins. In contrast to metabolically active biological processes, biosorption is a metabolically passive process. In this process, contaminants are physically or chemically bound to the surfaces of biological materials. Despite biosorption's numerous benefits, researchers are still working to address issues such as biosorbent regeneration, large-scale application, and pollutant-specific heterogeneity in biosorbent efficiency. The remarkable tunability and multifunctionality of biosynthesized nanocomposites, especially those containing carbon-based components, surpass those of traditional materials. The problem of pharmaceutical contaminants, heavy metals, pesticides, and dyes in the environment requires immediate, workable remedies. Abundant, low-cost, and environmentally friendly biomass waste is an easily accessible carbon source, making it a promising material for biochar production. Meanwhile, rapid urbanization and the growing demand for household water have significantly strained global water resources, leading to a rise in water-related challenges [1, 2]. The degradation of water resources has been driven by the release of inorganic pollutants from industrial and agricultural sources, including heavy metals, pesticides, and organic compounds. Contaminated water not only threatens public health but also contributes to water scarcity due to the presence of hazardous substances.

Considering the rising environmental concerns about the conventional methods of wastewater treatment, biosorption offers biodegradability, low operating expenses, and the ability to regenerate and reuse biosorbents. This chapter reviews the principles, techniques, and numerous types of biosorbents and provides insight into their use in the removal of pollutants. It explores the factors that determine the efficiency of biosorption, such as pH, temperature, and biosorbent characteristics, and highlights the existing developments in the field. Challenges and future strategies are also addressed to develop biosorption as a viable and scalable method for the large-scale treatment of industrial wastes in their water forms [3 - 6].

PRINCIPLES AND MECHANISMS OF BIOSORPTION

The concept of biosorption is that, given the right biological materials, pollutants in water, particularly heavy metals, can be absorbed and removed. The process does not need any metabolic activity but relies on contact between the biosorbent and the pollutant. The functional groups on the surface of the biosorbent react with contaminants in a number of ways, causing biosorption. Biological materials and contaminants interact in a wide range during biosorption. To maximize the effectiveness of biosorption in wastewater treatment, environmental cleanup, and the recovery of precious metals, one must be acquainted with its underlying principles and mechanisms [7]. Fig. (**1**) shows the principles and mechanisms of biosorption.

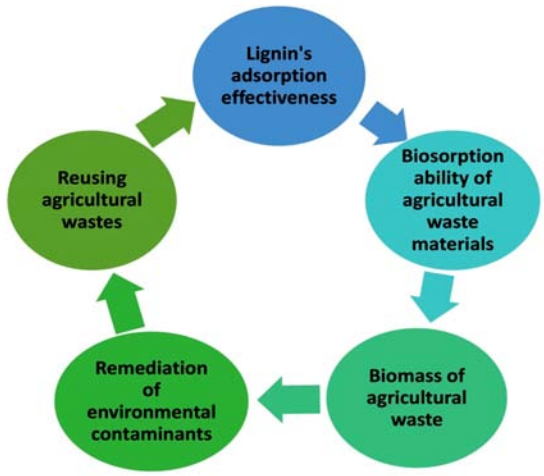

Fig. (1). Principles and mechanism of biosorption.

Environmental cleanup of pollutants using biosorbent material is done in multiple ways. Biosorption uses biomolecules or microbial cells to remove contaminants from water or wastewater. Biosorption involves binding, adsorption, and diffusion. In the adsorption process, the biomolecules or microbial cells in the biomass attract contaminants in the aqueous phase and bind them using biosorbent functional groups, including carboxyl, amino, or hydroxyl groups. Contaminants can be bound to biosorbents *via* ion exchange, complexation, chelation, or electrostatic attraction. Some factors that can affect the efficiency of biosorption include surface area, surface chemistry, temperature, contaminants in the aqueous phase, pH, and the biosorbent. Biosorbents can be regenerated by desorption, heat treatment, or chemical treatment after biosorption. Biosorption is one of the possible methods of purifying water contaminated with harmful dyes and heavy metals [8].

Fungi would be a good choice for removing heavy metals from water-based solutions due to their ability to trap and collect them. Chitosan is a biopolymer derived from chitin, a natural material that can be used to alter fungal biomass and enhance its biosorption capacity. Certain waste materials, such as metals and dyes, present in wastewater are removed using a chitosan-modified fungus. There are many species of bacteria and fungi that can be modified or developed to combat pollutants. Moreover, the biosorption process can be sustained because

CHAPTER 9

Principles and Applications of Membrane Bioreactors in Wastewater Treatment

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Abstract: Membrane Bioreactor (MBR) technology has emerged as an effective wastewater treatment technology compared to traditional wastewater treatment methods, producing high-quality effluents with lower energy consumption for both municipal and industrial discharges. This chapter discusses the important concepts and different applications of MBR technology for treating wastewater. Moreover, a brief discussion of the operating parameters of MBR, such as fouling, hydraulic and sludge retention times, and aeration intensity, has been included. These parameters determine the performance and sustainability of the system. The chapter provides an overview of different MBR configurations used in wastewater treatment. One challenge of MBR is membrane fouling, which reduces the lifespan of the membrane and necessitates its replacement. In order to mitigate this challenge, research has been carried out on hybrid systems, integrating MBR systems with nanofiltration and reverse osmosis processes. The chapter also covers the utilisation of digital tools, including machine learning algorithms, in the last section. It also discusses optimisation techniques for MBRs, focusing on improving performance under operating scenarios.

Keywords: Emerging contaminants, Membrane bioreactor, Resource recovery, Sustainablility, Water reuse, Wastewater.

INTRODUCTION

MBRs have evolved significantly and are now essential to modern wastewater treatment technology. MBRs were first designed in the late 1960s, but early implementations were limited by high costs and the short lifespans of available membranes. MBRs are now among the most sophisticated wastewater treatment solutions, thanks to improved membrane materials, manufacturing processes, and

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MBR design. For the first time, the combination of bioreactors and ultrafiltration and microfiltration membrane technologies has transformed the industry and provided treated wastewater that meets the most demanding discharge regulations [1, 2]. Over the decades, the integration of ultrafiltration and microfiltration membranes with biological treatment processes has revolutionized effluent quality standards, enabling compliance with stringent regulatory requirements [3].

Historical Development

The development of the first MBR systems dates back to the 1960s, when membranes for solid-liquid separation were introduced to improve the efficiency of the activated sludge process. The first systems were limited by expensive, energy-intensive membranes with a limited lifespan. Therefore, during this time, MBRs were mostly used for experimental and small-scale applications [2].

The technological boom of the 1990s and early 2000s saw rapid advances in MBR systems driven by improvements in membrane materials, especially those used for microfiltration and ultrafiltration. MBRs became more practical for large-scale use. New approaches, such as air scouring, were used to enhance operational efficiency and extend the lifespan of MBRs by reducing membrane fouling [3].

MBR technology began to gain traction in the 2000s as it became more commercially viable for the treatment of municipal and industrial wastewater. New designs for the membranes also improved energy requirements and compactness of treatment systems. The use of MBRs entered new phases of development for municipal wastewater treatment, decentralized systems, and industrial facilities [4].

The shift from external membrane modules to submerged configurations reduced energy requirements and improved system compactness. MBRs have been widely adopted for municipal wastewater treatment plants, decentralized systems, and industrial facilities [5, 6].

Current Trends and Innovations

Recent modifications to MBR design demonstrate their potential to produce high-quality effluents for water reuse while reducing operational costs and energy consumption [5]. These designs include new configurations intended to optimize energy efficiency, reliability, and overall system performance. Reliability and efficiency have been enhanced through improved membrane fouling control strategies, advanced cleaning techniques, membrane coatings, and air scour cleaning [6]. The potential applications of hybrid systems that incorporate MBRs with other technologies, including but not limited to anaerobic digestion, remain to be fully explored. The efficiency and sustainability of these systems can be further enhanced by using improved membrane materials, including new nanomaterials and biobased polymers [7]. MBR technology has advanced wastewater treatment to achieve high-quality effluent, emphasizing its importance in water recycling and conservation, particularly in water-scarce regions [8, 9].

Importance of MBRs

Wastewater treatment has seen the emergence of new technologies that can treat water to a higher quality and enable its reuse, while allowing treatment facilities to be more compact. The integration of biological treatment and advanced filtration in MBRs has changed the way water is managed in the municipal, industrial, and agricultural sectors [9].

High-quality Effluent

With respect to contaminants, MBRs provide excellent removal of organic materials, pathogens, and suspended solids, rendering the effluent suitable for industrial, agricultural, and non-potable municipal reuse. MBR effluent quality meets the most demanding environmental discharge regulations, reducing environmental pollution and helping preserve aquatic ecosystems [10].

Compact System Design

The membrane module design in MBRs allows higher biomass retention in the bioreactor, enabling a smaller system footprint. This compact design is what makes MBRs suitable for areas with a high population density; treatment facilities can be located in closer proximity to waterwaste sources [1].

Water Reuse and Conservation

In water-stressed areas, MBRs can recycle water for non-potable uses, thereby conserving freshwater resources and reducing demand on municipal water supplies. This approach provides a sustainable strategy for water management and is an effective way to counteract the increasing levels of water stress worldwide [8].

Enhanced Biological Treatment

Unlike other technologies, MBRs provide longer retention times for the breakdown of pollutants and can withstand variability in both the volume and type of wastewater due to superior microbial biomass retention and extended sludge retention times. Therefore, MBRs are particularly useful for treating wastewater streams that are heavily and variably polluted by industrial activities [11].

CHAPTER 10

Microbial Communities in Constructed Wetlands for Sustainable Wastewater Remediation: Advances and Future Directions

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Abstract: Constructed wetlands (CWs) are natural, low-cost wastewater treatment systems that exploit plant-microbe interactions and have attracted considerable attention. Therefore, understanding the specific microbial processes, such as nutrient cycling and pollutant and heavy metal degradation, in CWs is imperative. Equally important is understanding the recent developments in the targeted manipulation of microbial communities to enhance the functionality of these treatment systems. In this study, case studies from different regions will be examined in terms of their scalability and adaptability. The study will also summarize emerging trends, such as genetically engineered microorganisms (GEMs) and biofilm technologies, for improving the sustainability and effectiveness of CWs for wastewater remediation. In conclusion, this work highlights the key role of microbial communities in CWs and emphasizes their significance as a sustainable and green approach to wastewater treatment, along with the importance of soil inorganic nutrients in enriching microbial quality under fluctuating environmental conditions or stress.

Keywords: Constructed wetlands, Microbial communities, Microbial biofilms, Sustainable environmental technology, Wastewater remediation.

INTRODUCTION

Water pollution is a growing global crisis threatening human health, aquatic ecosystems, and sustainable development. With about 80% of sewage being released into the environment untreated, it contributes to a rapidly increasing contamination of both surface and groundwater resources [1]. Industrial effluents and domestic sewage in cities lead to the overload of organic pollutants, patho-

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gens, nitrogen- and phosphorus-based nutrients, and heavy metals [2]. In rural areas, water bodies may be polluted with pesticides, antibiotics, and animal waste through agricultural runoff [3]. These pollutants not only contaminate water resources but also lead to eutrophication, loss of flora and fauna, and the spread of various diseases.

Conventional wastewater treatment methods (such as activated sludge processes and chemical precipitation systems) are often capital-intensive and energy-demanding and require skilled personnel for operation [4]. Due to financial, logistical, or infrastructural barriers, these systems may not be feasible in many developing countries or decentralized communities. In this context, sustainable and nature-based solutions like CWs are a promising alternative [5]. These goals are aligned with the United Nations Sustainable Development Goals (SDGs) [6], particularly goal 6 (Clean Water and Sanitation) and goal 13 (Climate Action).

CWs as Eco-technologies

CWs are engineered systems that mimic the natural hydrological, biological, and chemical processes of wetlands to biologically treat a variety of wastewaters, such as municipal, agricultural, or industrial sewage and stormwater runoff [7]. Such systems usually include shallow basins with porous substrates (gravel, sand, and/or soil) planted with emergent aquatic vegetation (*e.g.*, *Typha*, *Phragmites*, and *Scirpus*). Vegetation not only provides surface area for microbial colonization but also releases oxygen through root exudates, stimulating aerobic microbial processes [8].

CWs can be further divided into horizontal subsurface flow (HSSF), vertical flow (VF), surface flow (SF), and hybrid systems [9]. In contrast, HSSF systems convey wastewater horizontally through the substrate below the surface, while VF systems distribute water vertically and intermittently enhance oxygen diffusion [10]. Hybrid systems leverage both mechanisms for better therapy [11].

In addition, CW are characterized by low construction and maintenance costs, a natural aesthetic appeal, habitat creation for flora and fauna integrated with the urban environment, and the ability to operate without external energy inputs. Furthermore, CWs can act as carbon sinks under controlled conditions by sequestering CO_2 and methane emissions, thereby contributing to climate change mitigation [12]. As a decentralized treatment option, CWs are increasingly being adopted in rural, peri-urban, and disaster-prone parts of the world where conventional infrastructure is lacking or unreliable [13].

Microbial Communities in CWs

In CWs, microbial communities act as the primary biological drivers of pollutant degradation. Bacteria, archaea, fungi, and protozoa colonize substrate surfaces, plant rhizospheres, and biofilms, coordinating a range of metabolic processes essential for wastewater remediation [14]. These processes include aerobic and anaerobic decomposition of organic matter, nitrification, denitrification, sulfate and iron reduction, and phosphorus removal *via* sorption and precipitation. Toxic compounds, such as hydrocarbons and pharmaceutical residues, are transformed into less harmful forms through these microbial activities [15].

For example, ammonia-oxidizing bacteria such as *Nitrosomonas* convert ammonia to nitrite, while *Nitrobacter* oxidizes nitrite to nitrate. Denitrifying bacteria, including *Pseudomonas* and *Paracoccus*, convert nitrate to nitrogen gas under low-oxygen (anoxic) conditions. Sulfate-reducing bacteria, such as *Desulfovibrio*, also contribute to the bioremediation of heavy metals by transforming them into insoluble metal sulfides that precipitate from the water. Fermentative microbes and methanogens act in deeper anoxic zones to degrade complex organic matter [16, 17].

Environmental factors such as temperature, pH, oxygen availability, organic loading rates, hydraulic retention time (HRT), and vegetation type govern the efficiency and resilience of microbial activity [18]. Seasonal variations can alter microbial abundance and diversity, affecting overall treatment performance. Microbial diversity is further stimulated by plant roots through rhizodeposition, which releases sugars, amino acids, and organic acids that serve as substrates and signaling molecules. Recent studies employing metagenomics, 16S rRNA sequencing, and shotgun metaproteomics have significantly advanced our understanding of microbial community structure and adaptive mechanisms in dynamic wetland environments [19].

STATEMENT OF PROBLEM

Although CWs have proven to be effective, several challenges remain in maximizing their microbial potential. Maintaining microbial diversity and the stability of functional processes under fluctuating environmental conditions is one of the most critical issues. Changes in microbial communities can result from seasonal variations, shifts in influent composition, or alterations in hydraulic load, thereby affecting treatment stability and resilience. Such fluctuations can lead to inefficient removal of specific pollutants, particularly emerging contaminants such as pharmaceuticals and endocrine-disrupting compounds, due to the lack of targeted microbial management strategies.

CHAPTER 11

Bioremediation of Heav Metal-Contaminated Wastewater

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Abstract: The toxic and non-biodegradable properties of metals have made them a major cause of wastewater pollution. Metals such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), and nickel (Ni) are released from various industrial activities, including mining, electroplating, tanning, and chemical manufacturing, and they pose serious risks to human health and the environment. These heavy metal (HM) pollutants originate as a result of industrial activities like mining, electroplating, tanning, and chemical manufacturing. Although many conventional methods, such as chemical precipitation, ion exchange, and membrane filtration, exist to remove these pollutants, they have many disadvantages, including cost-ineffectiveness, incomplete removal, and the generation of secondary pollutants. In order to mitigate these challenges, bioremediation is seen as a promising approach for treatingHM-contaminated water. As the name suggests, bioremediation involves the use of biological agents, particularly microorganisms, algae, fungi, and plants, for the eradication, transformation, and stabilization of HMs in contaminated environments. For example, bacteria and fungi like *Pseudomonas*, *Bacillus*, and *Aspergillus* species have significant potentialfor the bioremediation of HMs *via* cell-surface adsorption, intracellular uptake, and enzymatic transformation. Large-scale employment of bioremediation can be made cost-effectivethrough the phytoremediation process. The efficiency of bioremediation is influenced by various factors, including pH, temperature, metal concentration, and the presence of other pollutants. Along with numerous benefits, bioremediation also faces several challenges, such as process scalability, slow remediation rates, and the potential biohazards. This chapter provides insight into bioremediation as a sustainable, cost-effective, andeco-friendly treatment of HM-polluted water.

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Keywords: Bioremediation, Biodegradable, Eco-friendly, Heavy metals (HMs), Phytoremediation, Pollutants, Sustainable, Wastewater.

INTRODUCTION

Increasing industrialization and urbanization has made HM based water pollution a significant environmental concern. Industrial effluents are usually contaminated with HMs such as Pb, Hg, Cd, Cr, Ni, and As as a result of different industrial activities like mining, electroplating, leather tanning, and chemical manufacturing [1]. These metals are hazardous because they are non-biodegradable, persistent, and have a high tendency to bioaccumulate. These HMs have the capacity to cause severe damage to biological systems, affecting not only microbial communities in the soil but also human organ systems. For example:

I. Pb contamination affects neurological activities and cognitive development, particularly in kids.
II. Cd causes kidney failure and bone fragility.
III. Hg accumulates in aquatic food chains and poses risks to human health through the consumption of fish and seafood.
IV. Cr in its hexavalent state is highly toxic and carcinogenic.

All these metals have the potential to bioaccumulate and biomagnify across trophic levels, making them toxic to both humans and the environment [1]. Traditionally, they were removed using conventional methods such as chemical precipitation, ion exchange, membrane filtration, coagulation-flocculation, and electrochemical treatment [2]. However, these approaches have several limitations, including high costs, incomplete metal removal, the need for skilled personnel, and the generation of secondary pollutants. These drawbacks have led to the development of a more sustainable and environmentally friendly alternative known as bioremediation. Bioremediation refers to the removal, degradation, or detoxification of pollutants through the use of biological organisms such as microorganisms, algae, fungi, and plants [3].

Bioremediation has long been employed in the degradation of organic contaminants, such as hydrocarbons and pesticides. However, its potential for HM removal has only recently gained significant attention. The approach offers several advantages, including cost-effectiveness, environmental friendliness, and the ability to be implemented directly on-site [3]. Bioremediation operates through various mechanisms such as metal binding, sequestration, transformation, and compartmentalization. Bioremediation involves the adsorption of HMs onto the cell walls of microorganisms, followed by their active transport into cells, transformation into less toxic forms, and eventual precipitation as insoluble compounds [4]. This makes bioremediation an effective alternative, especially in areas where conventional treatment methods are technically challenging or economically unfeasible. Besides removing HMs from water, bioremediation can also be applied in the development of constructed wetlands and biofilters. It represents an interdisciplinary approach, drawing from microbial ecology, environmental chemistry, and molecular biology. Advancements in all these areas have led to the development of a bioremediation approach, such as:

I. Metagenomic Analysis has provided insights into the diversity of microbial communities present in polluted water, helping identify key species and genes responsible for metal remediation [5].
II. Genetic engineering enhances the potential of these organisms, providing them with better tolerance to higher concentrations of metals, enabling the expression of specific metal-binding proteins, and improving the ability to metabolize metals more efficiently [5].

Despite its numerous advantages, bioremediation faces several challenges. The efficiency of this approach is significantly influenced by various factors, including temperature, metal speciation, pH, redox potential, and the presence of competing ions or organic matter. Nevertheless, the field is advancing rapidly through the development of more robust and effective strategies, such as the use of microbial consortia, bioaugmentation with genetically engineered strains, and the integration of bioremediation with nanotechnology and other emerging technologies [6]. Bioremediation represents a paradigm shift in environmental management, offering a viable and low-impact solution to some of the most persistent and toxic forms of pollution. This chapter explores various facets of bioremediation and highlights its future prospects, emphasizing its dynamic and promising potential as a sustainable remediation strategy.

OVERVIEW OF HM CONTAMINATION IN THE ENVIRONMENT

HMs enter the environment through both natural and anthropogenic pathways. While natural sources such as rock weathering, volcanic eruptions, and forest fires contribute to some extent, their impact is relatively minimal. In contrast, human activities have significantly increased the concentration of HM contaminants in the environment [7].

Natural Routes

Natural processes contribute significantly to the release of HMs into the environment. Weathering of metal-containing rocks introduces elements such as Fe, Mn, Cu, and Zn into surrounding soil and water systems. Volcanic eruptions

CHAPTER 12

Current Trends, Challenges, and Future Prospects in Microbial Wastewater Treatment

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Abstract: The microbial treatment of wastewater is becoming a cornerstone technology in the pursuit of sustainable water management and environmental protection. This approach involves utilizing diverse microbial communities to break down organic pollutants and improve nutrient removal processes, contributing to solutions for global water challenges. Key microbial techniques, including membrane bioreactors (MBRs), anaerobic digestion, advanced oxidation processes (AOPs), and constructed wetlands, are known for their effectiveness in removing a broad range of contaminants, such as pharmaceuticals and microplastics. Among these, MBRs stand out due to their high treatment efficiency and adaptability; they integrate biological treatment with membrane filtration, achieving superior removal of organic pollutants, pathogens, and emerging contaminants. This dual approach enables MBRs to produce high-quality effluent, often suitable for reuse. Innovations in bioreactor design and bioaugmentation, such as the introduction of specific microorganisms (*e.g.*, *Pseudomonas putida and Rhodococcus erythropolis*), have further enhanced degradation efficiency and nitrogen removal. Additionally, emerging technologies like microbial fuel cells for energy recovery, as well as future advancements in machine learning and synthetic biology, are expected to optimize treatment processes and enable targeted contaminant degradation. However, the field faces challenges, including scaling difficulties, high costs, regulatory requirements, and public perception issues, along with technical demands stemming from the complexity of wastewater and variable contaminant levels. The chapter emphasizes the importance of collaboration among researchers, industry stakeholders, and policymakers to address these challenges and integrate microbial solutions within a circular economy model, ultimately supporting sustainable global water management practices.

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Keywords: AOPs, Bioaugmentation, Emerging contaminants, Microbial activity, Wastewater treatment.

INTRODUCTION

As the world becomes increasingly urbanized and industrialized and faces an urgent need for clean water resources, proper management of wastewater has become a key priority in the contemporary world. The growth in population and expanding industrial activities result in a rising complexity and volume of wastewater, thereby creating the need for effective treatment solutions that ensure public health and environmental protection. Among all the treatment options in water treatment, microbial processes have become the bedrock of the technologies employed to exploit the inherent capabilities of microbes to degrade organic waste and purify water [1, 2].

Biological treatment processes involve different microorganisms, ranging from bacteria and archaea to fungi, that break down organic matter and remove harmful substances from wastewater. It is beneficial primarily because this method is efficient, cost-effective, and environmentally friendly. Microorganisms play fundamental roles in a wide range of treatment processes, whereby they metabolize pollutants into less harmful byproducts [3]. For instance, aerobic bacteria include species such as *Pseudomonas* and *Bacillus* that thrive in oxygen-rich environments and effectively transform organic matter into carbon dioxide and water [4, 5]. Conversely, anaerobic bacteria, including methanogens, function under low-oxygen conditions and help reduce the volume of sludge produced while producing methane gas, which can be converted into renewable energy [1, 6].

The significance of microbial diversity in wastewater treatment is profound. It enhances the robustness of the treatment process against changes in environmental conditions and leads to higher pollutants removal efficiencies. Metagenomic analyses have shown that wastewater treatment plants (WWTPs) harbour highly diverse microbial communities, and specific phyla, such as *Proteobacteria* and *Firmicutes,* contribute significantly to the degradation of organic matter and removal of nutrients [7]. Therefore, optimizing the treatment strategy to address the microbial community and ensure effective pollutant degradation is necessary.

Microbe interaction plays a very important role in the efficient treatment of wastewater. Synergistic interactions, such as syntrophy, involve mutually beneficial relationships between different microbial species that break down complex organic compounds that neither species could degrade independently [8, 9]. For example, methanogens utilize hydrogen or fatty acids produced by fermentative bacteria during anaerobic digestion. This highlights the importance of maintaining healthy microbial communities to achieve the desired treatment outcomes [10].

Another critical component involved in wastewater treatment using microorganisms is biofilms. These structured microbial communities form on the surfaces of reactors and provide a protective habitat that promotes pollutant degradation [11, 12]. Biofilms facilitate efficient contact between microbes and contaminants, thus enhancing the removal rates of pollutants such as Chemical Oxygen Demand (COD) and nitrogen compounds [12]. Technologies such as moving bed biofilm reactors (MBBRs) utilize the growth of biofilm on plastic carriers to increase the surface area for microbial colonization, thereby significantly improving treatment performance.

Further advancements in bioreactor design are expected to pave the way for more efficient systems as the science of microbial wastewater treatment continues to evolve. Innovations such as membrane bioreactors (MBRs), sequencing batch reactors (SBRs), and integrated fixed-film activated sludge (IFAS) systems are designed to enhance nutrient removal capacity and overcome the inherent challenges associated with conventional treatment methods [13].

Among all these developments, bioaugmentation has emerged as a promising strategy to enhance biodegradation by introducing specific microorganisms with specialized metabolic capabilities into contaminated environments. This approach is particularly useful when the indigenous microbial population cannot effectively degrade certain pollutants. For example, some strains, such as *Pseudomonas putida,* are known to degrade aromatic hydrocarbons and can therefore serve as important bioaugmentation agents in wastewater effluent treatment [14].

In addition to conventional microbial technologies, novel approaches are emerging that further enhance the effectiveness of wastewater treatment systems. Advanced oxidation processes (AOPs) involve the use of powerful oxidants to produce hydroxyl radicals that can degrade highly resistant contaminants [15]. Phytoremediation, on the other hand, aims to degrade contaminants and generate oxygen simultaneously through light-activated processes involving microorganisms or other phototrophic organisms, such as algae [16, 17].

Recent developments also include the integration of these emerging technologies with existing microbial processes. For example, the combination of microbial fuel cells (MFCs) with conventional wastewater treatment can generate electricity during wastewater treatment, thereby simultaneously providing a source of renewable energy while removing pollutants [18, 19]. Additionally, smart technologies are being incorporated into bioreactor designs to enable real-time

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